# Reactive power penetration limit of a wind farm when connected to a weak power system

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#### Abstract

When a wind farm (hereafter, WF) is connected to a weak grid, the linked bus voltage of the system rises above the specified value, and the reactive power is consumed, so the security and stability of the power system may be affected. In this research, we aim to solve the problem of reactive power shortage due to voltage fluctuation when a mega WF is linked to a weak gird. First, we investigated the optimal Wind Turbine (hereafter, WT) selection on MATLAB/Simulink and designed the WF. Next, we used MATLAB/Simulink and IEEE 30 Bus Test System to investigate the penetration limits of WF and its influences on weak grid using three cases. As results, Vestas V100:1.8MW (Doubly Fed Induction Generator: DFIG) became the optimal for our study and the capacity of mega WF became 54MW. Therefore, the penetration limits of WF to each case are measured and revealed in this paper.

Keywords: IEEE 30 bus test system, Mega Wind Farm (WF), weak grid, penetration limits

## 1. Introduction

As we all know, global warming on the earth caused many unusual phenomena. For instance, the changes of air and water temperature cause the decreasing of ice and snow in Arctic, and this causes the sea level risen and massive extinction of species, etc. In recent years, environmental awareness of global warming prevention has risen. Furthermore, because of the impact of nuclear power crises occurred after the Great East Japan Earthquake on March 11, 2011, nuclear power safety is also being concerned than ever. So, the utilization of sustainable energy such as wind power, which has less impact and good for environment, is promoted. Thus, by using more wind power with its infinite reserves, as they do not emit CO<sub>2</sub>, which causes global warming, fossil fuel depletion problem can be avoided. So, it continues to spread to the rest of the world including Germany, China, the United States and so on. Moreover, according to [1], since 1990s WF is rapidly increasing from 4.84 GW of its installation in 1995 to 197 GW in late 2010. Also, in 2017, more than 52 GW of WFs are installed, bringing total installations to 539 GW in more than 90 countries all around the world [2].

However, since the output of wind power fluctuates greatly with the change in wind speed, when WF is linked to a power grid (especially a weak grid). In addition, the voltage of the linked bus of the system rises above the specified value, and the reactive power is consumed, so the security of the power system and the stability of the system may be affected. In this case, FACTS such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are required [3]. According to [4], STATCOM is showing the better performance than SVC. Currently, the installation capacity of wind power is small and the influence on the grid is small, so it can be ignored. However, as the capacity of the WF increases in the future, the influence of the output fluctuation on the grid cannot be ignored. For this reason, the

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investigation of limitation of WF according to the connected grid need to be consider carefully in the future.

Conventional researches have been carried out to suppress the fluctuation of output by inserting a Dynamic Voltage Restorer (DVR) between independent or small-scale WT and a grid, introducing phase control by the DVR or by inserting energy storage system [5, 6]. As results, they claimed that voltage fluctuation is suppressed, however not much works on suppression of voltage fluctuation when linking mega WF to a weak power system has been reported.

Therefore, in this research, we aim to solve the problem of reactive power shortage due to voltage fluctuation when a mega WF is linked to weak power system.

## 2. Optimal WT Selection and WF Design

#### 2.1. WT output calculation

The annual generated power of wind turbine is the sum of generated output calculated for each wind speed from cut-in to cut-out speed as the following equation [7, 8]:

$$P_w = \sum [P(V) \times f(V) \times 8760] \tag{1}$$

Where  $P_w$  is annual generated power [kWh], P(V) denotes generated power at wind speed V [kW], which can be obtained from its power curve shown in Fig. 1.[8]. f(V) denotes annual wind-speed appearance rate which is given by

$$f(V) = \frac{\pi}{2} \frac{V}{\overline{V^2}} exp\left\{-\frac{\pi}{4} \left(\frac{V}{\overline{V}}\right)^2\right\}$$
(2)

Where  $\overline{V}$  is annual average wind speed [m/s], V is wind speed [m/s].



Fig. 1. Power curve of Vestas V100:1.8MW wind turbine

#### 2.2. Capacity factor (CF)

The capacity factor of a WF is main factor needed to measure the total amount of electricity acquired.

$$CF\left[\%\right] = \frac{P_{W}\left[kWh\right]}{P_{rated} \times 8760h} \times 100 \tag{3}$$

Where *CF* is capacity factor [%],  $P_w$  denotes annual average generated power [kWh], and  $P_{rated}$  represents rated output of WF. In general, *CF* is expected to be more than 20% [7]. Certain onshore WFs can reach capacity factor of over 60% [10].

## 2.3. Initial investment cost

Other main factor, which is needed to be investigated to find the optimal WT is initial investment cost. Hence, in this paper, data provided in Table 1. [11] is used to calculate initial investment cost given by equations (4&5).

| Table 1. C | Costs | for | WF | installation |
|------------|-------|-----|----|--------------|
|------------|-------|-----|----|--------------|

| WT fundamental cost                 | ¥0.25M/kW             |
|-------------------------------------|-----------------------|
| Start-up cost                       | ¥467.00M              |
| Road maintenance cost               | Flat: ¥25.00M/km      |
|                                     | Mountains: ¥85.00M/km |
| Transmission line construction cost | Flat: ¥35.00M/km      |
|                                     | Mountains: ¥55.00M/km |
|                                     |                       |

Initial investment cost *C* [M JPY]

$$C = E + 467 + 0.05tE \tag{4}$$

$$E = 0.25nP + 25b(A+1) + 35b(A+1)$$
<sup>(5)</sup>

Where t is operation year of WT, n denotes number of WT, P is rated output of WT [kW], A is number of WT lines and b is width between WT [km]. In this case, 5% of annual maintenance cost has been considered as well.

#### 2.4. WF design

In order to design WF, it is vital to consider about distance between windmills without losing significant power [12], in other words, windmills cannot be allocated closer than 5 times than WT diameter(D). However, in the area where the wind is not noticeable, if number of WTs is more than 16 the ideal distance between windmills is 9.3 D. However, that is not much different to 10 D[7]. Therefore, in this research the distance between windmills is 10 times of its diameter.

Since each WT has different characteristics and diameters, the scale of WFs in the flat area  $(5 \times 5 \text{km})$  is designed at average wind speed of 6m/s. In addition, we assumed the operating age of each WF as 17 years, and then we carried out the calculation of WT annual output, capacity factor and initial investment cost by using equations given above on MATLAB to investigate the optimal WT under condition provided.

#### 2.5. Calculation results

The calculation results in Table 2. has been shown that 9 types of WT are implemented to investigate the optimal WT, which includes V112: 3.08MW, V100: 2.6MW, V90: 2MW, V100: 1.8MW, V90: 1.8MW, V52: 850kW, V47: 660kW of Vestas company, Enron 1.5MW (height: 70.5m) and Bonus B54: 1MW. Moreover, MATLAB is implemented to calculate the WT annual output, capacity factor and initial investment cost under condition provided in section 2.4.

As results, it is found that V100: 1.8MW has the highest capacity factor of 35%, furthermore V90: 1.8MW, V112: 3.08MW have 28.6%, 28.5% of its capacity factor respectively. Capacity factor of different WT is shown in Fig. 2. (a). However, the annual output of V52: 850kW, V112: 3.08MW, B54: 1MW are the top 3highest 216GWh, 208GWh, 200GWh respectively. On the other hand, Annual output of V100: 1.8MW is 166GWh, which is obviously less than others. However, comparing its annual output with its installation scale, obviously V100: 1.8MW is the most effective WT as shown in Fig. 2. (b).

Therefore, according to the calculation results of annual output, capacity factor and initial investment cost, the V100: 1.8MW wind turbine is the most optimal wind turbine in the flat area of  $5 \times 5$ km with the average wind speed of 6m/s. In addition, the Installation scale is 54MW with 30 windmills which has 5 windmills on X axis, and 6 windmills on Y axis as shown in Fig. 3.

| Wind turbine | Installation | Capacity | Initial       | Annual | Actual        |  |
|--------------|--------------|----------|---------------|--------|---------------|--|
| [kW]         | scale        | factor   | investment    | output | profits       |  |
|              | [MW]         | [%]      | cost          | [GWh]  | [Billion JPY] |  |
|              |              |          | [Billion JPY] |        |               |  |
|              |              |          |               |        |               |  |
| 660          | 94.38        | 23.90    | 44.70         | 197    | 22.30         |  |
| 850          | 102.00       | 24.20    | 48.30         | 216    | 25.20         |  |
| 1000         | 105.00       | 21.80    | 49.70         | 200    | 18.50         |  |
| 1500         | 94.50        | 23.00    | 44.80         | 190    | 20.00         |  |
| V100: 1800   | 54.00        | 35.00    | 26.10         | 166    | 30.20         |  |
| V90: 1800    | 70.20        | 28.60    | 33.60         | 176    | 26.10         |  |
| 2000         | 78.00        | 28.00    | 37.20         | 191    | 27.80         |  |
| 2600         | 78.00        | 25.40    | 37.20         | 174    | 21.80         |  |
| 3080         | 83.16        | 28.50    | 39.70         | 208    | 31.00         |  |

Table 2. Calculation results of annual output, capacity factor, and initial investment cost



Fig. 2. Comparisons of each WT: (a) Capacity factor and (b) Annual output, Initial investment cost and Actual profit.

## 3. Optimal WT Selection and WF Design

## 3.1. IEEE 30 bus test system

The IEEE 30 Bus Test System represents a portion of the American Electric Power System in the Midwestern US. The IEEE officially recognizes this model as a benchmark since 1961. It was recommended to the power system researchers to use this model as a standard model system; therefore, the obtained results of similar simulation could be compared together. In this study, we also used IEEE 30 Bus Test System developed by Nagasaka Laboratory in MATLAB/Simulink for the first time [13]. Furthermore, the IEEE 30 Bus Test System model has 30 bus and 6 generators linked to Bus1, Bus2, Bus13, Bus22, Bus23 and Bus27. In addition, the original total installed capacity of 6 generators is about 189.2MW (Fig. 5).

In order to measure the penetration limits of WF at each bus, we simulated the IEEE 30 Bus Test System before connecting to a WF. Table 3. has shown the results of each bus from bus1 to bus30

respectively. According to the obtained results, we found that Bus8, Bus7, Bus2, Bus21, Bus12 and Bus30 are the higher demand buses respectively.



Fig. 3. Designed wind farm.



Fig. 4. IEEE 30 Bus Test System developed on MATLAB/Simulink by Nagasaka Laboratory.



# Fig. 5. DFIG wind turbine.

Table 3. Numerical data of each bus

| Bus<br>No. | Demand    |             | Voltage<br>[p.u.] |          | Bus      | Demand |           | Voltage<br>[p.u.] |   |          |          |
|------------|-----------|-------------|-------------------|----------|----------|--------|-----------|-------------------|---|----------|----------|
|            | P<br>[MW] | Q<br>[MVar] | v                 | V<br>max | V<br>min | No.    | P<br>[MW] | Q<br>[MVar]       | v | V<br>max | V<br>min |
| 1          | 0.00      | 0.00        | 1                 | 1.05     | 0.95     | 16     | 3.50      | 1.80              | 1 | 1.05     | 0.95     |
| 2          | 21.70     | 12.70       | 1                 | 1.10     | 0.95     | 17     | 9.00      | 5.80              | 1 | 1.05     | 0.95     |
| 3          | 2.40      | 1.20        | 1                 | 1.05     | 0.95     | 18     | 3.20      | 0.90              | 1 | 1.05     | 0.95     |
| 4          | 7.60      | 1.60        | 1                 | 1.05     | 0.95     | 19     | 9.50      | 3.40              | 1 | 1.05     | 0.95     |
| 5          | 0.00      | 0.00        | 1                 | 1.05     | 0.95     | 20     | 2.20      | 0.70              | 1 | 1.05     | 0.95     |
| 6          | 0.00      | 0.00        | 1                 | 1.05     | 0.95     | 21     | 17.50     | 11.20             | 1 | 1.05     | 0.95     |
| 7          | 22.80     | 10.90       | 1                 | 1.05     | 0.95     | 22     | 0.00      | 0.00              | 1 | 1.10     | 0.95     |
| 8          | 30.00     | 30.00       | 1                 | 1.05     | 0.95     | 23     | 3.20      | 1.60              | 1 | 1.10     | 0.95     |
| 9          | 0.00      | 0.00        | 1                 | 1.05     | 0.95     | 24     | 8.70      | 6.70              | 1 | 1.05     | 0.95     |
| 10         | 5.80      | 2.00        | 1                 | 1.05     | 0.95     | 25     | 0.00      | 0.00              | 1 | 1.05     | 0.95     |
| 11         | 0.00      | 0.00        | 1                 | 1.05     | 0.95     | 26     | 3.50      | 2.30              | 1 | 1.05     | 0.95     |
| 12         | 11.20     | 7.50        | 1                 | 1.05     | 0.95     | 27     | 0.00      | 0.00              | 1 | 1.10     | 0.95     |
| 13         | 0.00      | 0.00        | 1                 | 1.10     | 0.95     | 28     | 0.00      | 0.00              | 1 | 1.05     | 0.95     |
| 14         | 6.20      | 1.60        | 1                 | 1.05     | 0.95     | 29     | 2.40      | 0.90              | 1 | 1.05     | 0.95     |
| 15         | 8.20      | 2.50        | 1                 | 1.05     | 0.95     | 30     | 10.60     | 1.90              |   | 1.05     | 0.95     |

#### 3.2. DFIG wind turbine

In this study, DFIG, the most common variable speed WTs is used. It controls the rotor current to obtain the maximum output efficiency of the motor against variable wind speed. Moreover, Vestas V100: 1.8MW is also DFIG type turbine. Fig. 5. shows a DFIG circuit diagram in which an IGBT converter is connected to the winding. A typical DFIG WT has three control loops. Pitch control maintains rotor speed by controlling the pitch angle of the blade parallel to wind direction and stop at high wind speed.

Torque control moves WT's driving point according to maximum power curve. Moreover, power factor/voltage control maintains the power factor generator level value requested from grid system manager.



#### *3.3. Simulation system study*

Fig. 6. Simulation model

Fig. 6. shows the simulation system study, which WF is connected to the 135kV Bus. The electricity generated by turbine was 690V, then transformed to 33kV by transformer, and sent through the distribution lines. After, the voltage was raised again from 33kV to 135kV by the transformer in order to transmit it to the 135kV. However, when WF is linked to the grid, it becomes necessary to investigate how the reverse power flow affects the grid. In this study, we connected the WF with Main grid in the following cases:

- Case1: Buses studied in advance: Bus2, Bus6, Bus10, and Bus30.
- Case2: Buses with high demand: Bus2, Bus7, Bus8, Bus12, Bus21, and Bus30. (local generation, local consumption)
- Case3: Generator buses which are nearest high demand buses: Bus2, Bus13, Bus22, and Bus27. (compensation for power shortage)

Then, by increasing the rated output of WF gradually from 0MW, voltage and reactive power is measured in various simulations to investigate the influence of WF and the penetration limits of WF to IEEE 30 Bus Test System. Furthermore, in this study, we considered an operation when the rated output of WF is 0MW as a reference, and if voltage and reactive power are within  $\pm 5\%$ , we assume that our system is operating normally.

## 3.4. Simulation results

Table 4. and Fig. 7. represent WF influence to main grid when it is linked to Bus2.

Table 4. Numerical data of each bus

| WF    |       |        |      |         |
|-------|-------|--------|------|---------|
| [MW]  | Р     | 0      | V    | Status  |
|       | [MW]  | [MVar] | [kV] |         |
| 0.00  | 72.15 | 96.63  | 133  | Usual   |
| 1.00  | 71.37 | 97.16  | 135  | Usual   |
| 1.80  | 71.20 | 98.42  | 137  | Usual   |
| 3.60  | 63.07 | 94.67  | 136  | Usual   |
| 5.40  | 54.72 | 92.28  | 134  | Usual   |
| 5.50  | 54.43 | 92.53  | 133  | Usual   |
| 5.57  | 54.41 | 92.92  | 135  | Usual   |
| 5.58  | 53.42 | 91.57  | 136  | Unusual |
| 5.60  | 53.41 | 90.91  | 136  | Unusual |
| 5.70  | 53.53 | 91.72  | 134  | Unusual |
| 7.20  | 51.62 | 91.20  | 134  | Unusual |
| 9.00  | 37.92 | 89.14  | 133  | Unusual |
| 10.80 | 32.47 | 86.77  | 132  | Unusual |



Fig. 7. Reactive power and mega wind farm.

Table 5. Results of penetration limitations for each simulation

| Case  | Bus<br>No. | Penetration<br>limits | P<br>[MW] | Q<br>[MVar] | V<br>[kV] | Status |
|---|------------|-----------------------|-----------|-------------|-----------|--------|
|   | 2          | 5.57MW                | 54.41     | 92.92       | 135       | Usual  |
| Buses studied in                                | 6          | 4.63MW                | 22.89     | 21.29       | 131       | Usual  |
| advanced  | 10         | 600W                  | 15.39     | 1.85        | 132       | Usual  |
|   | 30         | 639W                  | 8.83      | 1.59        | 130       | Usual  |
|   | 2          | 5.57MW                | 54.41     | 92.92       | 135       | Usual  |
|   | 7          | 18MW                  | 19.14     | 9.77        | 129       | Usual  |
| Buses with high                                 | 8          | 17MW                  | 25.82     | 25.51       | 127       | Usual  |
| demand  | 12         | 598W                  | 9.63      | 6.39        | 126       | Usual  |
|   | 21         | 589W                  | 16.37     | 10.39       | 130       | Usual  |
|   | 30         | 639W                  | 8.83      | 1.59        | 130       | Usual  |
| Generator buses<br>near to high<br>demand buses | 2          | 5.57MW                | 54.41     | 92.92       | 135       | Usual  |
|   | 13         | 599W                  | 13.06     | 33.27       | 237       | Usual  |
|   | 22         | 611W                  | 11.75     | 5.64        | 132       | Usual  |
|   | 27         | 599W                  | 11.66     | 2.92        | 131       | Usual  |

In Bus2 case, it is usual operation if the voltage of Bus2 is within 126.36~139.65kV and the reactive power is within 91.80~101.46MVar. As the above results, it is found that as the rated output of WF is increased, the active power burden of supplier decreased. Obviously, the penetration limit of WF to Bus2 is 5.57MW due to the variation of reactive power that is over  $\pm 5\%$ , while the voltage is still under limitation.

The results of each simulation are shown in Table 5. For Case1, we found that Bus2, Bus6 have their penetration limits of WF at 5.57MW, 4.63MW respectively, while 600W, 639W for Bus10 and Bus30 are surprisingly weak.

Moreover, Bus12, Bus21 in Case2, Bus13, Bus22, and Bus27 in case3 are also less than 1kW of their WF penetration limits. This means the mega WF is unable to connect with these buses. However, Bus7, Bus8 are the strongest buses among investigated buses in 3 cases with their penetration limits of 18 and 17MW respectively.

## 4. Conclusions and Future Study

In this research, optimal WT under  $5 \times 5$ km of a flat area with average wind speed at 6m/s is investigated. It has been convinced that Vestas V100: 1.8MW WT is an optimal WT with its 54MW installation capacity. Furthermore, we also investigated the influence of WF to power system (IEEE 30

Bus Test System) in 3 cases. As results, the penetration limits of Bus10, Bus30, Bus12, Bus21, Bus13, Bus22, and Bus27 are less than 1kW, which mean we are not able to link a mega WF to these buses. However, Bus2, Bus6, Bus7, Bus8 have their penetration limits at 5.57MW, 4.63MW, 18MW, 17MW respectively.

Since, each bus of IEEE 30 Bus Test System has different characteristics, each bus penetration limits also must be different and unknown. Thus, it is vital to investigate the remained buses in the future. In addition, we are presently working on a novel control system to link the WFs to weak power systems by implementing the decomposition methods. The results will be presented in the future paper when available.

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