ORIGINAL ARTICLE

Study of the Maximum Penetration Rate of Wind Power in an Island Network

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Abstract: The Penghu islands have abundant wind resources; the capacity factor of local wind farms exceeds 47% and these wind farms are slated for expansion. However, wind turbine power output is unstable and excessive turbine installation may negatively affect system stability. This paper seeks to determine an upper limit of the wind power penetration in the Penghu region power system to minimize waste and optimize system safety.

Keywords: Penghu, capacity factor, wind power penetration

Introduction

In recent years, many countries have responded to the challenges of climate change by expanding investment in renewable, carbon-free energy sources, particularly wind power which is particularly suitable to resource conditions in Taiwan [1]. Taipower, the national electrical monopoly utility, has plans to install a large number of wind turbines in Penghu County, a small archipelago off Taiwan's southwest coast. However, wind power are characterized by intermittency, which means wind turbine output is not steady, and increased wind turbine capacity might have a significant impact on power system operation [2-6].

In this paper, PSS/E software is used to analyze the Penghu power system under assumptions of steady-state operation. The information collected includes the impedances of transmission lines and transformers as well as the predicted total system load, and the capacity of each diesel generator unit and each wind turbine. In the simulation, the number of diesel generator units in operation is determined based on the existing operation mode of the generator units in Penghu's Jianshan power plant, and the estimated generation output of wind turbines is assessed with reference to the local monthly average wind speed. Next, PSS/E is used to simulate and analyze transient stability under conditions involving certain system events, such as generator shutoff, transformer trip-off and transmission line trip-off. In this way, the system voltage, frequency and response characteristics are simulated under different loads.

The simulation accounts for Penghu's 11.4kV power distribution lines. Given as many as 32 feeder lines, feeder lines that are more sensitive to the voltage and frequency changes were selected as the important feeders; that is, three feeders, including the longest feeder, the shortest feeder and the feeder which is most sensitive to frequency change, are used in the system model as an evaluation factor.

This work seeks to determine the maximum wind power installation for Penghu's power system. The study includes analysis of load flow, transient stability, power quality, effects of different wind turbine models, short-circuit current, Taipower's power transmission criteria and related system operation guidelines.

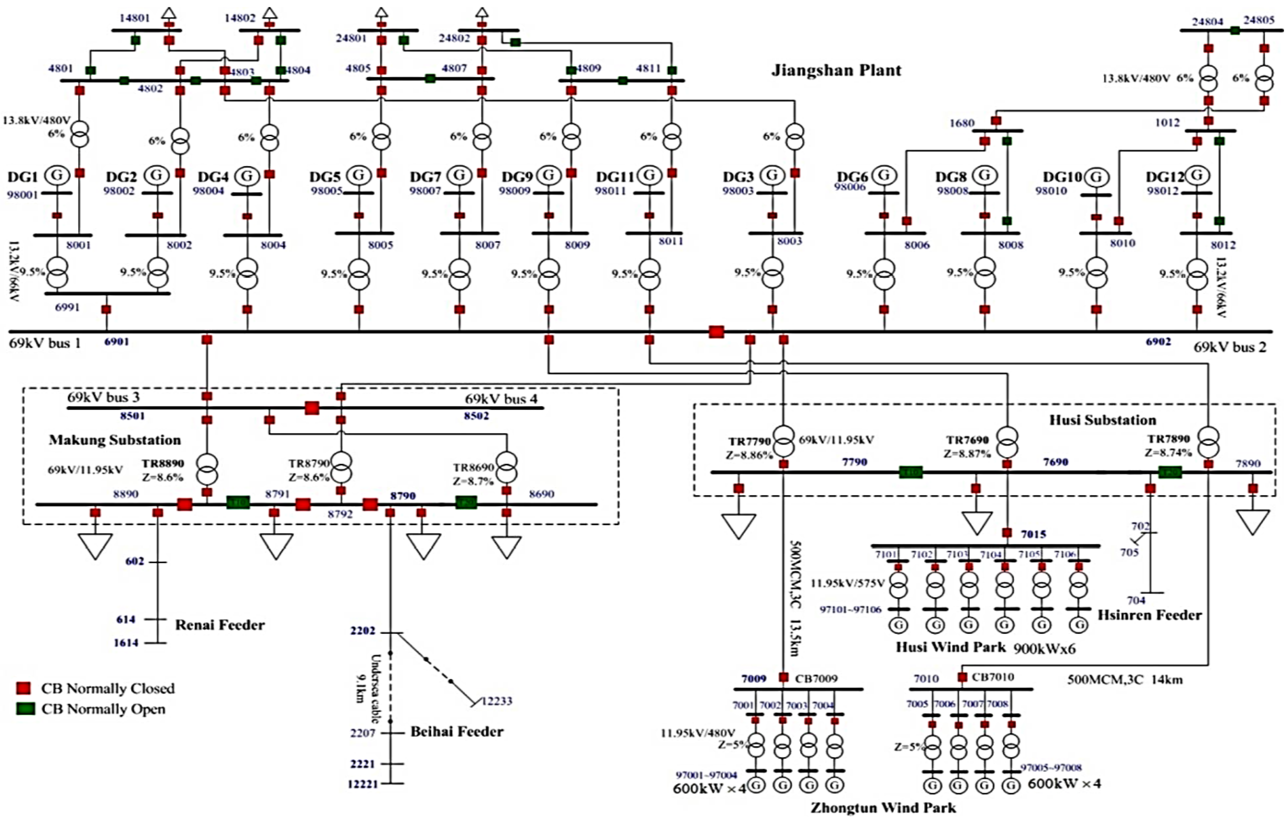

Figure 1. Power System diagram in Penghu.

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Factors for the Assessment of Wind Power Penetration

The term “penetration” in this paper is defined as the ratio of wind power generation to the system net-load. In this study, the longest feeder (Beihai), the shortest feeder (Renai) and the feeder which is the most sensitive to the frequent voltage change (Hsingren) of the Penghu’s power system were selected as indicative feeders to assess whether end-user power quality may be affected by wind turbine operation. In addition, the following five criteria are used to evaluate the maximum wind power penetration:

Line thermal capacity:

The integration of wind turbines must not be allowed to overload transmission lines in Penghu’s power system.

Power quality

The key issues include voltage flicker, harmonics and voltage quality [7]. Based on the IEC 61400-21 analysis, the first two items could be neglected because several research Institutes in Taiwan have monitored these factors in Penghu and no such problems were found. This paper, therefore, limits discussion to voltage quality. According to the planning criteria for Taipower's power transmission system, system voltage should be maintained between .95pu and 1.03pu during normal operation. Moreover, the tolerable range of the transient voltage change due to system events should be determined based on the operational ratings of local end-user equipment, such as personal computers.

Frequency quality:

The presented case study is based on Type C wind turbines. Therefore, the frequency limiting factor in the system is determined by Type C model characteristics. Likewise, frequency-sensitive equipment such as airport radar systems should also be taken into account. However, due to the installation of on-line UPS, it can be neglected.

Power supply reliability

The first-stage low-frequency shedding frequency of 57.4Hz is used as a limiting factor.

Circuit breaker interrupting capacity:

Wind turbine integration must not increase the short-circuit current beyond the capacity of existing circuit breakers.

Overview of Penghu's Power System

The Penghu area features a power system typical of island systems, with a maximum voltage rating of 69kV. The system consists of the Jiangshan thermal power plant, the Zhongtun and Husi wind parks, and the Husi and Makung substations. The Jiangshan thermal power plant includes 4 diesel generator units for phase 1 generation, each with an installed capacity of 12,285 KVA, and 8 diesel generator units for phase 2 generation, each with an installed capacity of 12,980 KVA. Therefore, the total installed thermal power capacity is 152.98MVA. These 12 diesel generator units are grid connected through 13.2kV/69kV step-up transformers. Each generator unit has two control modes: droop and isochronous controls. According to the operation experience in the Jiangshan Thermal Power Plant, the phase-1 units generally use droop controls and the phase-2 units use isochronous controls. Therefore, this work applies the actual operation experience to the generator control. Each of the eight wind power generator units in the Zhongtun wind park has a rated output of 600kW. After the step-up transformer to convert the voltage to 11.95KV, each set of four units is connected to the Husi substation bus through dedicated underground cables. Each of the six wind power generator units in the Husi wind park has a rated output of 900kW. Figure 1 shows the single line diagram of the whole Penghu system.

The Husi Substation is located within the Jiangshan power plant and has three primary transformers, each rated at 69kV/11.95kV with a capacity of 25MVA. The substation supplies the 11 feeders in Watong, Suokang, Hsinren, etc. Makung Substation is located in Makung City and has three primary transformers, each rated at 69kV/11.95kV with a capacity of 25MVA. The Makung Substation is connected to the Jiangshan thermal power plant through an underground cable consisting of 69kV two-circuit transmission lines. Makung Substation serves 21 feeders in Chenkung, Chungkuan, Linsen, etc.

Case Study

In this work, several critical system events are selected study the system impact of wind turbine integration. Each event is conducted based on different load flow simulations. In addition, we used the evaluation criteria mentioned in the previous section to determine the maximum wind power penetration, and the case study was analyzed accordingly as shown in Table 1. Case C1 simulates the system response when the power generation capacity of the wind turbine is unexpectedly reduced or drops to zero. Case C2 simulates the system response while one diesel generator unit trips offline and then the power output from all of the wind turbines is suddenly reduced to zero due to a change of wind speed. Case C3 simulates the system response in case of a wind gust. Cases C4-C9 simulate the system response as diesel generator units trip offline and the wind turbines suffer from a wind gust. Cases C10-C12 simulate the system response when the transformer trips and the wind turbines and the load form an islanding system. Cases C13-C16 simulate the system response as the diesel generator unit suffers from a ground fault, and the wind turbines either have stable output or encounter a wind gust.

Simulation Results

The transient stability analysis is performed under the 17 operating conditions shown in Table 2, in conjunction with the events shown in Table 1 so as to evaluate the maximum wind power penetration. Operating conditions A1-A5, H1 and E1-E2 are the examples for Type C wind turbines in Husi. Cases A2-A5 successively have one fewer wind turbines in operation in Husi than Case A1, thus Case A5 has four fewer wind turbines in operation in Husi. Operating conditions B1–B6, D1 and F1-F2 are for Type B wind turbines in Husi. Cases B2-B6 successively have one fewer wind turbine in operation in Husi than Case B1, thus, B6 has five fewer

Table 1. Simulation for various system incidents.

	Type of system incidents	Clearing time
C1	All wind turbines trip offline	
C2	DG8 trips followed by all remaining wind turbines trip offline after 10s	
C3	Wind gust (over 15 m/s) for 5s	
C4	DG2 trip	
C5	DG2 trips at 6s after wind gust	
C6	DG8 trip offline	
C7	DG8 trips at 6s after wind gust	
C8	Both DG2 and DG8 trip offline	
C9	Both DG2 and DG8 trip at 6s after wind gust	
C10	Transformer No.1 in Husi trips offline	
C11	Transformer No.2 in Husi trips offline	
C12	Transformer No.3 in Husi trips offline	
C13	DG2 (13.8kV Bus) has a ground fault	7 cycles
C14	DG2 (13.8kV Bus) has a ground fault at 4s after wind gust	7 cycles
C15	DG8 (13.8kV Bus) has a ground fault	7 cycles
C16	DG8 (13.8kV Bus) has a ground fault at 4s after wind gust	7 cycles

Table 2. Different system operating conditions.

Operational Status	Load (MW)	Wind Capacity (MW)	Wind Power Penetration (MW)	Spinning reserve (MW)	1st Phase on-line units number/Generation (MW)	2nd Phase on-line number/Generation (MW)
A1(Off-peak)	32.15	9.9	30.79	28.49	2/3.755	3/50
A2(Off-peak)	32.15	9.05	28.15	27.66	2/4.17	3/5.0
A3(Off-peak)	32.15	8.2	25.51	26.83	2/4.585	3/5.0
A4(Off-peak)	32.15	7.35	22.86	26.00	2/4.25	3/5.5
A5(Off-peak)	32.15	6.5	20.22	25.15	2/4.225	3/5.8
B1(Off-peak)	32.15	9.9	30.79	28.48	2/3.76	3/5.0
B2(Off-peak)	32.15	9.05	28.15	27.66	2/4.17	3/5.0
B3(Off-peak)	32.15	8.2	25.52	26.83	2/4.585	3/5.0
B4(Off-peak)	32.15	7.35	22.86	26.00	2/4.25	3/5.5
B5(Off-peak)	32.15	6.5	20.22	25.15	2/4.225	3/5.8
B6(Off-peak)	32.15	5.65	17.57	24.30	2/4.65	3/5.8
H1(Peak)	79.52	9.9	12.45	27.80	2/7.1	8/8.0
D1(Peak)	79.52	9.9	12.45	27.80	2/7.1	8/8.0
E1(Off-peak)	32.15	9.9	30.79	39.50	2/3.25	4/4.0
E2(Off-peak)	32.15	9.05	28.15	38.66	2/3.27	4/4.2
F1(Off-peak)	32.15	9.9	30.79	39.49	2/3.255	4/4.0

wind turbines in operation in Husi. H1 and D1 represent wind turbines operating at full capacity at peak load along with 10 diesel generator units. These 17 operating conditions consider different spinning reserve capacities and wind turbine types.

Case C1: All the wind turbines trip offline in the first second.

During the event, the frequency drops and then recovers to 60Hz within 10 seconds; however, the voltage varies within the range of 0.95 and 1.05 pu. The low-frequency shedding relays are triggered in Cases A1 (penetration of 30.79%) and B1 (penetration of 30.79 %), which implies that the wind power penetration levels for cases A1 and B1 are too high, and are therefore not discussed.

Case C2: DG8 trips at 1s, resulting in the first frequency drop and all wind turbines trip at the 10s, which causes the second frequency drop.

In Cases A2 (penetration of 28.15%), A3 (penetration of 25.51%), B2 (penetration of 28.15%), B3 (penetration of 25.51%), E1 (penetration of 30.79%), and F1 (penetration of 30.79%), the low-frequency shedding relays are triggered. The lowest frequencies in the cases A4 (penetration of 22.86%) and B4 (penetration of 22.86%) are relatively close to the setting of the low-frequency shedding relays, which suggests that their wind power penetration levels remain extremely high. Thus, these two cases will not be studied in the following section.

Case C3: In case of a wind gust, the system frequency rises to its highest point and then drops to its lowest point.

Different wind turbine models may react differently to wind gusts, but the transient frequency for each case is between 59.13Hz and 60.49Hz and low frequency load shedding is not activated. At 10s, all wind turbines recover to approximately 60 Hz, and their voltage variations are within the normal range of 0.95pu and 1.05pu.

Case C15: At 1s, the DG8 ground fault event occurs and the system frequency rises rapidly.

At 1.12s, DG8 trips offline and its frequency starts to drop to its lowest point. At 10s, the frequency recovers to approximately 60Hz, and the voltage quickly recovers to within the range between 0.95pu and 1.05pu when the fault is cleared. Moreover, the system frequency and voltage variations are within the normal range.

Case C16: Following a wind gust, the DG2 ground fault event occurs at 4s.

In the beginning, the system frequency increases rapidly due to the wind turbine output and ground fault event. At 4.12s, due to the tripping of diesel generator unit DG2, the frequency drops to the lowest level. In this case, both the frequency and voltage variations are within the normal range. Only in Case D1 does the wind turbine in Husi trip offline because the frequency protection relay was triggered. For the remaining cases, the high frequency lasts only for a short period so that the Husi wind turbine is not tripped.

According to the results of transient stability analysis, during off-peak periods, if 5 diesel generator units are in operation, the allowed maximum wind power penetration for Cases A5 and B6 are 20.22% and 17.57%, respectively, using Type C and B wind turbines. If 6 diesel generator units are in operation, the allowed maximum wind power penetration for Cases E2 and F2 increases to 28.15%. The results indicate that the number of online units and wind turbine type are the important factors affecting the upper limit of the wind power penetration. At peak-load periods, having all 6 wind turbines in Husi in operation does not have a significant impact on the system.

Conclusions

This study uses 5 guidelines and the IEC 61400-21 requirements to assess the maximum penetration of wind power in the Penghu power system. The research results not only may help prevent excessive turbine installation, but may also help optimize government and enterprise investment efficiency. According to the results of the load flow analysis, the lowest steady-state voltage always occurs in the Beihai feeder. By controlling each main transformer, the bus voltage can be kept within the normal range and the transmission lines are not overloaded. Simulations are conducted using Types B and C wind turbines. At off-peak times, if 5 diesel generator units are in operation (2 Phase-1 units and 3 Phase-2 units) and the Type C model is used, the maximum allowed penetration is 20.22% which would allow for full operation of 8 Chungtuen wind turbines and 2 Husi wind turbines, as in Case A5. On the other hand, if the Type B model is selected, the maximum penetration is 17.57% which would permit 8 Chungtuen wind turbines and only 1 Husi wind turbine to be in operation, as in Case B6. These results indicate that the selection of different wind turbines types may affect the upper limit of wind power penetration.

In the case of 6 online diesel generator units (2 Phase-1 units and 4 Phase-2 units), the maximum penetration is roughly 28.15% for both Types B and C wind turbines, which would allow 8 Chungtuen wind turbines and 5 Husi wind turbines to operate, as in Cases E2 and F2. As for the peak-load periods, the capacity would allow 8 Chungtuen wind turbine and 6 Husi wind turbines to operate without significant system impact.

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