第 25 卷第 2 期
2008 年 4 月

控 制 理 论 与 应 用
Control Theory & Applications

Vol. 25 No. 2
Apr. 2008

Article ID: 1000−8152(2008)02−0377−06

Performance analysis of different wind farm capacities to power grid

DONG Ping[1], CHENG Ka-Wai-Eric[1], GUO Pan[2]

(1. Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung hum, Hong Kong SAR, China;

2. Mathematics and Computing Department, JiangXi Science Technology Normal University, Nanchang Jiangxi 330013, China)

Abstract: The electrical connections of wind farm to power transmission line and power distribution line bring forward certain requirements in design and practice. The higher percentages of wind power generation are used in the network, the more substantial effect of the fluctuation may be resulted, making the analysis on stability, reliability and grid connection important to system engineers. Therefore the reliability and control strategies of existing power systems which contain wind power are needed to be re-examined. In this paper, the effects of different wind farm capacities to power grid are analyzed, and the causes, models and correlative results are presented.

Key words: wind farm; capacity; power generation; reliability

不同容量风电场对连接处的电网影响及其性能分析

董 萍[1], 郑家伟[1], 郭 攀[2]

(1. 香港理工大学 电机工程系, 香港特别行政区 红勘;
2. 江西科技师范大学 数学与计算机科学系, 江西 南昌 330013)

摘要: 风电场可以同输变电线路相连接, 由于风力发电的随机性, 风电很有可能给连接处的电网带来谐波污染、电压波动及闪变问题; 也会给发电和运行调度计划的制定带来很多困难. 对接有风电场的电力系统, 重新评估系统的发电可靠性, 分析风电容量可信度; 研究新的无功调度及电压控制策略以保证风电场和整个系统的电压水平和无功平衡, 及对孤立系统的稳定性影响等对于系统的工程师来说非常重要. 本文分析了各种不同容量的风电场对电网的影响并给出模型以及相关结果.

关键词: 风电场; 容量; 电力透入率; 可靠性

中图分类号: TM614 **文献标识码:** A

1 Introduction

Most of the wind farms are connected to power transmission line or power distribution line. Due to the uncertainty of the wind, some problems would be brought to power system where the wind farm connected to, such as harmonics, voltage pulsation and flicker. In addition, the uncertainty of the wind also brings some difficulties in fixing power generation and run schedules [1,2]. Therefore the higher percentages of wind power generation are used, the higher demand on the reducing fluctuation would be resulted and the more comprehensive analysis on stability, reliability and grid connection is needed. Since the ratio of wind power in modern power systems is high, the reliability and control strategies of new power system which contains wind power need to be re-examined.

“Stiff grid” and “weak grid” are defined differently, but it is difficult to differentiate. “Stiff grid” does not have all the “stiff” characters, because there are some grids whose characteristic is “stiff in frequency and weak in voltage” [3]. According to the basic model of the power grid, two different models are defined for different wind farms. First-order equivalent circuit is used to represent grid approximately, and it is a normal and simple method. This simple equivalent circuit of grid is shown in Fig. 1.

Where, Z_1 is the electric load of short-circuit, so the capacity of short circuit is

$$S_k = \sqrt{3}U_n I_k. \tag{1}$$

The ratio of short circuit is

Received 20 July 2007; revised 17 October 2007.
Foundation item: supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (PolyU 5224/04E).

$$R_{sc} = \frac{S_k}{S_r}, \tag{2}$$

where, S_k is the short-circuit capacity of grid; S_r is the rated capacity of wind farm. Ratio of short circuit indicates the stiff or weak level of power grid. When the value of R_{sc} is bigger, the grid is stronger. According to the grid model, the models of wind farm which are connected to different grids can be established.

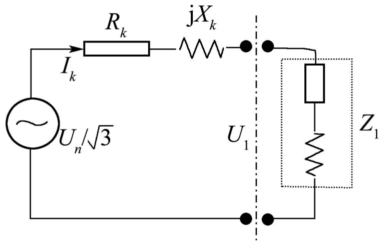


Fig. 1 Equivalent circuit of power grid

2 Modeling of wind farm

A) Wind farm model connected to “stiff grid”.

According to the basic model of the grid, this “stiff grid” means the infinity grid, that is, the grid is the source which can supply unlimited amount of active power and reactive power while keeping whose voltage and frequency constant. The connection of the wind farm to the stiff grid is shown in Fig.2.

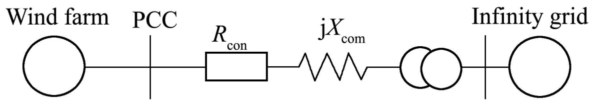


Fig. 2 Connection circuit between wind farm and stiff grid

Single unit wind turbines in the wind farm are constant speed wind turbines, They are connected in parallel. On the end, all the unit wind turbines are connected to the infinity grid by transformer.

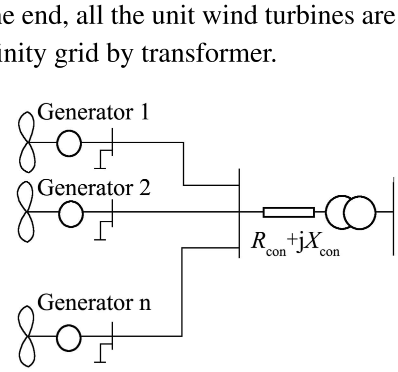


Fig. 3 Wind farm with “constant speed” wind turbines

Wind farm model is made up of three modules: wind speed model, model of single unit wind power conversion system and connection style model of wind farm.

1) Wind speed model.

Four components are used to simulate the wind speed[4]:

$$V = V_B + V_{WG} + V_{WR} + V_{WN}, \tag{3}$$

where, V_B is basic wind speed, V_{WG} is gustiness, V_{WR} is tapering wind speed and V_{WN} is random-noise wind speed. In the wind farm, due to the wind direction and wake effect, different wind regime is distributed to each single unit wind turbine. In order to imitate the actual condition of the wind farm, a series of assumptions are given: (a) The basic wind speed in the whole wind farm is the same, that is, the basic wind speed is constant and is the same for each single unit wind turbine; (b) According to the geographic position, the wind regime of each wind turbine is different. For example, wind speed model can consist of basic wind speed and gustiness, or basic wind speed, tapering wind speed and random-noise wind speed, etc; (c) The wind park effect is considered.

2) Model of single unit wind turbine.

A single unit wind turbine in the wind farm is a constant speed wind turbine, and the relation between output power and wind speed is shown in Fig.4.

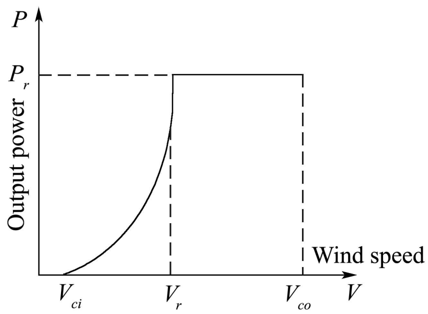


Fig. 4 Output power of wind turbine

Where, V_{ci}, V_r, V_{co} are the cut-in wind speed, dated wind speed and cut-off wind speed, respectively. P_r is the rated output power of wind turbine. When the wind speed is lower than the cut-in wind speed or is higher than the cut-off wind speed, the output power of the wind turbine is zero. When the wind speed is between V_{ci} and V_r, the output power of the unit is

$$P = P_r(A + BV + CV^2), \tag{4}$$

where, V is wind speed and the values of factor A, B and C can be obtained from the parameters of the single unit wind turbine.

Due to the effect of wind speed disturbance and the dynamic behaviour of the wind turbine, the above system is different from the real one. But this difference is usually very small and can be ignored in general model. The effect caused by air density, air pressure and temperature are small and also neglected in this model.

So in this wind farm, each wind turbine can be treated as a PQ node, and this can simplify the whole model. In this system, the asynchronous generator model can be represented as a resistance if the parameters and slip of the generator is known. The slip can be obtained by the output power curve of the wind turbine and the wind speed. Thus, the static model of the whole turbine is expressed as Fig.5.

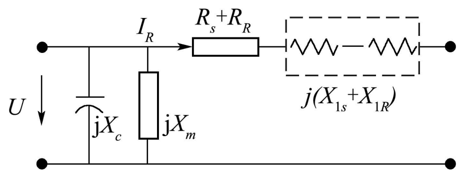


Fig. 5 Static model of wind turbine

Where U is the terminal voltage of the generator; X_C is the compensating capacity, X_m is the mutual inductance. R_s, R_R, X_{ls}, X_{lR} are the stator resistance, rotor resistance and leaking inductance respectively. The reactive power is derived here as in Boucherot motor [5]:

$$Q = U^2\frac{X_c - X_m}{X_c X_m} + X\frac{U^2+2RP_f}{2(R^2+X^2)} - X\frac{\sqrt{(U^2+2RP_f)^2 - 4P_f^2(R^2+X^2)}}{2(R^2+X^2)}, \quad (5)$$

where, $X = X_{ls} + X_{lR}$, $R = R_s + R_R$ and P_f is the output power of wind turbine.

3) Connection style model of wind farm.

Wind farm is made up of a number of single unit wind turbines. The output power of the wind farm is the sum of the output power of all units. The total values of P and Q can be obtained as shown in Fig.6.

It is clear that the output power of the wind farm is larger than the real system because the effect of wake and the loss in the energy transportation have not been considered in the modeling process. In order to determine the output power accurately, efficiency coefficient ρ is defined. It is a function of the wind turbine number and distribution, the typical value is 0.90∼0.95[6], and the real output power of the wind farm is

$$\begin{cases} P_{\text{farm}} = \rho \cdot P_{\text{total}}, \\ Q_{\text{farm}} = \rho \cdot Q_{\text{total}}. \end{cases} \quad (6)$$

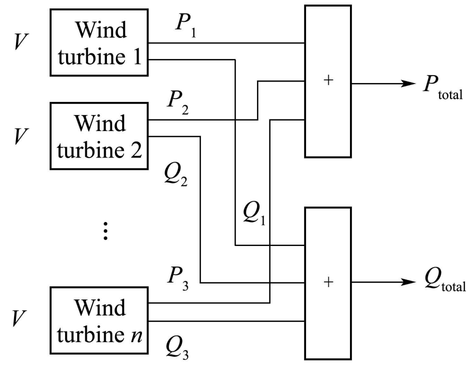


Fig. 6 PQ model of wind farm

Define U_{PCC} as the voltage of the wind farm connected to power grid and R_{con}, X_{con} are the line resistance and line reactance respectively. The equation to define the relation between wind farm capacitor and power grid is shown in Fig.7.

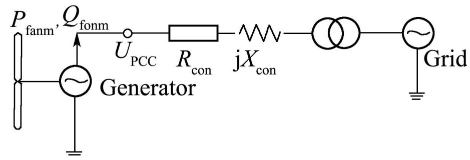


Fig. 7 Connection circuit between wind farm and stiff grid

The energy loss and voltage drop caused by transformer could be ignored, therefore,

$$\frac{P_{\text{farm}} + \mathrm{j}Q_{\text{farm}}}{U_{\text{PCC}}} = -\frac{U_{\text{grid}}}{R_{\text{con}} + \mathrm{j}X_{\text{con}}} * \frac{1}{m}, \quad (7)$$

where m is the turns ratio.

B) Wind farm model connected to "weak grid".

"Weak grid" normally appears in remote areas, because the length of electric transmission line is long and the voltage level of the power grid is low. The method to establish the wind farm model connected to "weak grid" is the same with the wind farm model which connected to "stiff grid". Three modules are included in this model, too.

1) Wind speed model.

Wind speed model is the same as the model used in the wind farm model connected to "stiff grid".

2) Model of single unit wind turbine.

The precise model of single unit wind turbine is required because the transient performance of the power system which is connected to wind farm would be considered. In this wind farm, single unit wind turbine in the wind farm is also a constant speed wind turbine. Then, the precise single unit model can be given as[7]

$$\dot{x}=\begin{bmatrix}\dfrac{R_r}{L_r} & s\omega_s\\ -s\omega_s & -\dfrac{R_r}{L_r}\end{bmatrix}x+\begin{bmatrix}\dfrac{R_r}{L_r}L_m & 0\\ 0 & \dfrac{R_r}{L_r}L_m\end{bmatrix}y, \quad (8)$$

$$\dot{z}=\varepsilon_2[M_{Aw}-\frac{gL_m}{L_r}(\psi_{dr}i_{qs}-\psi_{qr}i_{ds})], \quad (9)$$

$$\varepsilon_1\dot{y}=\begin{bmatrix}-\dfrac{R_rL_m}{L_r\Delta\omega_s} & \dfrac{(1-s)L_m}{\Delta}\\ -\dfrac{(1-s)L_m}{\Delta} & \dfrac{R_rL_m}{L_r\Delta\omega_s}\end{bmatrix}x+ \begin{bmatrix}-\dfrac{L_r^2R_s+L_m^2R_r}{L_r\Delta\omega_s} & 1\\ -1 & -\dfrac{L_r^2R_s+L_m^2R_r}{L_r\Delta\omega_s}\end{bmatrix}y+ \begin{bmatrix}\dfrac{1}{\Delta} & 0\\ 0 & \dfrac{1}{\Delta}\end{bmatrix}u, \quad (10)$$

where, $\varepsilon_1 = 1/\omega_s$, $\varepsilon_2 = n/(J_w+n^2J_G)$, $x = [\Psi_{dr},\Psi_{qr}]^{\mathrm{T}}$, $y = [i_{ds},i_{qs}]^{\mathrm{T}}$, $z = \omega_G$, $u = [U_{ds},U_{qs}]^{\mathrm{T}}$. Ψ_{dr} and Ψ_{qr} are the flux linkage; i_{ds}, i_{qs}, U_{ds}, U_{qs} are the stator current and voltage respectively; ω_s is the angular speed of reference axis; $s = (\omega_s - g\omega_G)/\omega_s$ is slip of the generator; R_r is the resistance of excitation coil; L_m is the inductance of excitation coil; L_{ls}, L_{lr} are the linkage inductance of stator, rotor; $\Delta = L_sL_r - L_m$. R_{line}, X_{line} is the resistance of power line.

Output power of the single unit wind turbine is

$$\begin{cases}P=\mathrm{Re}(U\cdot i^*)=U_{ds}i_{ds}+U_{qs}i_{qs},\\ Q=\mathrm{Im}(U\cdot i^*)=U_{qs}i_{ds}-U_{ds}i_{qs}.\end{cases} \quad (11)$$

3) Connection style model of wind farm.

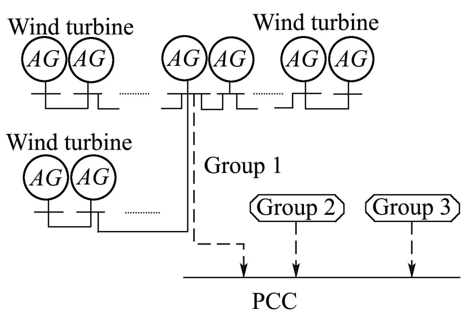


Fig. 8 “Group” network of wind farm

Due to the characteristic of “weak grid”, the normalized model which used in the modeling of wind farm connected to stiff grid can not be used in this part. But the “group classification” method will be used. The “group classification” means that the model is divided into different groups according to the wind and geographic locations. If wind and geographic locations of the unit wind turbines are similar, these unit wind turbines are considered being in one group. So, a series of small wind farms are classified by using this method in the whole wind farm.

According to different connection styles, the wind farm and the power grid could be thought as a normal power system. Only in the generator part of the wind turbine will be included. For example, the 9 nodes system of IEEE could be thought as including two “group classification” models of wind farm.

Where, Z_i is the line resistance; G is the other power generation station. Every wind farm could be analyzed by using the “group classification” model.

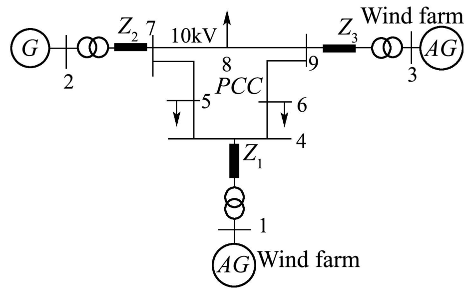


Fig. 9 Connection circuit between wind farm and weak grid

3 Maximal penetrating power of two wind farm madel

In order to meet the need of system stability, maximal penetrating power of wind farm must be equal to the ratio of maximal wind power of system to the maximal electric load, that is[8]:

$$\text{maximalpenetratingpower} = \frac{\text{maximalwindpower}}{\text{maximalelectricload}} * 100. \quad (12)$$

The maximal wind power which the system could accept is not only affected by the fixed electric network and the dynamic performance of the power system, but also has relation with the run schedule. A method based on the optimal algorithm to calculate maximal penetrating power is presented[9], and it takes account of the random wind power. Stochastic programming is adopted and genetic algorithm is used to solve the equations. In this paper, maximal penetrating power is analyzed in the stable state.

A) Penetrating power of wind farm connected to “stiff grid”

Model of this wind farm is the same as Fig.10, and the voltage U_{PCC} is 10 kV; Power grid voltage is 110 kV which is thought as the infinity grid. Analysis to the wind farm is as block diagram (Fig.11). In this time, wind turbine works in the steady state; generator is asynchronous whose saturation effect is ignored; the variation range of the 10 kV power grid is from -5% to $+5\%$. Voltage of infinity grid is constant.

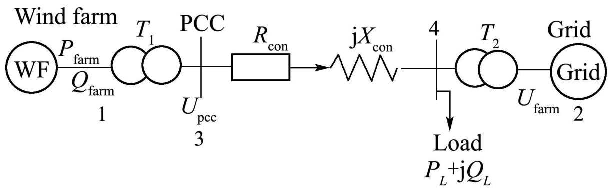


Fig. 10 Wind farm connected to "stiff grid"

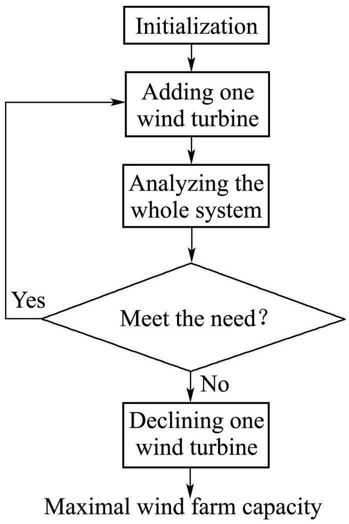


Fig. 11 Calculation of Maximal capacity of wind farm

Simulation parameters of the system are normalized and given in Table 1.

Table 1 Simulation parameters

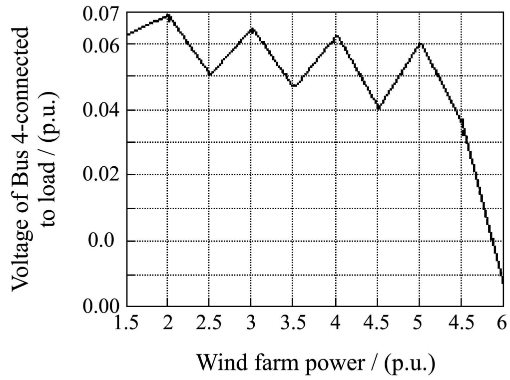
$P_L = 4.5$ p.u.	$X_{T1} = 0.01$ p.u.
$Q_L = 1.35$ p.u.	$X_{T2} = 0.00667$ p.u.
$R_{con} = 0.01387$ p.u.	$U_2 = 0.1$ p.u.
$X_{con} = 0.1624$ p.u.	$\Theta_2 = 0$

Assume that the electric load is equal to $R + jX$, then:

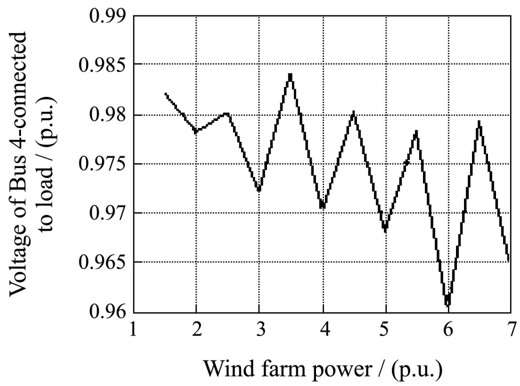
$$P_L + jQ_L = U^2 \frac{R + jX}{R^2 + X^2}. \qquad (13)$$

The analysis of power flow is used in this system to get the voltage and current of every node. Wind farm connected to stiff grid could be considered 2-generator system. Reactive power of wind farm is the function of its active power[10,11] because there are no compensation devices, whereas reactive power is zero. Simulation results are shown in Fig. 12.

The simulation results show that maximal penetrating power will be improved by adding the compensation devices, and it could reach 50%, if the secondary bus over-voltage is ignored.



(a) No compensation capacity



(b) With compensation capacity farm

Fig. 12 Load voltage curve of wind farm

B) Penetrating power of wind farm connected to "weak grid".

The model of wind farm connected to weak grid is shown as Fig.13.

In this figure, wind farm connected to Bus5, and compensating capacitors whose capacity is 50 Mvar is loaded in Bus3. Voltage levels of Bus5, Bus6 and Bus7 are 220 kV. The simulation parameters are shown in Table 2 and Table 3.

Wind farm is connected to Bus3 by Bus5. Bus3 is the sensitive node of the system, and it has the maximum effects to the whole system. After the power flow analyzed, the maximal penetrating power of wind farm is given as Fig. 14.

The maximal penetrating power of this wind farm is lower than that connected to stiff grid, and the simulation results show that the maximal penetrating power can also be improved by adding compensation devices. The maximal penetrating power of this wind farm is 14%.

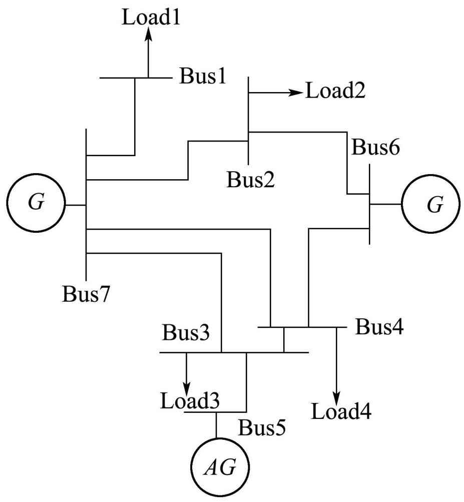


Fig. 13 Diagram of wind farm connected to "weak grid"

Table 2 Electric load

Number	P/MW	Q/MVar
Load1	40	30
Load2	110	−20(capacitive)
Load3	110	100
Load4	100	48.83

Table 3 Power line resistance

Start and end node of line	Resistance R/Ohm	Reactance X/Ohm
1∼7	2	65
2∼7	22.8	62.6
3∼7	6.7	65
4∼7	6.7	70
2∼6	6.7	15
3∼4	27	35
4∼6	6.75	25

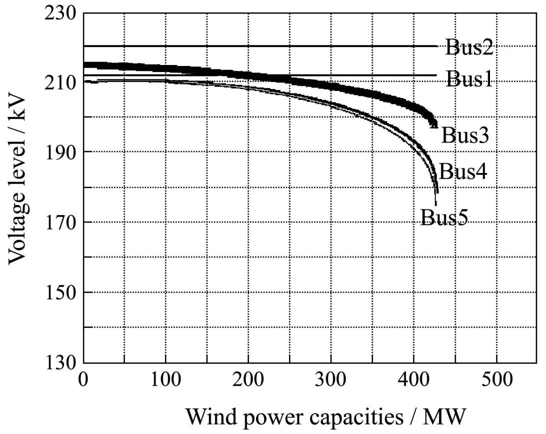


Fig. 14 Maximal wind power connected to weak grid

4 Conclusion

Two models established in this paper could present most connection styles between wind farm and power system. They are the basis for the study of the power system which contains wind power.

Simulation results show that penetrating power of wind farm could be improved by changing run schedule by means of connecting with other power grid or improving control ability of each wind farm. The alternative is the proposed method of adding compensation devices. Two models have different penetrating wind power and the results are better than real values in Chinese mainland. In Chinese mainland, wind farm capacity is expected to be less than 8% in order to meet the need of grid voltage and system stable. But in Europe, wind farm capacity could reach 20% and even higher in Denmark for reasons of different run schedules and opening network structures.

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