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Quasi-steady-state Model of Doubly-fed Wind Power System for Grid-Connected Simulation

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Abstract. With the wind power increasing quickly, its impact on power system becomes greater, thus the dynamic simulation study on grid-connected wind power generators has a significant importance. This paper focuses on introducing the quasi-steady-state approximation method into analyzing the operation characteristics of grid-connected doubly-fed wind power generators. Based on the detailed dynamic model of a variable-speed constant-frequency (VSCF) doubly-fed wind power generator, which consists of wind speed model, the integrated model of wind turbine and drive system, pitch angle control model, converter control model, and the integrated model of generator and converter, the quasi-steady-state approximation method is introduced and applied to simplify the detailed dynamic model to be an order-reduced model, that is, the quasi-steady-state (QSS) model. The accuracy of the QSS model is shown by comparing simulation results of QSS model and the detailed model.

Introduction

The impact of grid-connected wind farms on power system stability becomes more and more significant due to wind farm's enlarging scale [1]. Moreover, the intermittence and fluctuation of the wind power is a big obstacle for its development since the voltage quality of power system consequently deteriorates owing to the voltage drop at the coupling point. All in all, it is imperative to research the characteristics of grid-connected wind farms by means of simulation.

Some papers have already discussed the modeling methods and operation characteristics of grid-connected wind farms. Paper [2] summarized the transient-state simulation models of three typical wind power generators, i.e., constant-speed constant- frequency generators and variable-speed constant- frequency generators of doubly-fed and direct-drive, and discussed the application of these models in studying the grid-connected wind farms. Paper [3] established an overall dynamic model for grid- connected doubly-fed wind power generators, which included models of the back-to-back converter and corresponding controller. These papers established either the electromagnetic transient model or the electromechanical transient model in detail, but both have high orders and need a large amount of data, making the simulation complex and difficult.

Sauer and Kokotovis studied the multi-time scale system and got some important results in [4]. Paper [5] used the multi-time scale theory to simplify the model of the grid-connected doubly-fed wind power generators. Papers [6] and [7] explored how to reduce the order of power system model based on the multi-time scale theory. In [8], the quasi-steady-state approximation method was adopted to simplify the power system simulation model for analyzing the mid- and long-term voltage stability.

This paper established a detailed model of the variable-speed constant-frequency doubly-fed wind power generators with referring to the model of GE's 1.5 MW wind power generator, which contains wind speed model, the integrated model of wind turbine and drive system, pitch angle control model, converter control model, and the integrated model of generator and converter. Then according to the laws of quasi-steady-state approximation, the detailed model is simplified to be an order-reduced QSS model with only keeping up the time constants of mid- and long-term scale. The order-reduced QSS model is fit for analyzing the characteristics of gird-connected doubly-fed wind power generators, which is verified by simulation.

Detailed Model of VSCF Doubly-fed Wind Power Generators

The developed detail model includes the wind speed model, the integrated model of wind turbine and drive system, the pitch angle control model, the converter control model, and the integrated model of generator and converter, as shown in Figure 1.

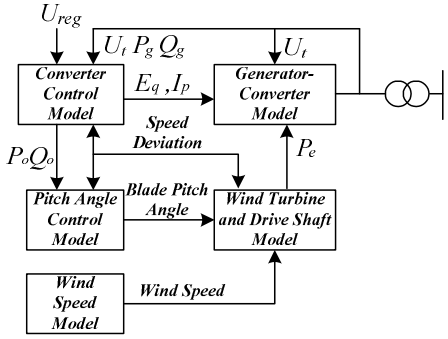


Fig.1 Dynamic model of VSFC doubly-fed wind power generator

1.1 Wind Speed Model

A popular wind speed model of four components, that is basic wind v_a, gust wind v_b, ramp wind v_c, and noisy wind v_d, is chose here [9]. Thus the actual wind speed v_w is expressed as:

$$v_w = v_a + v_b + v_c + v_d \tag{1}$$

1.2 Integrated Model of Wind Turbine and Drive System

The input mechanical power to the wind turbine from the wind energy available is proportional to the cube of wind speed v_w. Some wind energy is lost during the transformation [9]. The transformation formula is

$$P_w = \frac{1}{2} A\rho v_w^{\ 3} C_p(\lambda,\beta) \tag{2}$$

where P_w is the mechanical power, A is the area swept by the rotor blades in m^2, ρ is the air density in kg/m^3, v_w is the wind speed in m/s, β is the blade pitch angle in degrees, $\lambda = \omega_m R / v_w$ is the tip speed ratio, in which R is the radius of the wind turbine in m, ω_m is the rotor speed of the wind turbine in rad/s, C_p is the rotor power coefficient, which is a function of λ and β as follows:

$$C_p(\lambda,\beta) = 0.22\left(\frac{116}{\lambda_1} - 0.4\beta - 5\right) e^{-\frac{12.5}{\lambda_1}} \tag{3}$$

where， $\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$.

The drive system of doubly-fed wind power generator usually contains gearbox, drive shaft, and rotor. Here the wind turbine and the drive system are jointly equivalent to be a one-lumped mass block. The dynamic model is

$$2H\frac{d\omega}{dt} = T_w - T_e \tag{4}$$

where H is the inertia time constant of the equivalent lumped mass, ω is the rotor speed, and T_w is the mechanical torque, and T_e is the electromagnetic torque.

1.3 Pitch Control Model

When the wind turbine is rotating, the pitch control can adjust the pitch angle of the blades to change the angle between the air flow and the blades. The pitch angle of the VSCF doubly-fed wind power generator can be changed in the range of 0 degree to 90 degree, maintaining the maximum rotor power coefficient C_p to have the maximum input mechanical power [10]. The pitch control system of VSCF doubly-fed wind power generator includes two parts, i.e., pitch angle control and pitch angle compensation, as shown in Figure 2.

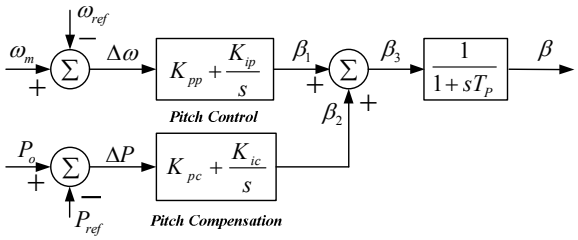
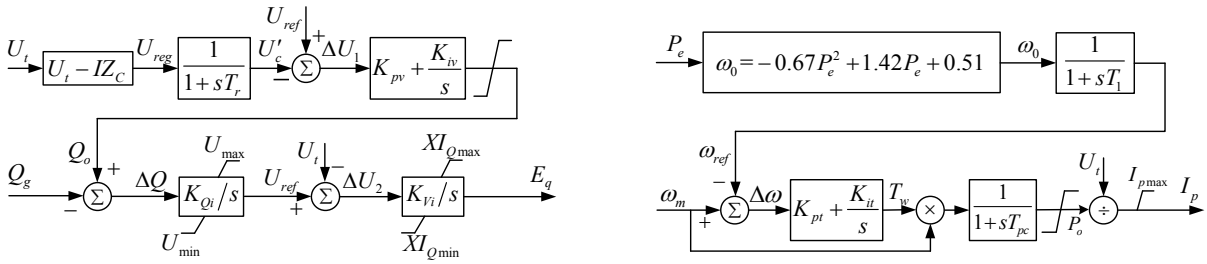


Fig.2 Pitch control model

Where, ω_m is the rotating speed of the wind turbine, ω_{ref} is the referenced rotating speed, P_{ref} is the referenced active power, P_o is the output active power of the converter, β is the pitch angle of the blades.

1.4 Converter Control Model

The converter control system can achieve the decoupling control of the active and reactive powers [11], and consists of two parts: reactive power control and active power control. The two control models are shown in Figure 3.



(*a*) Reactive Power Control (*b*) Active power control

Fig.3 Converter control model

(1) *Reactive Power Control*

As shown in Figure 3(*a*), the reactive power control command Q_o is determined by monitoring the voltage of the key node U_{reg}. And the reactive voltage command E_q is generated by the close-loop voltage control block after contrasting the terminal voltage of generator U_t with a voltage command gotten by comparing Q_o with the reactive power Q_g measured at the terminal of wind turbine.

(2) *Active Power Control*

As shown in Figure 3(*b*), the referenced rotating speed of wind turbine ω_{ref} is calculated accoring to the speed-power formula. The speed deviation $\Delta\omega$ between the referenced and actual rotating speeds is the input into a PI controller to get an output mechanical torque T_w. This torque multiplies with the actual rotating speed ω_m to get the active power command P_o. The active current command I_p is got by dividing P_o with the terminal voltage U_t.

1.5 Integrated Model of Generator and Converter

Different from the traditional models of synchronous generators, here the generator and the converter are equivalent to be a controlled current source I as a whole [11]. The current I is calculated based on the reactive voltage command E_q, the active current command I_p, and the equivalent transient reactance of generator X''. Since the convert's response is fast, a time delay block with a less constant is used to reflect the convert's dynamic behavior. The integrated model of generator and converter is shown in Figure 4. This integrated model can demonstrate the overall dynamic behavior of VSCF doubly-fed wind power generator and converter with relative accuracy.

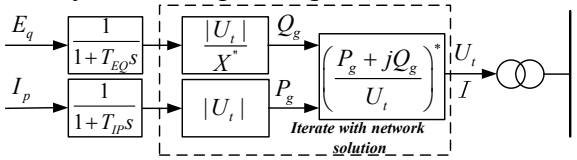


Fig.4 Integrated model of generator and converter

QSS Method

To improve simulation's efficiency and accuracy, Van Cutsem and other scholars proposed the quasi-steady-state approximation method in recent years [7]. This method has a clear physical concept, and ignores components' dynamic behaviors of short-term for exactly reflecting power system's dynamic characteristics of mid- and long-terms.

Wind power generation system is a complex nonlinear system. Its dynamic behavior can be completely described by a set of difference-differential-algebraic equations (DDAE) with continuous and discrete variables.

$$0 = g\left(x, y, z_c, z_d\right) \tag{5}$$

$$\dot{x} = f\left(x, y, z_c, z_d\right) \tag{6}$$

$$\dot{z}_c = h_c\left(x, y, z_c, z_d\right) \tag{7}$$

$$z_d\left(k+1\right) = h_d\left(x, y, z_c, z_d\left(k\right)\right) \tag{8}$$

where x is a vector of state variables corresponding to the transient process, y is a vector of algebraic values in the power system, such as a bus's voltage amplitude and phase; z_c represents the continuous variables, and z_d represents the discrete variables.

The QSS method originates from a discovery that the short-term and long-term phenomena of a power system can be distinguished clearly in the time domain. For the long-term simulation, the short-term dynamic processes are considered to converge to a steady state so fast that the differential equations of fast dynamic elements are replaced by the steady-state algebraic equations. Therefore the electromechanical transient equations described by equation (6) can be amended as follows:

$$0 = f\left(x, y, z_c, z_d\right) \tag{9}$$

QSS Model of VSCF Doubly-fed Wind Power Generator

According to the laws of QSS approximation, the wind speed model described by Equation (1) does not involve any differential computation, so the wind speed's QSS model remains the same. For the integrated model of wind turbine and drive system described by Equation (2) and (4), since the value of the inertia time constant H is generally between 4s and 5s, which is long enough to be retained, the integrated QSS model of wind turbine and drive system remains the same.

For the pitch control model shown in Figure 2, since the value of the time-delay constant T_p is generally set to be 0.01s, which is short enough to be ignored, the order-reduced QSS model of the pitch control is

$$\begin{cases} s\beta_1 - K_{pp}s(\omega_m - \omega_{ref}) = K_{ip}(\omega_m - \omega_{ref}) \\ \Delta P = P_o - P_{ref} \\ s\beta_2 - K_{pc}s\Delta P = K_{ic}\Delta P \\ \beta = \beta_1 + \beta_2 \end{cases} \tag{10}$$

For the converter control model shown in Figure 3, the value of the time constant T_r for the measurement block is generally set to be 0.01s, and the values of the two one-order time-delay constants T_1 and T_{pc} are generally set to be 0.02s. All the three time constants are short enough to be ignored, thus the order-reduced QSS model of the converter control is

$$\begin{cases} \Delta U_1 = U_{ref} - (U_t - IZ_c) \\ sQ_o - K_{pv} s\Delta U_1 = K_{iv} \Delta U_1 \\ sU_{ref} = K_{Qi}(Q_o - Q_g) \\ sE_q = K_{Vi}(U_{ref} - U_t) \\ \omega_{ref} = -0.67P_e^2 + 1.42P_e + 0.51 \\ \Delta\omega = \omega_m - \omega_{ref} \\ sT_w - K_{pt} s\Delta\omega = K_{it}\Delta\omega \\ I_p = (\omega_m T_w)/U_t \end{cases} \tag{11}$$

For the integrated model of generator and converter shown in Figure 4, since the time-delay constants T_{EQ} and T_{IP} are all generally set to be 0.02s, which are short enough to be ignored, the order-reduced QSS model is

$$\begin{cases} Q_g = \dfrac{E_q |U_t|}{X^*} \\ P_g = I_p |U_t| \\ I = f(P_g, Q_g, U_t) \end{cases} \tag{12}$$

Simulation Study

The 3-generator 9-bus topology of Western Systems Coordinating Council (WSCC) in USA is taken as the example system for simulation study [12], as shown in Figure 5. A 100 MW wind farm is connected at Bus 8 and is equivalent to be a VSCF doubly-fed wind power generator. The base value of power is 100 MVA.

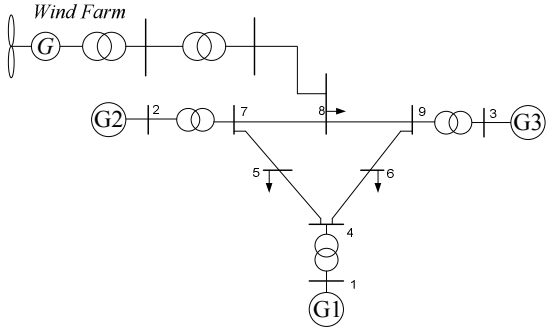


Fig.5 3-generator 9-bus WSCC system connecting a wind farm

To test and verify the accuracy of the QSS model, simulations based on the established detail model with a step size of 0.001s (be called FTS for short) and the QSS model with a step size of 0.2s (be called QSS for short) are both done and a comparison is made.

4.1 Characteristics of Wind Power under Wind Disturbance

Suppose the wind speed changes according to the curve in Figure 6. The total simulation time is 100 seconds. Simulation results of the wind farm's active and reactive powers for the two models are shown in Figures 7 and 8.

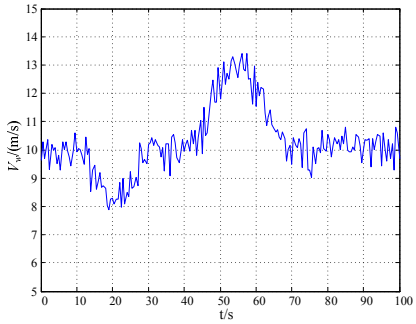


Fig.6 Wind speed

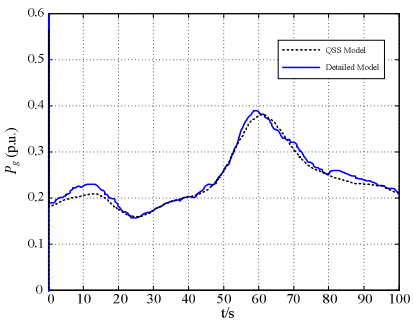


Fig.7 Output active power

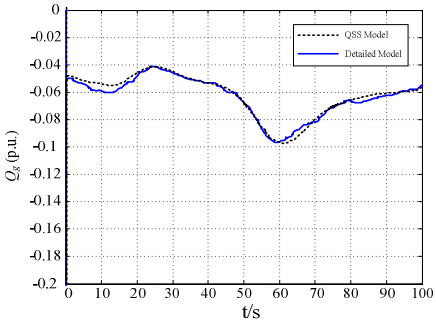


Fig.8 Output reactive power

From Figures 7 and 8, we can see that the output active and reactive powers vary accordingly when the wind speed changes. The QSS curve is smoother than the FTS curve because the QSS model does not care about the rapid-changing processes and has a longer step size. Although there is a slight deviation, the trend of the two curves is consistent, making no difference for dynamic characteristic analysis in the mid- and long-term scales. Therefore, the QSS model is appropriate for analyzing the dynamic characteristics of grid-connected wind power generators under disturbed wind. And the computation burden decreases significantly for the QSS model.

4.2 Characteristics of Wind Power under Fault Disturbance

The wind speed maintains at 12 m/s. The total simulation time is shortening to be 10 seconds in order to observe the characteristics of grid-connected wind power after short-term faults. A three-phase short-circuit fault occurs on the line 5-7 at the moment of 3.5s and is cut at 3.8s along with a reclosure. Simulation results of the wind farm's active and reactive powers and the voltage at the coupling point (Bus 8) for the two models are shown in Figures 9-11.

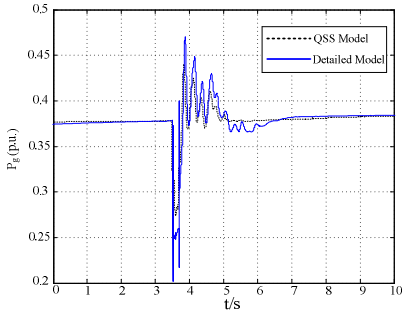


Fig.9 Output active power

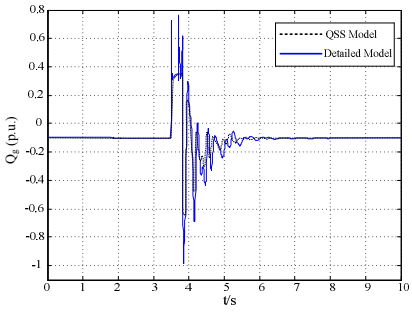


Fig.10 Output reactive power

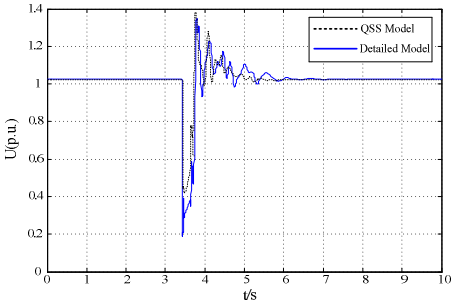


Fig.11 Voltage at the coupling point

As seen from Figures 9 and 10, when the fault occurs, there is a big volatility in the wind farm's output powers. Since the QSS model ignores the rapid-changing processes, the FTS curve performs better at reflecting the power volatility during the fault. After the fault is cut, the output powers gradually recover, and the FTS and the QSS trend to be the same.

As seen from Figure 11, during the fault, the voltage at the wind farm's coupling point drops to a low value, and when the fault is cut, the voltage can gradually recover after a period of fluctuation. Since the QSS model ignored the rapid-changing processes related to the voltage control, its curve has a slight deviation in the transient stage with the FTS curve, but both curves stay at 1.02 p.u. finally. Moreover, the QSS model greatly cuts down the computation burden and is applicable for the long-term dynamic simulation analysis of power system in the time domain.

Conclusions

This paper establishes a detail model of VSCF doubly-fed wind power generator. According to the laws of QSS approximation, an order-reduced model of grid-connected wind power is formed based on the detail model through ignoring the rapid-changing transient processes and keeping the mid- and long-term slow dynamic processes. The implicit trapezoidal integration method is used to jointly solve the differential and difference equations. Through a comparative simulation between FTS and QSS, the effectiveness of the developed QSS model is verified.

Acknowledgment

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