Design for the Different Penetrating Power Based on Wind Farm Models Connected to Power Grids

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Abstract—**Wind farm model is the base to design and research the wind farm system. In order to analyze the relationship between wind farm and power system which it is connected in details, two different models, connected to stiff grid and weak grid, were developed in this paper. In addition, based on the two models, the maximal capacities of the different wind farm were analyzed and the correlative results were presented.**

Keywords -- Wind power, penetrating power, power grids

I. INTRODUCTION

Wind farm can connect to power transmission line and power distribution line. Due to the peculiarity of wind energy, it will bring some problems to power system, such as harmonic wave, voltage pulsation and flickering. In addition, the uncertainty of wind energy also brings some difficulties in fixing power generating and running schedule [1, 2]. Therefore the higher percentage of wind power generation are being used, the effect of the fluctuation may be resulted and therefore analysis on stability, reliability and Grid connection is needed. So the reliability and control strategies of new power system which contains wind power need to be reconsidered. The weight of wind power in the whole power system obtained more focus now.

"Stiff grid" and "weak grid" are different to define and differentiate. "Stiff grid" doesn't have all the "stiff" characters, because there're some grids whose characteristic is "stiff frequency and weak voltage" [3]. According to the basic model of the power grid, two different models are defined to different wind power conversion system. First-order equivalent circuit is used to represent grid approximately, and it is a normal and simple method. The simple equivalent circuit of grid can be seen as Fig. 1.

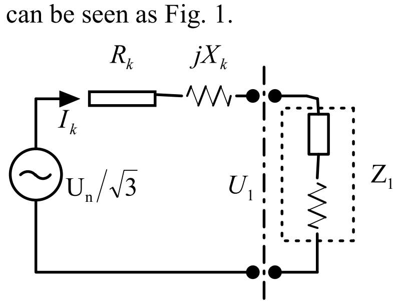

Fig. 1 Equivalent Circuit of Power Grid

In above figure, if Z_1 is short-circuit electric load, the capacity of short circuit is:

$$S_k = \sqrt{3}U_n I_k \qquad (1)$$

It is one characteristic of normal grid, and the other one is the ratio of short circuit:

$$R_{sc} = \frac{S_k}{S_r} \qquad (2)$$

where, S_k is the short-circuit capacity of grid; S_r is the rated capacity of wind farm or wind power conversion system. Ratio of short circuit can respond the stiff or weak level of grid. The value of R_{sc} is bigger, and the grid is stronger. In accord with the grid model, models of wind farm which connected to different grid can be established.

II. 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 the plenty active power and reactive power and whose voltage and frequent are constant. The style of the wind farm connected to the stiff grid can be given as follow figure:

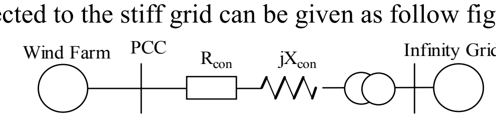

Fig. 2 Connection Circuit between Wind Farm and stiff grid

Single unit wind power conversion system in the wind farm is constant speed wind turbine, and each one is connected in parallel. In addition, it is connected to the infinity grid by transformer.

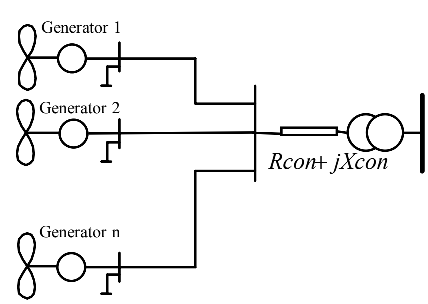

Fig. 3 Wind Farm with "Constant Speed" Wind Turbine

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.

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1. Wind speed model

Model to simulate wind speed consists of four components [4]:

$$V = V_B + V_{WG} + V_{WR} + V_{WN} \qquad (3)$$

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 effect of wind direction and wake effect, wind regime of each single unit wind power conversion system is different. In order to represent the actual condition of the wind farm, series assumptions are given as follows: (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 to each single unit wind power conversion system. (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 consists of basic wind speed, tapering wind speed and random-noise wind speed, et al. (c) The effect of wake effect is considered.

2. Model of single unit wind power conversion system

Single unit wind power conversion system in the wind farm is constant speed wind turbine, and the relationship between output power and wind speed of each one is as Fig. 4.

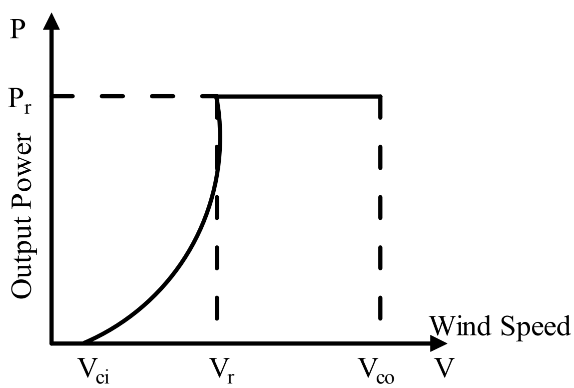

Fig. 4 Output Power of wind turbine

In above figure, V_{ci}, V_r, V_{co} is the cut-in wind speed, dated wind speed and cut-off wind speed, respectively. P_r is the dated 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 power conversion system is zero. When the wind speed is between V_{ci} and V_r, the output power of the unit is:

$$P = P_r (A + BV + CV^2) \qquad (4)$$

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 power conversion system.

Due to the effect of wind speed disturbance and the dynamic behaviour of the wind turbine, there are some difference between above one and the real system. But such difference is usually very small and can be ignored in general model. The effect due to air density, air pressure and temperature are small and are neglected in this model study for the wind turbine.

So in this wind farm, each wind turbine can be looked as the 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. And the slip can be obtained by the output power curve of the wind turbine and the wind speed. The static model of the whole system is hence expressed as Fig. 5.

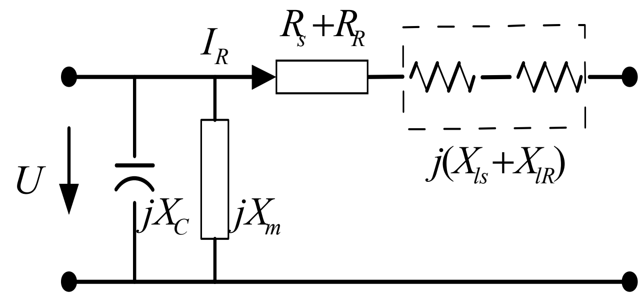

Fig. 5 Steady State Model of wind turbine

In the figure, 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]:

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

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 power conversion systems, and the output power of the wind farm is the sum of the output power of every unit. The values of P and Q can be seen as Fig. 6.

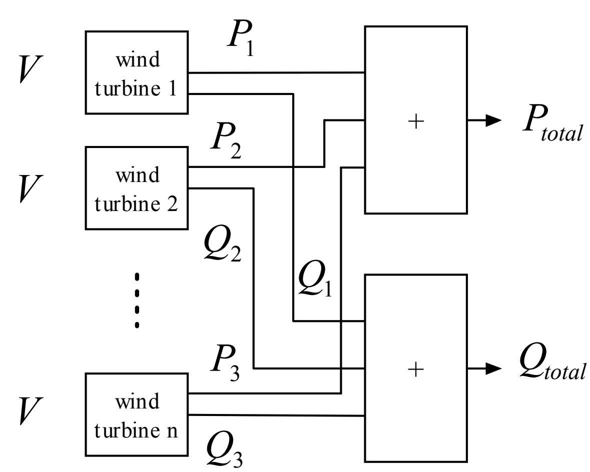

Fig. 6 PQ model of Wind Farm

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 transferring have not been considered in the modelling process. In order to make the output power accurately, efficiency coefficient ρ is defined. It is the function of the wind turbine number and distribution, but it is difficult to establish model. The typical value is 0.90-0.95 [6], and the real output power of the wind farm is:

$$\begin{cases} P_{farm} = \rho \cdot P_{total} \\ Q_{farm} = \rho \cdot Q_{total} \end{cases} \tag{6}$$

Assumption that U_{pcc} is the voltage of the wind farm connected to power grid and R_{con}, X_{con} are the line resistance and line reactance respectively. Then equation to define the relationship between wind farm capacitor and power grid can be given according to the Fig. 7.

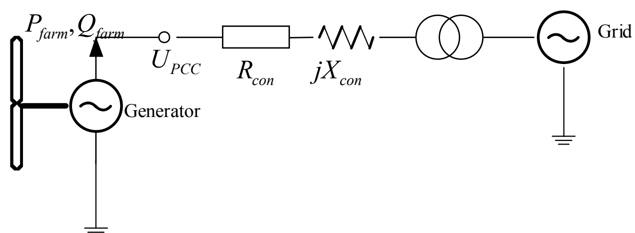

Fig.7 Connection Circuit between Wind Farm and stiff grid

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

$$\frac{P_{farm} + jQ_{farm}}{U_{PCC}} = -\frac{U_{grid}}{R_{con} + jX_{con}} * \frac{1}{m} \tag{7}$$

where, m is the turn's 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 level of grid voltage is low. 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 power conversion system

The precise model of single unit wind power conversion system 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 power conversion system in the wind farm is constant speed wind turbine, too. Then, the precise single unit model can be given as follows [7]:

$$\dot{x} = \begin{bmatrix} \frac{R_r}{L_r} & s\omega_s \\ -s\omega_s & -\frac{R_r}{L_r} \end{bmatrix} x + \begin{bmatrix} \frac{R_r}{L_r} L_m & 0 \\ 0 & \frac{R_r}{L_r} L_m \end{bmatrix} y \tag{8}$$

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

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

where, $\varepsilon_1 = 1/\omega_s$, $\varepsilon_2 = n/(J_w + n^2 J_G)$, $x = [\psi_{dr}, \psi_{qr}]^T$; $y = [i_{ds}, i_{qs}]^T$; $z = \omega_G$; $u = [U_{ds}, U_{qs}]^T$. 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; $\Delta = L_s L_r - L_m$. R_{line}, X_{line} is the resistance of power line.

Output power of the single unit wind power conversion system is:

$$\begin{aligned} P &= \mathrm{Re}(U \cdot i^*) = U_{ds} i_{ds} + U_{qs} i_{qs} \\ Q &= \mathrm{Im}(U \cdot i^*) = U_{qs} i_{ds} - U_{ds} i_{qs} \end{aligned} \tag{11}$$

3. Connection style model 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 could not used in this part. But the grouping classification model will used. The grouping classification model is established by the similarity of wind regime and geographic position of each single unit wind power conversion system, that is, a series of small wind farms are classified in the wind farm.

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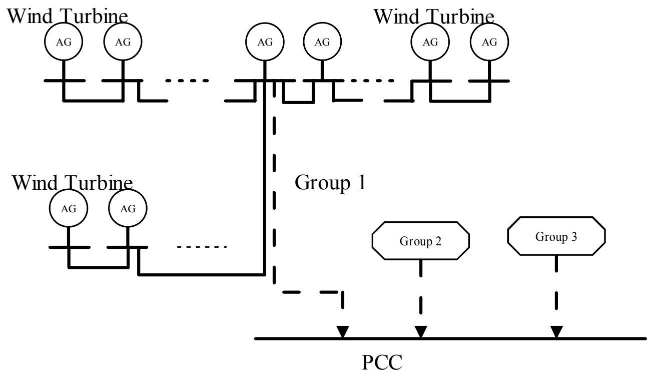


Fig. 8 “Group” network of wind farm

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

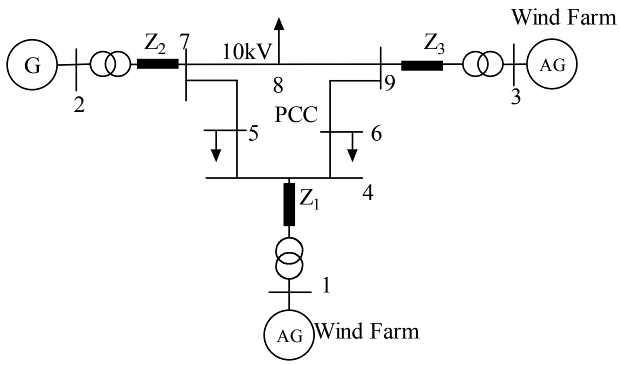


Fig. 9 Connection Circuit between wind farm and weak grid

In the figure, Z_i is the line resistance; G is the other power generation station. Every wind farm could be analyzed by the grouping classification model.

III. Design For Maximal Penetrating Power of Two Wind Farm Model

After meeting the need of system stable, maximal penetrating power of wind farm is the ratio of maximal wind power of system accepted and maximal electric load, that is [8]:

$$\text{maximal penetrating power} = \frac{\text{maximal wind power}}{\text{maximal electric load}} * 100\% \tag{12}$$

The maximal wind power which the system could accept not only is affected by the fixed electric network and the dynamic performance of the system, but also has relationship with the running schedule. A method based on the optimal algorithm to calculate maximal penetrating power is presented [9], and it considers the randomicity of 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} of is 10kV; Power grid voltage is 110kV which is thought as the infinity grid. Analysis to the wind farm is as block diagram (Fig. 11). In this time, the model of wind power conversion system is stable; generator is asynchronous whose saturation effect is ignored; the variation range of the 10kV power grid is from -5% to +5%. Voltage of infinity grid is constant.

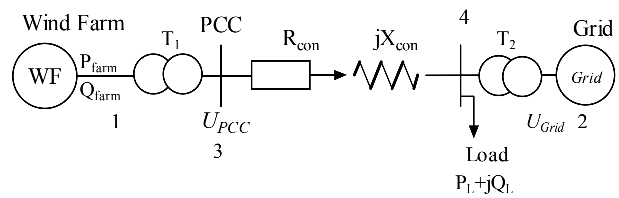


Fig. 10 Wind farm connected to “stiff grid”

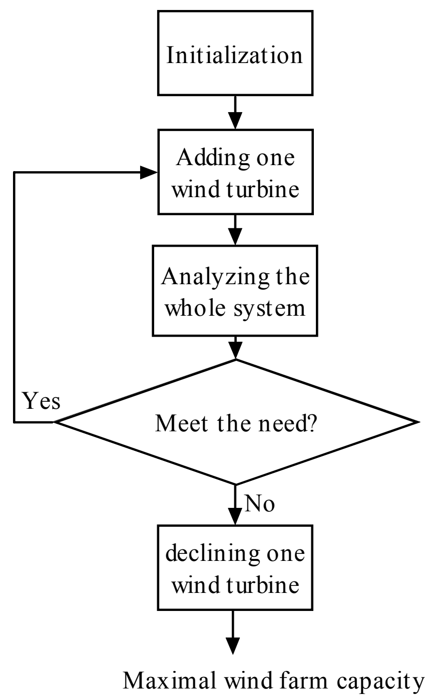


Fig. 11 Calculation of Maximal capacity of wind farm

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

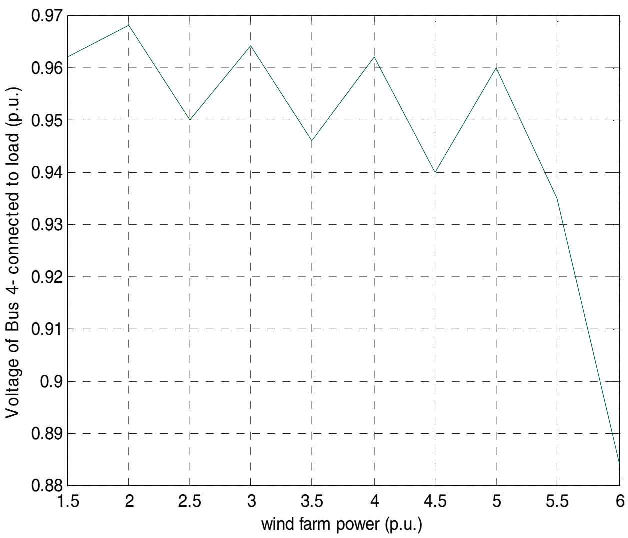
Table 1 Simulation Parameters

P_L=4.5p.u.	X_{T1}=0.01p.u.
Q_L=1.35p.u.	X_{T2}=0.00667p.u.
R_{con}=0.01387p.u.	U_2=1p.u.
X_{con}=0.1624p.u.	Θ_2=0

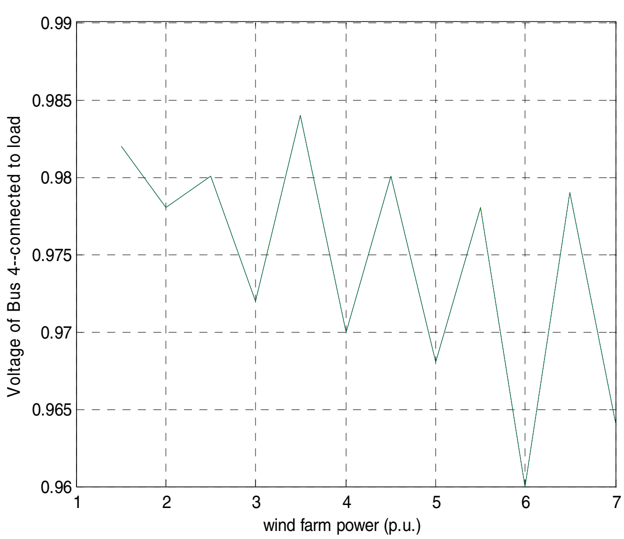
Electric load used the constant resistance, and assumption that is equal to $R+jX$, then:

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

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 as 2-generator system. Reactive power of wind farm is the function of its active power [10, 11-14] because there are no compensating devices, whereas reactive power is zero. The following figures give the simulation results.



a) No compensation capacity



b) With compensation capacity
Fig.12 Load Voltage curve of Wind Farm

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

B. Penetrating Power of Wind Farm Connected to "weak grid"

The model of wind farm connected to weak grid is shown as Fig. 14.

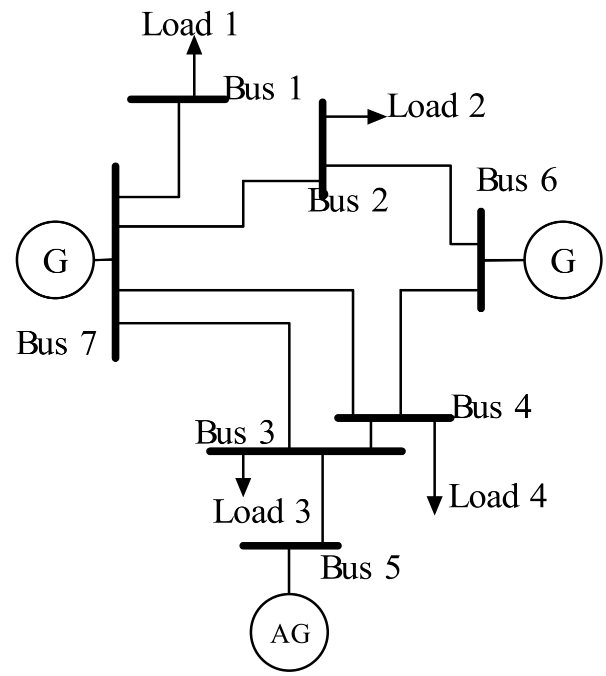


Fig. 14 Diagram of wind farm connected to "weak grid"

In this figure, wind farm connected to Bus 5, and compensating capacitors whose capacity is 50MVar is loaded in Bus 3. Voltage level of Bus 5, Bus 6 and Bus 7 is 220kV. The simulation parameters are shown in Table 2 and Table 3 for the electric load and power line impedance used in the study respectively.

Table 2 Electric load

Number	P(MW)	Q(MVar)
Load 1	40	30
Load 2	110	-20(capacitive)
Load 3	110	100
Load 4	100	48.83

Table 3 Power line resistance

Start and end node of line	Resistance R(Ω)	Reactance X(Ω)
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

Wind farm is connected to Bus 3 by Bus 5. Bus 3 is the sensitive node of the system, and it has the max effects to whole system. After the power flow analysis, the maximal penetrating power of wind farm is given as Fig. 15.

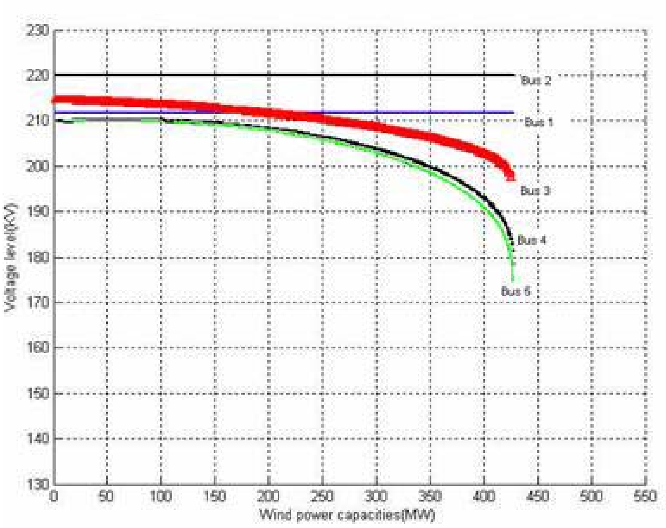


Fig. 15 Maximal Wind Power Connected to weak grid

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 could be improved by adding compensating devices, too. The maximal penetrating power of this wind farm is 14%.

IV. Conclusion

Two models developed in the paper the most common connection styles between wind farm and power system. They are the base to research the power system which contains wind power. The optimal design related to the penetration power, model and to the connection of the grid has been presented.

Simulation results show that penetrating power of wind farm could be improved by changing running schedule by means of connecting with other power grid or improving control ability of each wind farm. The alternative is the proposed method which is namely adding compensating devices. Two models having different penetrating wind power have been studied. The parameters for penetrating power are based on larger values than the actual vales used 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 stability. But in Europe, wind farm capacity could reach 20% and even to more in Denmark because they adopted the different running schedules and opening network structure.

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