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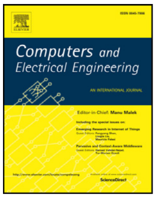

# Power quality analysis for the distribution systems with a wind power generation system [☆]

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## ABSTRACT

This paper investigates the impacts of a large wind power generation system (WPGS) on the distribution system. The installation of various types of distributed generators (DGs) on the distribution system will significantly affect the operating, planning and maintaining strategies of the utility. In this paper, one practical distribution system of Taiwan Power Company (Taipower) is selected for study. Various power quality issues like steady state voltage variation ratio, reverse power, flicker, short-circuit current as well as harmonic are investigated and calculated by applying the computer program simulation and the simplified calculation methods suggested by the International Electrotechnical Commission (IEC). The results will be compared with the Taipower relative standards to demonstrate the feasibility of the WPGS to be installed in the distribution feeder.

## 1. Introduction

The efficiency improvement of electric appliances and the development of renewable energy are considered to be the most critical issues for the sustainable environment [1]. Among various types of renewable energy sources, the wind power and solar energy have been promoted dramatically world-wide for the distributed generations (DGs) in recent years. Among the renewable energy power-generation systems in Taiwan, wind power systems offer the greatest potential in comparison to existing systems. In the end of 2013, the total installed capacity of wind power generators has achieved 610 MW and is expected to have 4200 MW by 2030.

In general, most of the DGs have smaller installation capacity and have to be connected to the distribution network for providing electric power to the utility as well as local loads. DGs may make a contribution to improve power quality and reliability, reduce peak load demand and eliminate the reserve margin [2–4]. However, it is also a challenge for utilities to execute the planning, operating and maintaining of the distribution networks when the DGs penetration is getting higher. Therefore it is necessary to have a maximum installation capacity limitation of DGs according to the values of voltage magnitude, voltage variation ratio, flicker, fault current, harmonic, unbalance, reverse power and wholesale power.

This paper is organized as follows. Section 2 presents the impacts of DGs on distribution system. In Section 3, a Taipower feeder with a WPGS is selected as a case study. And lastly, Section 4 presents the conclusion.

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## 2. Impacts of DGs on distribution system

To maintain the quality of electricity, reliability and stability of the power supply, and safety of the public, the Taipower has the guidelines for the installation of renewable energy power generation systems. The guidelines cover various assessment items such as voltage variation ratio (VVR), flicker, fault currents and harmonic. Each assessment item was analyzed using a relatively complete power program to execute the load flow, short-circuit fault and harmonic analysis. In addition, the simplified calculation methods recommended by the International Electrotechnical Commission IEC [5] are also included and explained as follows.

### 2.1. Steady state VVR

The steady-state voltage fluctuations generated by wind turbines in distribution systems is expressed as

$$\Delta V(\%) = n \times \frac{S_{A\,\max \times 1\ \min}}{S_{pcc\,\min}} \times \cos(\Psi_k + \phi) \tag{1}$$

where $n$ denotes the number of wind generators, $S_{Amax\times 1min}$ is the maximum rated effective power in the wind field over 1 min, $S_{pcc\ min}$ represents the minimum three-phase short-circuit capacity at the point of common coupling(PCC), $\Psi_k = \tan^{-1}(X_k/R_k)$ represents the grid impedance angle at bus $k$, and $\varphi$ denotes the power factor angle of the wind generator.

Furthermore, the load flow simulation results can also be used to calculate the VVR by the following equation:

$$VVR_k(\%) = \frac{V_k^{DG} - V_k}{V_k} \times 100\% \tag{2}$$

where $V_k$ and $V_k^{DG}$ are the voltage magnitude at bus $k$ without and with DG, respectively.

### 2.2. Flicker

The IEC61400-21 standard was also adopted to calculate the voltage flicker created by the wind turbines. This formula can be used to determine both the short-term voltage flicker severity index $P_{st}$ and long-term voltage flicker severity index $P_{lt}$, It is expressed as

$$P_{st} = P_{lt} = c(\Psi_k, \nu_a)\frac{S_n}{S_{pcc\,\min}} \tag{3}$$

where $S_n$ is the maximum rated effective power in the wind field over 1 min, and $c(\Psi_k, \nu_a)$ denotes the voltage flicker coefficient. Taipower uses $\Delta V_{10}$ to assess the voltage flicker severity, and it can be expressed approximately as

$$\Delta V_{10} \cong \frac{P_{st}}{3}. \tag{4}$$

### 2.3. Fault current

For wind turbines directly installed in distribution systems, the short circuit power ($S_{SC}$) of the wind generators can be written using the following equation:

$$S_{SC} = n \times \sqrt{3} \times V_{WT_{rated}} \times I_{SC} \tag{5}$$

where $V_{WT\,rated}$ and $I_{SC}$ denote the rated voltage and short circuit current of the wind generator.

For wind turbines installed in systems through static power converters (SPCs), the SPC automatically shut down when the fault currents supplied by the power generators exceed the acceptable range. In this study, the fault currents were set as two times the rated current of the SPC.

### 2.4. Harmonics

In the IEC61400-3-6 guidelines, the formula for calculating the harmonic currents created by wind turbines at the PCC is given as:

$$I_h = \sqrt[\beta]{\sum_{i=1}^{N_{wt}} \left(\frac{I_{h,i}}{n_i}\right)^{\beta}} \tag{6}$$

where $I_h$ is the $h$th harmonic order at the PCC; $N_{WT}$ is the number of wind turbines; $I_{h,i}$ is the $h$th harmonic order at the $i$th wind turbine; $n_i$ is the transformer ratio. $\beta = 1$ when $h < 5$, $\beta = 1.4$ when $5 \le h \le 10$ and $\beta = 2$ when $h > 10$.

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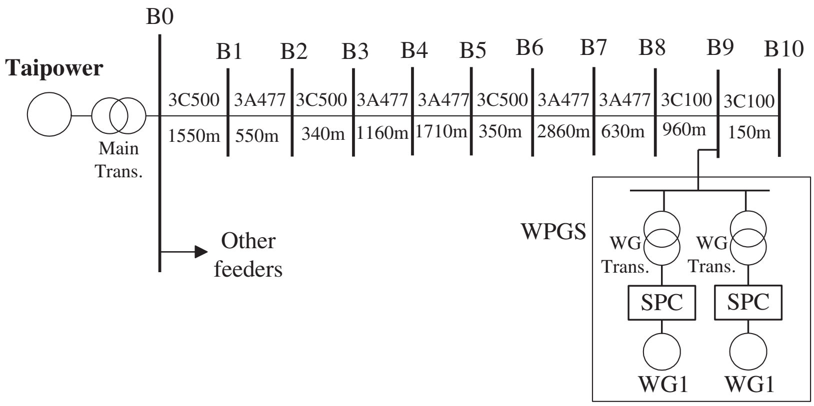

**Fig. 1.** Distribution feeder architecture.

**Table 1**
Buses load in the study system.

| | Peak | | Off-peak | |
|---|---|---|---|---|
| Bus | $P$ (kW) | $Q$ (kvar) | $P$ (kW) | $Q$ (kvar) |
| B0 | 11900.2 | 3911.4 | 3000 | 985.71 |
| B3 | 1653.5 | 544.47 | 401.7 | 130.45 |
| B4 | 1350.3 | 443.84 | 334.5 | 109.94 |
| B5 | 381.5 | 125.52 | 91.2 | 29.98 |
| B7 | 381.5 | 125.52 | 91.2 | 29.98 |
| B8 | 184.6 | 60.67 | 60.8 | 19.98 |
| B10 | 127.3 | 41.84 | 30.4 | 10.00 |

## 3. Case study

Fig. 1 shows a one-line diagram of the distribution feeder in Taipower system. The rated voltage ratio of the main transformer is 69/11.4 kV and the feeder shown in the figure was divided into 10 buses (Buses B0–B9). A WPGS with two wind turbines was assumed to be installed at B9. The feeder power lines were underground cable lines 3C500XP2, overhead lines 3A477XPW, and 3C100 mm$^2$. Table 1 shows the bus loading during peak condition. The two wind turbines installed at Bus B9 had two synchronous power generators interfaced two SPCs with a rating of 2300 kW each. Subsequently, the output of SPCs were connected to the step-up transformer with a 0.4/11.4 kV voltage ratio.

### 3.1. *Voltage variation analysis*

Various load flow analyses were executed to obtain the steady-state voltage, reverse power, and line current under peak operation condition.

Case 1 simulates the original system without considering the WPGS. It is found that there is 16.09 MW active power supplied through the main transformer at substation. Fig. 2 shows a curve depicting the changes in voltage in the buses on the main trunk of the feeder. Curve *a* indicates that all of the voltages in the buses were within the normal range, with the lowest voltage of 0.985 per unit (pu) occurring at B10 and the highest voltage of 1.006 pu occurring at B0.

Case 2 considers the 4.6 MW WPGS at B9. Also, the WPGS was operated at power factor 1.0 and 0.85 lagging. After that, the active power supplied by the substation was reduced from 16.09 MW to 11.59 MW. According to Curve b in Fig. 2, the lowest voltage (1.003 pu) occurred at B2, whereas the highest voltage (1.021 pu) occurred at B9 for the WPGS at power factor 1.0. For Curve c, which had a power factor of 0.85 lagging, the lowest voltage (1.016 pu) is at B0, whereas the highest voltage (1.077 pu) is at B9.

At peak loading condition, the load flow simulation results show that the sum of the feeder load was 4.009 MW, which was less than the output power generated by the WPGS. In addition, a reverse power of 350 kW was generated. The voltages at the PCC(B9) were 0.985, 1.021, and 1.077 pu for the systems without WPGS, with WPGS at power factor 1.0, and with WPGS at power factor 0.85 lagging, respectively. This shows that the VVR was 3.6% for the WPGS with a power factor of 1.0, and 9.2% where the power factor was 0.85 lagging.

The IEC formulas were also used to calculate the VVR caused by the WPGS. The minimum three-phase short-circuit capacity and the $X/R$ values at the PCC, which were obtained from the fault current analysis, were 32 MVA and 2.92, respectively. Under

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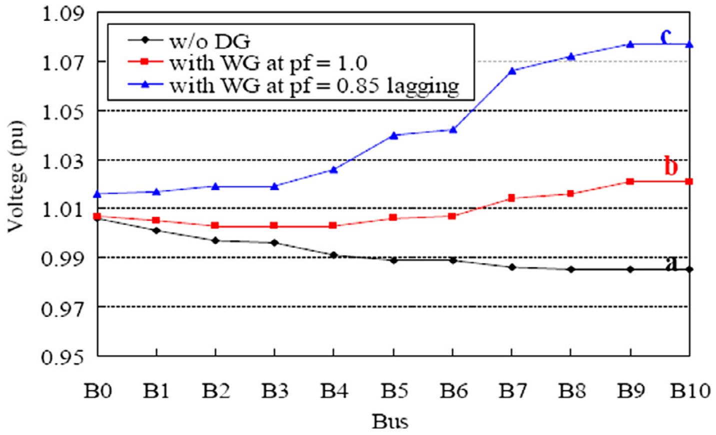

**Fig. 2.** Voltage magnitude at the buses of the feeder under peak load.

peak operation, the wind turbines with a power factor of 1.0, the following steady state VVR was observed at the PCC:

$$\Delta V\,(\%) = 2 \times \frac{2.3}{32}\cos\left(\tan^{-1}2.92\right) = 4.64\% \tag{7}$$

However, when the power factor of the turbines was set to 0.85 lagging, the VVR at the PPC would become

$$\Delta V\,(\%) = 2 \times \frac{2.3}{32}\cos\left(\tan^{-1}2.92 - \cos^{-1}0.85\right) = 11.13\% \tag{8}$$

These results were similar to those obtained through the load flow analysis (3.6% and 9.2%), indicating that when the power generators were operated at a power factor of 0.85 lagging, the steady-state voltage fluctuations exceeded the Taipower limitation value of 5%.

### *3.2. Voltage flicker analysis*

The voltage flicker coefficient ($c(\Psi_k, \nu_a)$) of the study case was set as 4.3 and $S_{pcc\ min}$ was found as 143 MVA. By Eq. (3), the short-term voltage flicker severity index $P_{st}$ is calculated as follows:

$$P_{st} = c(\Psi_k, \nu_a)\frac{S_n}{S_{pcc\,\min}} = 4.3 \times \frac{2 \times 2.3}{143} = 0.138 \tag{9}$$

This value was converted into $\Delta V_{10}$ as:

$$\Delta V_{10} \cong \frac{0.138}{3} = 0.016\% \tag{10}$$

It is found that the calculation value is lower than the 0.45% requirement set by the Taipower.

### *3.3. Fault current analysis*

For the study system, the three-phase short-circuit capacity at the 11.4-kV side of the substation is 143 MVA. The maximum current supplied by the WPGS was hypothesized to be two times of the SPC rated current. Therefore, given power rating 2300 kW for each SPC, the maximal fault current of the WPGS was obtained.

$$I_{WG} = \frac{2 \times 2 \times 2300}{\sqrt{3} \times 11.4} = 466\ \text{A} \tag{11}$$

Fig. 3 shows the curve of the total fault current and the curves of the fault currents supplied by WPGS and the Taipower when the main trunk feeder buses encountered three-phase short-circuit ground faults. The farther the point of fault was from the substation, the smaller the fault current supplied by the Taipower became. Total highest (7728 A) and lowest (2087 A) fault currents occurred at B0 and B9, respectively. The maximum short-circuit fault current did not exceed the Taipower guideline of 10 kA.

### *3.4. Harmonic analysis*

Because wind turbines that use SPCs produce a certain level of harmonic pollution, an analysis was performed to determine its effect on the feeder. Table 2 shows the harmonic currents created by one SPC for each harmonic order. To account for the

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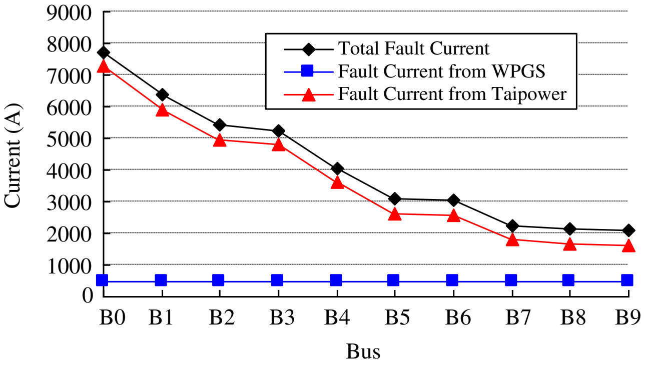

**Fig. 3.** Fault current at each bus of the feeder.

**Table 2**
Harmonic currents created by the WPGS.

| Harmonic order | Harmonic current (%) | Harmonic order | Harmonic current (%) |
|---|---|---|---|
| 1 | 100 | 13 | 0.6 |
| 2 | 0.3 | 14 | 0.2 |
| 3 | 0.2 | 15 | 0.2 |
| 4 | 0.2 | 16 | 0.2 |
| 5 | 0.4 | 17 | 0.5 |
| 6 | 0.2 | 18 | 0.2 |
| 7 | 0.4 | 19 | 0.2 |
| 8 | 0.2 | 20 | 0.2 |
| 9 | 0.2 | 23 | 0.2 |
| 10 | 0.2 | 25 | 0.2 |
| 11 | 0.4 | 29 | 0.2 |
| 12 | 0.2 | - | - |

**Table 3**
Harmonic currents at the PCC.

| Harmonic order | Harmonic current (A) | Harmonic current (%) | Harmonic order | Harmonic current (A) | Harmonic current (%) |
|---|---|---|---|---|---|
| 1 | 239.46 | 100 | 13 | 1.437 | 0.6 |
| 2 | 0.718 | 0.3 | 14 | 0.479 | 0.2 |
| 3 | 0.479 | 0.2 | 15 | 0.479 | 0.2 |
| 4 | 0.479 | 0.2 | 16 | 0.479 | 0.2 |
| 5 | 0.958 | 0.4 | 17 | 1.197 | 0.5 |
| 6 | 0.479 | 0.2 | 18 | 0.479 | 0.2 |
| 7 | 0.958 | 0.4 | 19 | 0.479 | 0.2 |
| 8 | 0.479 | 0.2 | 20 | 0.479 | 0.2 |
| 9 | 0.479 | 0.2 | 23 | 0.479 | 0.2 |
| 10 | 0.479 | 0.2 | 25 | 0.479 | 0.2 |
| 11 | 0.958 | 0.4 | 29 | 0.479 | 0.2 |
| 12 | 0.479 | 0.2 | - | - | - |
| $I_{THD} = 1.35\%$ | | | | | |

**Table 4**
Harmonic voltages at the PCC.

| Harmonic order | Harmonic voltage (V) | Harmonic voltage (%) | Harmonic order | Harmonic voltage (V) | Harmonic voltage (%) |
|---|---|---|---|---|---|
| 1 | 6581.8 | 100 | 13 | 66.1 | 1.004 |
| 2 | 5.4 | 0.082 | 14 | 23.6 | 0.359 |
| 3 | 5.4 | 0.082 | 15 | 25.1 | 0.381 |
| 4 | 7.1 | 0.108 | 16 | 26.6 | 0.404 |
| 5 | 17.7 | 0.269 | 17 | 70.1 | 1.065 |
| 6 | 10.6 | 0.161 | 18 | 29.5 | 0.448 |
| 7 | 24.5 | 0.372 | 19 | 30.9 | 0.469 |
| 8 | 13.9 | 0.211 | 20 | 32.3 | 0.491 |
| 9 | 15.6 | 0.237 | 23 | 36.3 | 0.552 |
| 10 | 17.3 | 0.263 | 25 | 38.8 | 0.590 |
| 11 | 37.8 | 0.574 | 29 | 43.7 | 0.664 |
| 12 | 20.5 | 0.311 | – | – | – |
| $V_{THD} = 2.28\%$ | | | | | |

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worst-case scenario (i.e., the frequency converter outputs have identical phase angles), the harmonic current $\beta$ at each harmonic order in Eq. (6) was set at 1.

Tables 3 and 4 show the simulation results of the harmonic current and voltage calculated at PCC for each harmonic order, respectively. It is found that harmonic orders 13 and 17 exhibited relatively larger harmonic currents (0.60% and 0.50%, respectively). The total harmonic current distortion was 1.35%. These results confirmed that the harmonic currents and total harmonic current distortion were within the Taipower guidelines, and that the total harmonic voltage distortion (2.28%) was lower than IEEE recommendations [6].

## 4. Conclusion

In this study, a simulation analysis and simplified IEC formulas were used to calculate the steady-state voltage variation ratio, reverse power, voltage flicker, fault current, and harmonic of a distribution system containing WPGS. It is found that two methods obtain very close VVR values which were 3.6% and 4.64% when the WPGS power factor was 1.0. However, when the power factor was 0.85 lagging, the VVR exceeded the 5% limit. The maximum reverse power, voltage flicker, and fault current were 350 kW, 0.016%, and 7.728 kA, respectively. The harmonic currents at each level and total harmonic current distortion were within standards. These results showed that the WPGS can be installed on the feeder if the operating power factor can be controlled accurately.

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