The joint simulation of doubly-fed wind turbines

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Abstract. As a clean and safe renewable energy, wind power has been rapidly commercialized in recent years. In order to analyse some faults in wind turbines by software, a joint simulation model of 1.5 MW doubly-fed wind turbine is built in this paper. In the system, the 3D model of the transmission system was established by SolidWorks, which was imported into Adams to build the virtual prototype model. The other parts of the system are built by MATLAB/Simulink. Thus the advantages of Adams in mechanical multibody dynamics and MATLAB/Simulink in wind turbines control system are combined. The simulation result of the wind turbine output power under natural wind speed proves the validity of the model.

1. Introduction
Wind energy is a new kind of clean energy. It has the outstanding advantages of large reserves, wide distribution and small pollution, so it has been rapidly commercialized in recent years. However, wind turbines are usually installed on high mountains or at sea in remote areas, the poor working environment and the randomness of wind speed will affect the quality of the output power or even cause the failure of the unit. Therefore, establishing reasonable & accurate model by further studying of wind turbines modeling method is of great significance for improving the power quality of wind turbines [1].

The structure and operating principle of wind turbines are very complex. In order to get a comprehensive study, some joint simulations are done. For example, in literate [2], ADAMS and MATLAB are used to simulate the various misalignment conditions of the wind turbine transmission system to obtain the corresponding stator current; in literate [3], a co-simulation model of MW-class wind turbine system is established by using Simpack and Matlab/Simulink software, etc. In general, MATLAB/Simulink performances well in wind turbines modeling and their control parts, yet the simulation of mechanical faults of the transmission system is very limited [4]. While Adams, by contrast, can well simulate internal actual structure and more fairly reflect the circulation of the driving part. Therefore, the joint simulation technology based on Adams and MATLAB/Simulink has been used in many fields due to its irreplaceable advantages. For example, in literature [5], the mechanical model of brake was built by Adams and the ABS control system was established by MATLAB/Simulink, the simulation results met the national standards; In literature [6], a 3d model of a 4-dof SCARA robot was established by Adams to construct kinematics simulation. The step function and sine function were used as inputs, and the control algorithm was used to manipulate the robot joint by MATLAB/Simulink. The motion trajectory conformed to the expected planning; In literature [7], a model of a new transmission system of wind turbine was established by Adams. Using
MATLAB/Simulink, the simulation of the new speed control scheme based on intelligent fuzzy PID was carried out, the rotation angle of hydraulic torque converter at various speeds and the change of turbo-pump speed ratio are studied. It can be seen that joint simulation technology based on Adams and MATLAB/Simulink can be applied to the wind turbines and other complex electromechanical systems. In this paper, Adams and Simulink was combined to simulate 1.5 MW doubly-fed wind turbine, which not only provides a new modeling method for complex wind power system, but also provides a good way for further research on the unit. At last, the effectiveness of the model is proved.

2. The implementation of the joint simulation
The wind turbine system can be divided into four parts: Wind turbine, transmission system, variable pitch actuator, doubly-fed generator and its control system. Among them, the 3D model of the transmission system was established by SolidWorks, which was imported into Adams to build the virtual prototype model. The specific process has been described in detail in literature [8], which will not be repeated here. The other parts of the system are built by MATLAB/Simulink [9].

2.1. The model of the wind turbine
According to the aerodynamic principle and Bates theory of wind turbine, the power generated by wind turbine after absorbing wind energy is given as:

\[ P = 0.5C_p(\beta, \lambda) \rho \pi R^2 v^3 \]  

(1)

The corresponding mechanical torque is:

\[ T = \frac{P}{\omega} \]  

(2)

Where, \( \rho \) is air density (kg/m\(^3\)); \( v \) is wind speed (m/s); \( \beta \) is pitch angle (deg); \( \omega \) is wind turbine speed (rad/s); \( R \) is wind wheel radius (m); \( \lambda \) is blade tip speed ratio; \( C_p(\beta, \lambda) \) is wind energy utilization coefficient, which is closely related to blade tip speed ratio and pitch angle, the relationship between them can be approximated with a group of exponential functions:

\[
C_p(\beta, \lambda) = 0.22 \left( \frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-12.5 \frac{1}{\lambda_i}}
\]

\[
\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta - 0.035 \beta^3 + 1}
\]

(3)

2.2. Virtual prototype of transmission system based on adams
- Creating driving torque SFORCE_2 and load torque SFORCE_1 in the transmission virtual prototype, as shown in figure 1.

Figure 1. Driving torque and load torque in virtual prototyping.
Creating two input state variables $T$ and $T_e$ for the system, setting the functions of driving torque SFORCE_2 and load torque SFORCE_1 as VARVAL(T) and VARVAL(Te) respectively. Thus associating the state variable with the torque by specifying $T$ and $T_e$ as the two elements of the control platform input state variable PINPUT_Torque, as shown in figure 2(a).

The output state variable zhuanzi_velo of the model is created, which is the angular velocity of rotation of the output rotor axis centroid relative to the earth around the Z axis. Its function formula is set as $WZ(MARKER_376, MARKER_380) \times 180/\pi$, which is specified as the output state variable POUTPUT_Velo of the control platform, as shown in figure 2(b).

2.3. Variable pitch actuator model
The main function of the variable pitch actuator is to convert a demand into actual pitch angle by adjusting the attack angle of the blade to airflow, so that the energy utilization of the turbine is adjusted to control the output power of the unit. The electric variable pitch actuator used in this paper
can be represented as follows:

\[
\frac{d\beta}{dt} = \frac{1}{T_{\beta}} (\beta_r - \beta)
\]  

(4)

Where, \( T_{\beta} \) is the time constant, let it be 0.2s; \( \beta_r \) is the reference input of the pitch angle.

2.4. Doubly-fed generator and its control system

2.4.1. Mathematical Model of Doubly-fed Generator. Doubly-fed generator can feed power to the grid through stator and rotor. The stator winding is connected to the power grid; the rotor winding is connected to the grid through the bidirectional converter. By adjusting the amplitude, phase, frequency, phase sequence of the excitation voltage on the rotor side to control the magnetic field and rotating speed of the generator. The dynamic model of the doubly-fed generator is established in the two-phase synchronous rotating d-q coordinate system after the normal motor direction is selected.

Stator voltage equation:

\[
\begin{align*}
    u_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \\
    u_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds}
\end{align*}
\]

(5)

Rotor voltage equation:

\[
\begin{align*}
    u_{dr} &= R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_s \psi_{qr} \\
    u_{qr} &= R_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_s \psi_{dr}
\end{align*}
\]

(6)

Stator flux linkage equation:

\[
\begin{align*}
    \psi_{ds} &= L_s i_{ds} + L_m i_{dr} \\
    \psi_{qs} &= L_s i_{qs} + L_m i_{qr}
\end{align*}
\]

(7)

Rotor flux linkage equation:

\[
\begin{align*}
    \psi_{dr} &= L_s i_{dr} + L_m i_{ds} \\
    \psi_{qr} &= L_s i_{qr} + L_m i_{qs}
\end{align*}
\]

(8)

Electromagnetic torque equation:

\[
T_e = 1.5n_p L_m (i_{qs} i_{dr} - i_{ds} i_{qr})
\]

(9)

\[
\begin{align*}
    P_s &= \frac{3}{2} (u_{ds} i_{ds} + u_{qs} i_{qs}) \\
    Q_s &= \frac{3}{2} (u_{qs} i_{ds} - u_{ds} i_{qs})
\end{align*}
\]

(10)

Where u, R, i, Ψ, L, P, Q are voltage, resistance, current, flux, inductance, active power, reactive
power; subscript s, r represent stator and rotor, respectively; subscript d, q represents the d-axis and q-axis components of the d-q coordinate system; \( \omega_l \) is the electrical angular velocity (rad/s) of the grid; \( \omega_e \) is the angular velocity of the rotor excitation current (rad/s); \( L_m \) is the mutual inductance; \( n_p \) is the pole pair of the motor.

2.4.2. Structure and control strategy of dual PWM converter. AC-DC-AC dual PWM converters is mainly composed of grid-side converter, rotor-side converter and DC-link. The main circuit structure is shown in figure 4. The two converters form the structure of "back-to-back". The main circuit structure of them is identical, and the working state is reciprocal.

In figure 4, \( e_s \) is the phase voltage of the grid; \( L_g, R_g \) are the equivalent inductance and resistance of the grid-side converter; \( i_{gs} \) is the grid-side phase current; \( u_{gs} \) is the grid-side converter phase voltage; \( i_d \) is the output current of the grid-side converter; \( i_{dc} \) is the input current on the DC side; \( U_{dc} \) is the DC voltage; \( C \) is the DC link capacitance; \( i_L \) is the load current of the DC side; \( i_e \) is the rotor excitation current; \( L_S, R_S \) are equivalent inductance and resistance between the rotor side inverter and the rotor; \( e_{is} \) is the induced voltage on the rotor side; Q1~Q6 are the main switch of the inverter.

The stator voltage-oriented vector control scheme is adopted for the rotor-side converter to realize the control objective of active and reactive power decoupling [10,11]. The grid voltage-oriented control scheme is used for the grid-side converter to ensure the constancy of DC bus voltage and the stable sinusoidal waveform of the current input to the grid [12].

2.5. Establishment of the joint simulation model
Put adams_sub, the controllable module of the transmission system, into the control model of the wind turbine established by MATLAB/Simulink. The input and output signals of each module are connected, the joint simulation of the wind turbine is established as shown in figure 5.
3. The analysis of simulation results
Set the parameters related to the simulation method, for example, select single-machine co-simulation mode, set the animation mode to interactive, set the simulation mode to discrete, set the exchange interval to 0.005 s, output one exchange for each simulation step, and the others use the default settings.

The wind turbine parameters in this paper are: wind turbine radius $R=41.38$ m, rated wind speed $v_e=10$ m/s, cut-out wind speed $v_{out}=25$ m/s, air density $\rho=1.225$ kg/m$^3$, rated power $P_e=1.5$ MW.

When the natural wind speed shown in figure 6 is put into the model, the output power under Proportional Integral (PI) pitch controller is shown in figure 7.

It can be seen from figures 6 and 7 that when the wind speed exceeds the rated value, the pitch controller starts to work, the designed PI controllers can keep the output power at 1.5MW. This proves the correctness of the joint simulation model.

4. Conclusions
In this paper, a joint simulation model of 1.5 MW doubly-fed wind turbine is built, which not only enriches the modeling methods, but also provide a platform for fault diagnosis and pitch controller
design. The simulation result of the wind turbine output power under natural wind speed proves the effectiveness of the model.

In the following research, the performance of various pitch controllers and misalignment fault diagnosis between the gearbox and the generator will be further studied on this joint simulation model.

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