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Applicability Analysis of Single-Machine Equivalent Method for Modeling Wind Farm Containing Full-Converter Wind Turbine Generators with PMSG

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Abstract. For the analysis of the applicability of single-machine equivalent method for modeling wind farm containing full-converter wind turbine generators(WTG) with permanent magnet synchronous generator(PMSG), at frist, single-machine equivalent methods of equivalent model are provided, then the detailed and equivalent wind farm model is built on simulation software DIgSILENT/Power Factory platform. At last, for wind speed fluctuations and grid disturbance, the applicability of single-machine equivalent method is analyzed by comparing dynamic response at point of interconnection between equivalent model and the detailed model of wind farms. Results show that this method is suitable for the dynamic equivalent modeling of wind farm containing directly driven wind turbine with PMSG in certain situations.

Key words

Equivalent method, full-converter wind turbine generators with PMSG, wind farm, modeling

1. Introduction

With the increasing of the capacity and number of large-scale wind farms integration, the fluctuations and intermittent of wind power output will challenge power system security and stability greatly. Theory and method for dynamic equivalent modeling of wind farms has become an urgent basic and applied research project[1].

At present, the discussion of the relevant the dynamic equivalents modeling of the wind farm is concerned mainly in fixed-speed wind turbines and doubly fed induction generator wind turbines[2-12], and the literature of dynamic equivalence methods are few studied for modeling wind farm containing full-converter WTG with PMSG. In [13],the dynamic equivalent permanent magnet synchronous generator wind farm modeling method applicable to magnetic transient simulation analysis is given . For a braking resistor in the DC circuit as as the LVRT control,according to wind speed clustering equivalents, the equivalent of the wind turbine model and the simplified method of crowbar model are given[14] . But dynamic equivalents method is rarely studied under the wind speed fluctuations, also when the LVRT control is neglected, or when the over-dimensioned capacitor is taken as the LVRT control, equivalents method is rarely studied. Currently,common equivalent method is single-machine equivalent method, People are very concerned about the applicability of single-machine equivalent model.

2. WTG with PMSG Model

In the PMSG model, the flux is assumed to be sinusoidally distributed along the air gap and no damping winding is considered. The mathematical equations are constructed by aligning the d-component of machine vectors to the rotor flux. The dq-axis voltage equations of the machine have the following form.

$$v_{ds} = R_s i_{ds} - \omega_r L_{qs} i_{qs} + L_{ds}\frac{di_{ds}}{dt} \tag{1}$$

$$v_{qs} = R_s i_{qs} + \omega_r L_{ds} i_{ds} + \omega_r \psi_{pm} + L_{qs}\frac{di_{qs}}{dt} \tag{2}$$

where R_s is the stator resistance; v_{ds} and v_{qs} are the d and q components of the terminal voltage vector**,** respectively ; i_{ds} and i_{qs} are the d and q components of the stator currents, respectively ; L_{ds} and L_{qs} are the d and q components of the stator inductance, respectively; ω_r is the synchronous electric angular velocity; Ψ_{pm} is the rotor flux linkage.

The dynamics of the dc-link can be expressed as

$$C\frac{du_{dc}}{dt} = \frac{P_{gen} - P_c}{Cu_{dc}} \tag{3}$$

where P_{gen} and P_c are the generator and grid-side converter active power, respectively; C is the dc-link capacitance; u_{dc} is DC voltage.

Full-Converter model used in this work has been constructed in the dedicated power systems analysis software package PowerFactory supplied by DIgSILENT GmbH. The converter controllers are used to regulate the converter currents and voltages and the active power and reactive power output of the FCWTG. Fig.1 shows the block diagram of the control for the machine-side rectifying converter. The rectifying converter is used to control the generator AC voltage *Vac* and the output active power P of the PMSG.

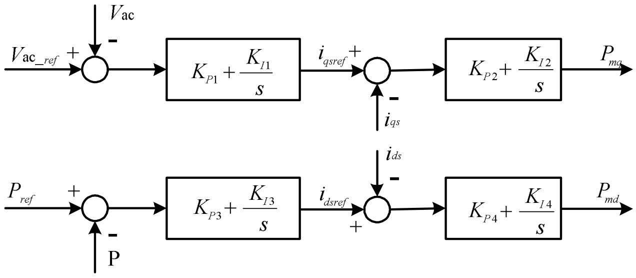

Fig. 1. Generator-side converter control block diagram

Fig. 2 shows the control scheme for the grid-side inverting converter. The inverting converter is used to control the reactive power *Qgrid* and the DC link voltage *Udc*.

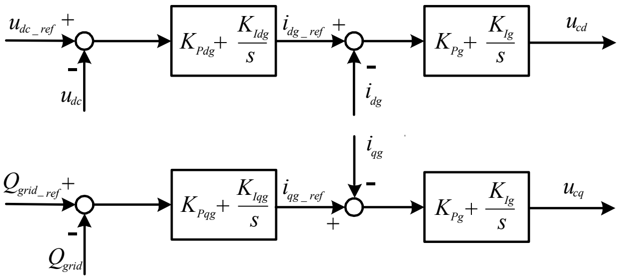

Fig. 2. Grid-side converter control block diagram

3. Single-Machine Equivalent Method

According to the fault isolation of double pulse width modulation (PWM) converters for directly driven wind turbine with permanent magnet synchronous generator (PMSG), when the low voltage Ride-through (LVRT) control is neglected, or when the over-dimensioned capacitor is taken as the LVRT control, the wind farm with PMSG can be equivalent into a wind turbine generator. Single-machine equivalent wind farm model is shown in Figure 3.

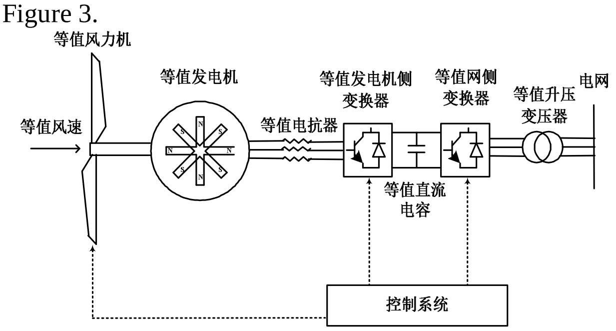

Fig. 3. Single-machine equivalent wind farm model

As shown in Fig.3, the parameters of the various parts of equivalent model are calculated as follows:

A. Generator parameters

$$\begin{cases} S_{eq} = nS, x_{m\_eq} = \dfrac{x_m}{n}, x_{1\_eq} = \dfrac{x_1}{n}, r_{1\_eq} = \dfrac{r_1}{n}, x_{1\_eq} = \dfrac{x_1}{n} \\ x_{2d\_eq} = \dfrac{x_{2d}}{n}, x_{2q\_eq} = \dfrac{r_{2q}}{n}, x''_{2d\_eq} = \dfrac{x''_{2d}}{n}, x''_{2q\_eq} = \dfrac{x''_{2q}}{n} \end{cases} \quad (4)$$

Where n is the number of wind turbines; Subscript eq indicates equivalent abbreviations; S is generator apparent power; x_1 and r_1 are the generator stator resistance and reactor, respectively; x'_{2d} and x'_{2q} are the d and q components of the transient reactance, respectively; x'_1 is transient reactance; x''_{2d} and x''_{2q} are the d and q components of the sub-transient reactance, respectively.

B. Shafting parameters

$$H_{g\_eq} = nH_g, H_{t\_eq} = nH_t, K_{s\_eq} = nK_s \quad (5)$$

where H_t and H_g are the inertia for turbine and generator, respectively; K_s is spring for turbine.

C. Transformer parameters

$$S_{T\_eq} = nS_T, Z_{T\_eq} = \frac{Z_T}{n} \quad (6)$$

where S_T and Z_T are apparent power and impedance of transformer, respectively.

D. Reactor parameters

$$S_{D\_eq} = nS_D, Z_{D\_eq} = \frac{Z_D}{n} \quad (7)$$

where S_D and Z_D are apparent power and impedance of reactor, respectively.

E. Control parameters

In addition to the power measurement module, equivalent wind turbine control parameters are the same as parameters of pre-equivalent wind turbine. Power measurement module need for capacity adjustment, and its control point need to be adjusted according to the post-equivalent bus. The reference capacity of measurement equivalent modules of the generator-side and grid-side converter are calculated as follows:

$$S_{eq} = nS \quad (8)$$

F. Converter parameters

$$S_{eq} = nS \quad (9)$$

$$C_{eq} = nC \quad (10)$$

where S_{eq} is apparent power of converter; c_{eq} is the dc-link equivalent capacitance.

G. Reactive power reference value of wind turbine

$$Q_{ref\_eq} = \sum_{i=1}^{n} Q_{ref\_i} \quad (11)$$

where Q_{ref} is reactive power reference of wind turbine.

H. Cable charging capacitor

As the voltage difference of wind turbines can be neglected in wind farm, the equivalent charging capacitance is equal to sum of all cables equals charging capacitor before equivalence.

I. Equivalent wind speed

When all wind turbines are rated power output, the equivalent wind speed is calculated as follows:

$$v_{eq1} = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (12)$$

When wind turbines are not all rated power output, at first active power of each wind turbine are obtained through wind speed and wind power curve, and then calculate the average power, at last the equivalent wind speed is calculated by the wind power curve. The equivalent process is as follows, the output power of the kth wind turbine is calculated as follows:

$$p_k = f(v_k) \quad (13)$$

where f is the fitting function of the curve of wind speed and power ; v_k is wind speed of the kth wind turbine. Equivalent wind speed is calculated as follows:

$$v_{eq} = f^{-1}\left(\frac{1}{n}\sum_{i=1}^{n} f(v_i)\right) \quad (14)$$

4. Simulation results

Figure.4 shows the configuration of the wind farm used for this study. The wind farm under consideration has 9 direct-drive permanent magnet synchronous wind turbine of 1.5MW,3.3 kV each. A transformer 35 /3.3 kV boosts up the voltage and a medium voltage line at 35kV connects it to the wind farm substation. The wind farm substation present a transformer110/35 kV coupling at 110 kV the wind farm to the power network at the point of common coupling (PCC). wind farm model is built on simulation software DIgSILENT/Power Factory platform. Electric parameters of wind farm under consideration are shown in Table I.

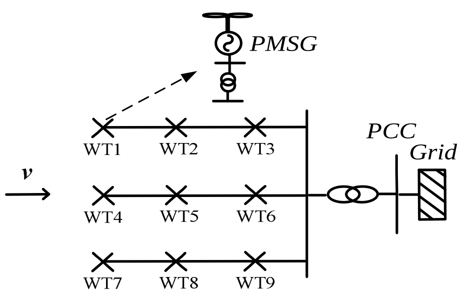

Fig. 4. Single line diagram of wind farm

Table I. Electric parameters of wind farm

Generator	S/MW	1.5	U/kV	3.3
	r_1(pu)	0.0001	x_1(pu)	0.05
	x'_{2d} (pu)	1.5	x'_{2q}(pu)	1.5
	T'_1/s	0.1	x'_1(pu)	0.25
	x''_{2d} (pu)	0.17	x''_{2q} (pu)	0.17
	T''_{2d}/s	0.02	T''_{2q}/s	0.05
Wind turbine	S/MW	1.5	r/m	30
Reactor	S/MW	1.7	U/kV	3.3
Converter	S/MW	1.7	U/kV	3.3
	U/kV	6.6	C/uF	1000
Transformer 1	S/MVA	1.7	X_t (%)	6
Transformer 2	S/MVA	50	X_t (%)	11

A. wind fluctuations in the wind farm

The wind speed of the wind farm consider influence of wake effect and time delay. Assuming winds blow from left to right across wind farm and each row of wind turbines have the same wind speed. Figure.5 shows wind speed of three rows wind turbines (In Figure.5, 1, 2 and 3 represent each row of wind turbines, respectively), equivalent wind speed by using equivalent the method given in this paper(The short red line in Figure.5), and the average wind speed of three rows wind turbines(dotted linein Figure.5). Figure.6 compares the active power, reactive power and voltage magnitude of the detailed model(solid line in Figure.5) and single-machine equivalent model at the PCC by using equivalent wind speed and the average wind speed, respectively.

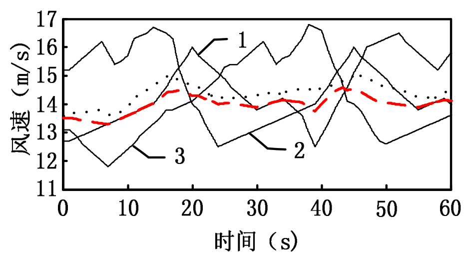

Fig. 5. wind speed fluctuations

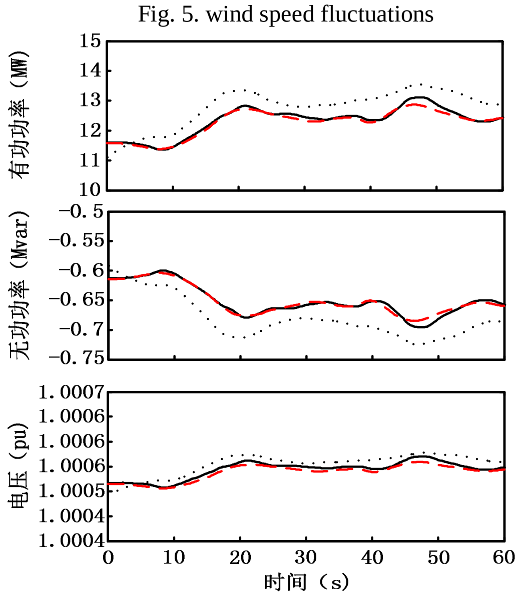

Fig. 6. Dynamic response of wind farm at point of interconnection under wind speed fluctuations

As explained in Fig. 6, equivalent models by using the equivalent wind speed provide higher accuracy than equivalent models by using the average wind speed. The simulation results show that the proposed equivalent model provides the same accuracy the dynamic characteristics as the detailed model.Thus the validity of the equivalent method is confirmed under wind speed fluctuations.

B. Grid Faults

In order to evaluate the validity of single-machine equivalent method for power system transient studies, a three-phase short circuit is applied at the PCC at t = 0.5 s and is clear in 150 ms. Wind speed of all wind turbines are shown in Table II. For transient stability analysis, it can be assumed that wind speed is constant during the fault occur. Figure.7 compares the active power, reactive power and voltage magnitude of the equivalent model and the detailed model of the wind farm at the PCC, respectively.

Table II. Wind speed of wind turbine

Wind turbine	Wind speed /m/s	Wind turbine	Wind speed /m/s	Wind turbine	Wind speed /m/s
1	9.1	2	9.3	3	9.7
4	9.9	5	10.3	6	10.5
7	11.4	8	12.7	9	15

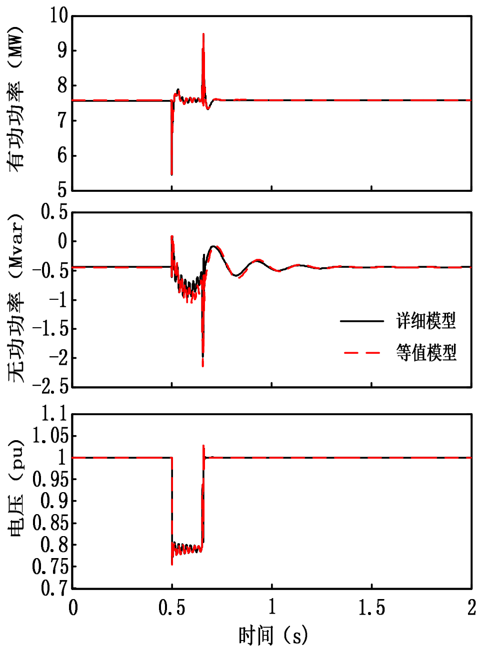

Fig. 7. Dynamic response of wind farm at point of interconnection under grid disturbance

Figure.7 show that the proposed equivalent model provides the same accuracy the dynamic characteristics as the detailed model for active power and voltage magnitude, only the accuracy of reactive power of proposed equivalent model degrades slightly. It have two reasons for error as follows: ① equivalent model ignores equivalence of wind farm cable impedances; ②During failure the speed and pitch angle of wind turbine have small changes, these will result in a smaller equivalent error. The simulation results show that single-machine equivalent method is suitable for the dynamic equivalent modeling of wind farm containing directly driven wind turbine with PMSG under faults.

5. Conclusion

According to the fault isolation of double pulse width modulation (PWM) converters for directly driven wind turbine with permanent magnet synchronous generator (PMSG), when the low voltage Ride-through (LVRT) control is neglected, or when the over-dimensioned capacitor is taken as the LVRT control, the wind farm with PMSG can be equivalent into a wind turbine generator, and the parameters calculating methods of equivalent model are provided. The applicability of single-machine equivalent method is analyzed by simulations. The simulation results show that equivalent models by using the equivalent wind speed provide higher accuracy than equivalent models by using the average wind speed under wind speed fluctuations, and the proposed equivalent model provides the same accuracy the dynamic characteristics as the detailed model under faults. It can conclude that this method is suitable for the dynamic equivalent modeling of wind farm containing directly driven wind turbine with PMSG.

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