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Determination of Maximum Wind Power Penetration in an Isolated Island System by Considering Spinning Reserve

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Abstract: The abundant wind resources in the Penghu area, where the capacity factor of wind turbines can reach 45%, have inspired authorities to build more wind turbines in a diesel-based power system. However, because the wind turbine output is unstable, high wind power penetration in the system may relatively affect the power quality (voltage and frequency) and reliability of the system. Previous studies have suggested that the optimal penetration level for wind power generation under the present dispatching criteria in Penghu is 26.3%. The present study suggests that the criteria for current unit scheduling should be modified; in particular, the spinning reserve (*SR*) capacity of the diesel engines should be increased without affecting the reliability and power quality of the power system. Such an increase could help avoid the construction of high-cost energy storage systems.

Keywords: wind power penetration; dispatching criteria; spinning reserve (*SR*); reliability and power quality

1. Introduction

According to statistics from the Global Wind Energy Council, the cumulative installed capacity of wind turbines worldwide reached 396.6 GW at the end of 2014 [1]. In particular, the Taiwanese offshore islands of Penghu possess excellent wind power resources, and throughout the year, the average capacity factor of wind turbines can reach 45%. In recent years, increasing environmental awareness has resulted in many countries investing in research activities pertaining to renewable energy for reducing carbon dioxide emissions. The energy costs of island systems are typically greater than those of large grid systems because island systems use diesel generator units, which involve higher fuel costs, unless the location is rich in fossil fuel resources. Therefore, most countries worldwide typically initiate plans for developing renewable energy on remote islands; an example is the development of low-carbon islands in many areas globally. In Taiwan, the electricity costs of the remote islands, comprising Penghu, Kinmen, and Matsu, account for approximately 15%–20% of the total annual deficit of the Taiwan Power Company (Taipower).

An increasing number of studies are being conducted on wind power. Regarding the current status of Taiwan's environmental conditions and development of various renewable sources of power, in Taiwan, currently, wind would be the most viable renewable energy source [2]. Accordingly, Taipower has planned to install many wind turbines in the Penghu area. However, wind power output is not steady, and hence, the higher the wind turbine capacity is in the supply system, the greater the impact is on the electricity network [3–8]. Therefore, the economics of power generation is crucial for these islands. In addition to the economic aspect, the island system poses many technical challenges for power system operation, which must be overcome.

These challenges raise concerns about the reliability and quality of wind power [9–11]. Changes in the wind power determined from an analysis of historical wind power data justify the concerns about the reliability of wind power. According to the present scheduling criteria, Penghu treats wind turbine generation as a negative load. For low wind power penetration, the scheduling criteria do not substantially influence system operation [12,13], and therefore, the criteria remain applicable. According to the scheduling criteria in which the net load is used to determine the number of operating diesel generators, fewer generators are required during off-peak load periods (35 MW) when wind power penetration is relatively high; therefore, these criteria is likely to underestimate the spinning reserve (*SR*) or the number of operating diesel generators required by the system [14].

The increase in wind power penetration in modern power systems engenders a variety of technical, economic, and regulatory issues [15,16]. For example, high wind power penetration would necessitate an increase in the number of online diesel units with a high *SR* to address the unstable nature of wind power [17–20]. Currently, the wind power penetration limit in an island system is determined mainly on the basis of technical constraints related to conventional diesel generators [21]. Such constraints involve dynamic response parameters, which are often quantified using a maximum penetration coefficient with a typical value of approximately 30% of the system load [22]. In particular, the dynamic security of a system with high wind power penetration should be carefully examined [23]. The Ministry of Economic Affairs, Taiwan, implemented the Penghu Low Carbon Island Project with the intention of fully exploiting the local natural resources of Penghu. Therefore, in the future, numerous onshore and offshore wind turbines are expected to be added to the current power system. The enhancement of the installed wind turbine capacity should rapidly increase wind power penetration. However, the intermittency of wind power output could affect the power quality (e.g., voltage and frequency) and supply reliability of the system, thereby affecting power grid planning and operation scheduling of the Penghu power system.

Although dynamic-security problems may be solved by establishing sufficient energy storage facilities [24], increasing the number of wind turbines may require developing storage facilities with the same capacity as the energy generating capacity, which would engender a considerable increase in the capital costs. Therefore, to support an increase in the wind generating capacity, a strategy for increasing the reserve capacity to cope with the error in wind power forecast is proposed in the current study; the strategy involves increasing the number of online diesel units [25]. Owing to the high potential of wind energy resources, the operation scheduling criteria for thermal units of the Penghu power system should be modified. The new scheduling criteria should consider the characteristics of the Penghu power system and the maximum wind power penetration permissible.

On the basis of the current unit scheduling criteria of the local power utility (Taipower) and the operation guide of the North American Electric Reliability Corporation (NERC), this study suggests increasing the number of online diesel units for facilitating the integration of more wind turbines into the power system. Currently, the *SR* is underestimated because the current scheduling criteria do not consider the effective load-carrying capability (ELCC), especially since the load corresponding to high wind power penetration is an off-peak load. Therefore, this propose referred to the NERC operation guide to evaluate the *SR* capacity. The exact percentage of the *SR* capacity was determined. However, since a high number of wind turbines will be set up installed in Penghu, to limit the output of the wind turbines, the current criteria should not be used for unit scheduling.

2. Sample Power System

The Penghu power system is a typical island system, and it includes diesel and wind turbine engines (Figure 1). It comprises the Jiansan thermal power plant (Phase-I: set of four 10,443 kW diesel engines; Phase-II: set of eight 11,000 kW diesel engines), the Zhongtun wind park (eight 600 kW wind turbines), the Husi wind park (six 900 kW wind turbines), two substations (Makung and Husi), a 69 kV double-line-circuit transmission line, and thirty-two 11.4 kV feeders [26].

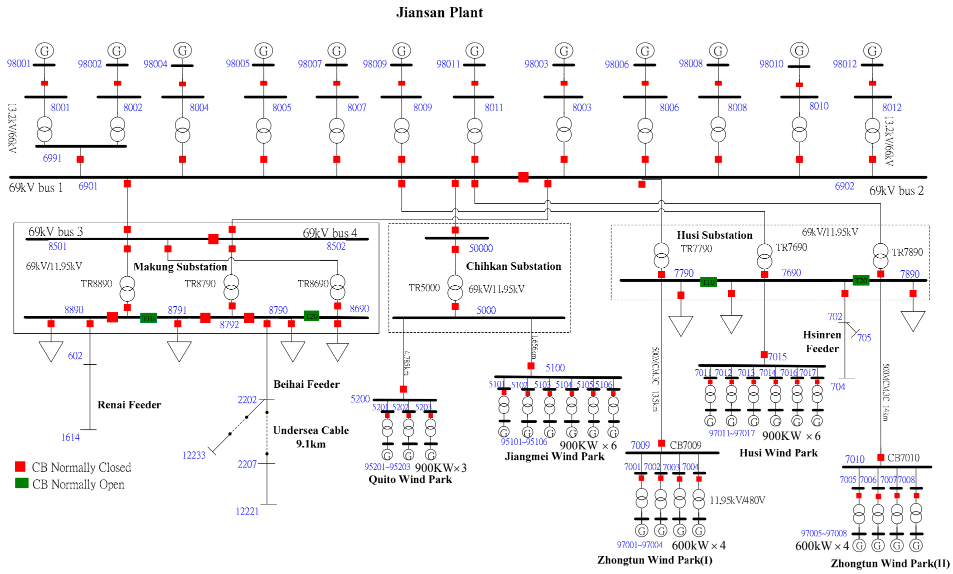

Figure 1. Single-line diagram of the Penghu power system.

Although the average annual capacity factor of wind turbines in the Penghu system may exceed 45%, the output of wind power during the summer peak periods is small; specifically, the output of wind power is inversely proportional to the load demand in Penghu. The intermittency of wind power in winter may adversely affect the power quality and reliability of the system, thereby hindering the planning and operation of the power grid [26,27].

Owing to the rapidly increasing load demand and excellent wind resources, many onshore and offshore wind turbines are expected to be installed in the Penghu area [28]. Taipower has chosen 13 places to build onshore wind farms in Penghu, and once these wind farms become operational, the installed capacity of wind power in Penghu is expected to reach approximately 125 MW. In this study, the Jiangmei and Quito wind farms, which are currently in the planning stage, were also considered in a simulation analysis. The probable locations of these wind farms are shown in Figure 1.

Future plans for the construction of a high number of onshore and offshore wind turbines suggest that the wind power penetration in Penghu will increase rapidly with the increasing load. When the wind power penetration is low, the output from the wind turbines may be regarded as corresponding to a negative load [12]. Therefore, the current scheduling criteria (Table 1) applied to the Jiansan thermal power plant consider the net load demand as the load demand minus the total output of all the wind turbines, and the net load may be used to determine the number of online diesel generators. These scheduling criteria may not be appropriate when an increase in wind power penetration adversely affects the reliability and quality of power supply.

An underfrequency load shedding protection scheme has been used in Penghu to prevent incidents (trips of conventional unit or wind turbine, ground faults, wind gust, etc.) from causing system crashes and blackouts; the details of the scheme are presented in Table 2. Taipower uses the automatic underfrequency load shedding relays on the feeders at the Makung and Husi substations as the main power defense strategy for Penghu's power system. The load shedding operation is divided into three stages, with the first, second, and third stages being set at 57.4, 57.2 and 57.0 Hz, respectively. The operating times of each relay and circuit breaker are 5 cycles and 45 ms, respectively. The models of governors, exciters, and wind inverter control used in the dynamic analysis performed in the present study were IEET2, ESAC8B, DEGOV1 and GGOV1, and they are shown in Figures A1–A4 in the Appendix A, respectively.

Table 1. Current unit scheduling criteria of the Penghu power system. DG: diesel generator.

Net System Load [1] (kW)	On-Line DGs	Phase-I Units			Phase-II Units		
		Installed Capacity	Generation (kW)	No.	Installed Capacity	Generation (kW)	No.
≤35,000	5	10,443	7000	2	11,000	7000	3
35,001–50,200	6		7500	2		8800	4
50,201–61,500	7		7500	2		9300	5
61,501–72,000	8		7500	2		9500	6
72,001–81,500	9		7500	2		9500	7
81,501–89,000	10		7500	3		9500	7
89,001–98,500	11		7500	3		9500	8
98,501–106,000	12		7500	4		9500	8

[1] Net system load = system load − wind generation.

Table 2. Load shedding protection scheme.

Load Shedding Scheme / Operation Pattern	Load Shedding Capacity (MW)			Total Load Shedding Capacity (MW)
	Stage I (57.4 Hz)	Stage II (57.2 Hz)	Stage III (57 Hz)	
Summer Peak Load	14.44	11.92	11.4	37.76
Summer Off-Peak Load	7.22	5.95	5.57	18.74
Winter Peak Load	8.61	7.20	7.60	23.41
Winter Off-Peak Load	5.17	4.32	4.56	14.05

3. Factors Considered for Determination of Maximum Wind Power Penetration

In this study, the maximum wind power penetration was determined from the specifications of the Grid Code of Taipower and the International Electrotechnical Commission (IEC) 61400-21 standard [29]. The IEC 61400-21 standard provides a methodology for measuring and assessing the power quality characteristics of grid-connected wind turbines. The methodology also helps determine the effect of wind turbines on the voltage quality of the Penghu power system. Furthermore, it includes the effect of different numbers of wind turbines.

Because the IEC 61400-21 standard only facilitates the assessment of the power quality in the steady state, the effect of wind power on the transient stability following incidents involving the system or changes in the wind speed can hardly be determined. Therefore, the transient stability should be analyzed to assess whether the integration of wind turbines into the Penghu power system can meet the local utility requirements when system incidents occur. Subsequently, on the basis of such an analysis, it can be decided whether a more comprehensive and rigorous determination of the limit of wind power penetration is required.

The study considered the longest feeder (Belhai feeder, 27.2 km), shortest feeder (Renai feeder, 815 m), and voltage-sensitive feeder (Hsinren feeder, which is connected to the airport and radar station) in the Penghu power system as indicative feeders to determine whether their voltage quality can be affected by the integration of wind power into the power system. Furthermore, the following five criteria were used to evaluate the maximum wind power penetration:

(1) Thermal capacity of transmission lines: problems of overload or voltage violations are not permissible because of the integration of wind turbines with the power system.
(2) Criteria for steady-state voltage: according to Taipower's operation standard, for normal operation, all voltages of buses should be maintained between 0.95 and 1.03 pu. Specifically, steady-state voltage deviations should be within this tolerance range.
(3) Criteria for frequency: the recommended protection values against high or low frequencies should not be violated in any incident when wind turbines are integrated for operation.
(4) Reliability of power supply: no incident should cause load shedding. This implies that the first-stage frequency of under frequency shedding should not be reached when wind turbines are integrated for operation.

(5) Interrupting capacity of circuit breakers: the integration of wind turbines should not induce short-circuit currents to exceed the ratings of the existing circuit breakers.

4. Wind Power Penetration Analyses

In wind power penetration analysis, the voltage and frequency at each load should be considered. To obtain practical analysis results, this study considered the voltage and frequency at three indicative distribution feeders in Penghu. Specifically, the longest, shortest, and most sensitive feeders in the Penghu power system were analyzed to determine whether the frequency and voltage were within the permissible range. This study also considered the currently installed wind turbines and wind turbines planned for the future in the Penghu power system and simulated the operation of a high-wind-power-penetration system.

The Penghu area has abundant wind resources. In winter, the average wind speed can exceed 20 m/s and instantaneous wind gusts can reach 40 m/s. In view of the rapid changes in the wind speed at Penghu, extreme situations such as the rapid shutdown of wind generators, persistence of wind gusts etc.

To determine the basic operating status, this study first performed load flow analyses on the basis of typical peak and off-peak load patterns in the Penghu power system. Subsequently, severe incidents (Table 3) were considered to perform a systematic analysis. Furthermore, the maximum wind power penetration was determined according to the assessment criteria described in Section 2. In the beginning, transient stability analysis was performed by gradually increasing the numbers of online diesel units and wind turbines. The frequency/voltage deviations were examined using dynamic simulation results from PSS®E software (32.0 Version, Siemens Energy, Inc., Schenectady, NY, USA). The transient stability analysis involved considering the settings of protection relays and the operating time of circuit breakers for reviewing transient responses and for investigating if the voltage and frequency of the three feeders were within the required range for the aforementioned assessment criteria. On the basis of the analysis results, the maximum wind power penetration permissible in the Penghu power system was determined.

Table 3. Incident cases considered for assessing the maximum wind power penetration permissible. WT: wind turbine. ST: transient stability case.

Case	Case Study	Clearing Time
ST01	All the wind turbines trip offline	-
ST02	All WTs trip 10 s after DG8 trips offline	-
ST03	All WTs trip 10 s after DG2 trips offline	-
ST04	Wind gust (over 25 m/s) for 5 s	-
ST05	DG2 trips offline	-
ST06	DG2 trips 6 s after a wind gust	-
ST07	DG8 trips offline	-
ST08	DG8 trips 6 s after a wind gust	-
ST09	DG2 (13.8 kV bus) has a ground fault	0.1 s
ST10	DG2 (Bus 13.8 kV) has a ground fault 6 s after a wind gust	0.1 s
ST11	DG8 (13.8 kV bus) has a ground fault	0.1 s
ST12	DG2 (Bus 13.8 kV) has a ground fault 6 s after a wind gust	0.1 s

Figure 2 presents the procedure involved in determining the maximum wind power penetration. The initial conditions involved a minimum off-peak load of 35 MW, which was recorded in 2012, and the initial system included eight and six wind turbines of the Zhongtun and Husi wind farms, respectively. According to historical operation records, the highest wind generation output in the Penghu power system can reach 10.5 MW, and the maximum wind power penetration can reach 30%. Under initial system conditions, after the 10.5 MW load is subtracted from the wind power, the remaining load (i.e., the net load) of 24.5 MW is supplied by diesel generators. According to the current unit scheduling criteria, the maximum number of online operating diesel units is five when the net system load is lower than 35 MW. Using the procedure in Figure 2 and by considering the maximum operating capacity of the diesel units and the aforementioned wind power penetration limit, this study performed load flow and transient stability analyses for determining whether indicators such as voltage and frequency were within the required range. The load flow analysis was performed on the basis of typical load patterns for understanding the basic operating status, and subsequently, severe incidents were considered for performing transient stability analysis. If the computed wind power penetration is in the permissible range, the number of wind turbines can be increased. Moreover, if increasing the number of wind turbines leads to a violation of the criteria on limits, then it signifies that the suggested wind power penetration has been exceeded; consequently, the number of online diesel units should be increased to provide more reserve capacity and enhance the power system capability to vary the reserve capacity. Thus, the maximum wind power penetration permissible in the Penghu power system was determined under severe incidents. The algorithm is explained step by step as follows:

Step 1) *Set initial conditions*

system load $\boldsymbol{L}$ = 35 MW;
number of online diesel units $\boldsymbol{N}$ = 5;
number of online wind turbines $\boldsymbol{M}$ = 0;

Step 2) *Calculate wind power penetration*

wind power generation $\boldsymbol{P_{\mathbf{wind}}} = 10.5 + \boldsymbol{M} \times 0.91$ (MW);
wind power penetration $\boldsymbol{D_{\mathbf{wind}}} = \boldsymbol{P_{\mathbf{wind}}}/\boldsymbol{L}$;

Step 3) *Inspect whether the wind power penetration retains the frequency/voltage in the permissible range and whether the wind power penetration causes a reliability problem*

perform load flow and transient stability analyses to obtain frequency/voltage deviations
if $\boldsymbol{D_{\mathbf{wind}}}$ causes a reliability problem, ***N = N + 1***;
else M = M + 1;

Step 4) *Check the operational limits of the online diesel units*

The outputs of the Phase-I and Phase-II units, ***P(I)*** and ***P(II)***, should be above their lower limits.
If P(I) > 3 MW or P(II) > 1 MW, then go to step 3;
else go to step 5;

Step 5) *Output the maximum wind power penetration and calculate the system fuel cost*

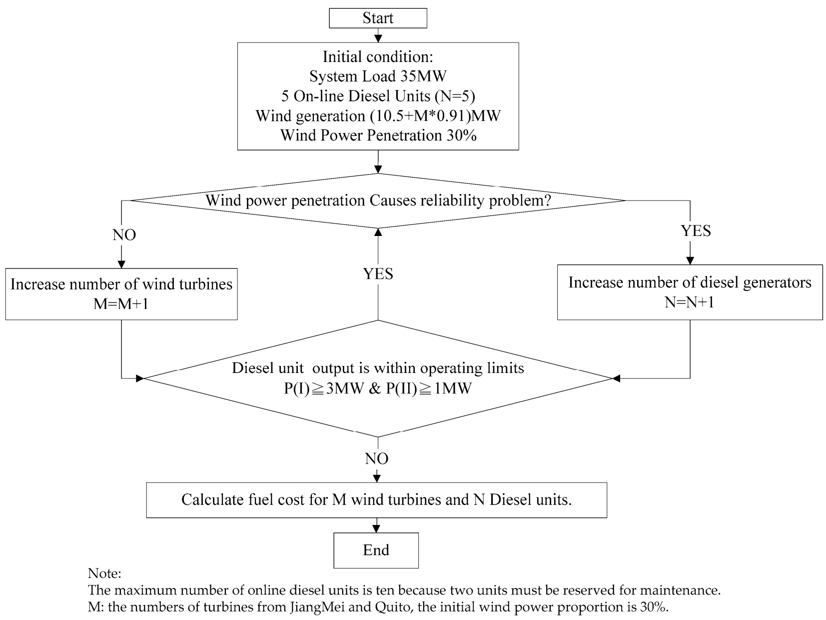

Figure 2. Flow chart for determining the maximum wind power penetration.

5. Results of Analysis for Determination of Maximum Wind Power Penetration

In contrast to traditional diesel units, the output of wind turbines is highly unstable. In this study, the maximum wind power penetration in the Penghu area was determined based on a minimum load of 35 MW. In the proposed process, the initial system load value can be replaced with any other value, and the maximum wind power penetration for different load levels can be determined. Considering the current unit scheduling criteria and various grid incidents described in Table 2, this study simulated the maximum wind power penetration for various operation patterns. The results are presented in Table 4. In the representation D*xy*M*zz*, *x* and *y* denote the numbers of operating diesel units in Phase-I and Phase-II, respectively, and *zz* represents the total number of turbines installed on the Jiangmei and Quito wind farms. The operation patterns D23M00, D24M00, D25M03, D26M05 and D27M08 are not permissible because they lead to low-frequency load shedding, and the details are presented in Table 5, where N denotes no load shedding and that the system frequency and all the bus voltages are within the required range; L1 and L2 represent the first- and second-stage load shedding, respectively. Furthermore, D and M denote the numbers of diesel generators and wind turbine generators, respectively. Tables 6 and 7 provide details of the load shedding cases (i.e., cases L1 and L2 in Table 5) and the lost generation of diesel units and wind turbines.

Table 4. Simulation results for the maximum wind power penetration for different operation patterns. *SR*: spinning reserve.

Operation Pattern	Total Wind Generation (MW)	Wind Power Penetration (%)	Allowed	*SR* (MW)
23M00	10.5	30.0	NO	23.6
D24M00	10.5	30.0	NO	33.8
D25M00	10.5	30.0	YES	43.8
D25M01	11.41	32.6	YES	44.6
D25M02	12.32	35.2	YES	45.3
D25M03	13.23	37.8	NO	46.0
D26M03	13.23	37.8	YES	56.5
D26M04	14.14	40.4	YES	57.2
D26M05	15.05	43.0	NO	58.0
D27M05	15.05	43.0	YES	68.6
D27M06	15.96	45.6	YES	69.4
D27M07	16.87	48.2	YES	70.2
D27M08	17.78	50.8	NO	71.0
D37M08	17.78	50.8	YES	81.0
D37M09	18.69	53.4	YES	81.8

Table 5. Results of low-frequency load shedding.

Diesel Generator	Wind Turbine Generator	ST											
		01	02	03	04	05	06	07	08	09	10	11	12
D23	M00	N	**L2**	**L1**	N	N	N	N	N	N	N	N	N
D24	M00	N	**L1**	N	N	N	N	N	N	N	N	N	N
D25	M00	N	N	N	N	N	N	N	N	N	N	N	N
D25	M01	N	N	N	N	N	N	N	N	N	N	N	N
D25	M02	N	N	N	N	N	N	N	N	N	N	N	N
D25	M03	N	**L1**	**L1**	N	N	N	N	N	N	N	N	N
D26	M03	N	N	N	N	N	N	N	N	N	N	N	N
D26	M04	N	N	N	N	N	N	N	N	N	N	N	N
D26	M05	N	**L1**	**L1**	N	N	N	N	N	N	N	N	N
D27	M05	N	N	N	N	N	N	N	N	N	N	N	N
D27	M06	N	N	N	N	N	N	N	N	N	N	N	N
D27	M07	N	N	N	N	N	N	N	N	N	N	N	N
D27	M08	N	**L1**	**L1**	N	N	N	N	N	N	N	N	N
D37	M08	N	N	N	N	N	N	N	N	N	N	N	N
D37	M09	N	N	N	N	N	N	N	N	N	N	N	N

Table 6. Analysis results of Incident ST02.

Operating Pattern	Lost Generation (MW)		Load Shedding Stage (MW)	Lowest Frequency (Hz)
	Diesel Units	Wind Turbines		
D23M00	5.50	10.5	Stage 1 (5.15 MW) Stage 2 (tripped, but no load shedding)	57.20
D24M00	4.63	10.5	Stage 1 (5.13 MW)	57.39
D25M03	3.21	13.23	Stage 1 (5.15 MW)	57.34
D26M05	2.38	15.05	Stage 1 (5.15 MW)	57.37
D27M08	1.65	17.78	Stage 1 (5.15 MW)	57.34

Table 7. Analysis results of Incident ST03.

Operating Pattern	Lost Generation (MW)		Load Shedding Stage (MW)	Lowest Frequency (Hz)
	Diesel Units	Wind Turbines		
D23M00	4.15	10.5	Stage 1 (5.15 MW)	57.24
D25M03	3.0	13.23	Stage 1 (5.15 MW)	57.37
D26M05	3.0	15.05	Stage 1 (5.15 MW)	57.39
D27M08	3.0	17.78	Stage 1 (5.15 MW)	57.36

In Table 6, for example, when the incident ST02 occurs, the lost conventional generation is 5.5 MW and the lost wind turbine generation is 10.5 MW. The system frequency for D23M00 drops to 57.2 Hz and causes a first-stage load shedding of 5.15 MW. The transient frequency and voltage curves are shown in Figure 3. Consider the case D25M03 in Table 7 as another example. When the incident ST03 occurs, the lost conventional generation is 3 MW and the lost wind turbine generation is 13.23 MW; furthermore, the system frequency drops to 57.37 Hz, leading to the first-stage load shedding. The simulation curves for this incident are shown in Figure 4.

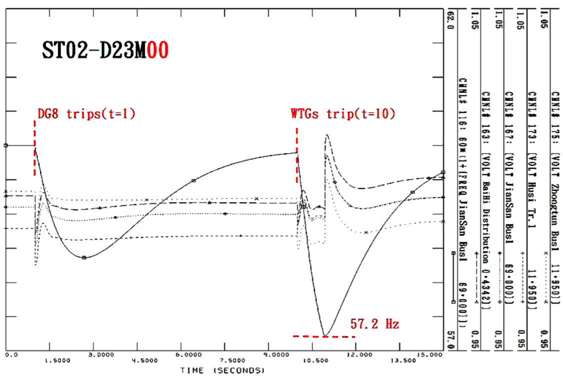

Figure 3. System frequency and voltage for operating pattern D23M00 and incident ST02.

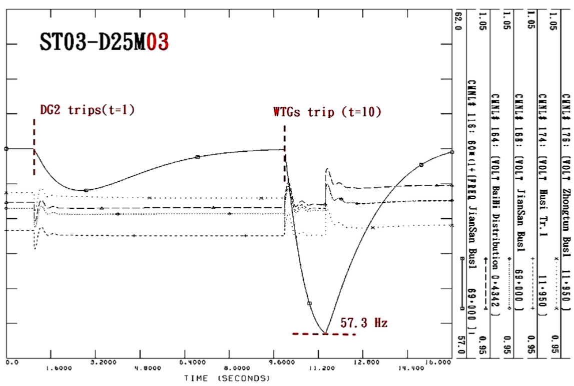

Figure 4. System frequency and voltage for operating pattern D25M03 and incident ST03.

In Table 4, case D23M00 violates the criteria of limits; this therefore necessitates increasing the number of online diesel units until they can provide sufficient *SR*. The number of online diesel units is hence increased to five (case D25M00). Subsequently, the number of online wind turbines should also be increased. Consequently, the operation patterns D25M01 and D25M02 do not violate the criteria of limits. However, when three wind turbines are added (case D25M03), the system operation violates the criteria of limits, necessitating the provision of additional diesel units. Accordingly, the operation pattern D25M03 is replaced by D26M03. The aforementioned process can be used to achieve the maximum wind turbines power penetration.

For the maximum proportion of wind turbines (53.4%) in Table 4, the online operating wind turbines already contain eight wind turbines at the Zhongtun wind farm, six ones at the Husi wind farm, six ones at the wind farm in Jiangmei (which is in the planning stage), and three ones at the wind farm in Quito (which is also in the planning stage). In this situation, if any additional online wind turbine is added to the system, the proportion of wind turbines may violate the criteria of limits when a system incident occurs, and such violation would reduce the reliability of the power system. In other words, the maximum wind power penetration is 53.4% for a load of 35 MW in Penghu. The maximum wind power penetration for other load values can also be determined using the proposed process. In the proposed process, the calculated value of the upper limit on the proportion of wind turbines is strongly influenced by the *SR* and the number of online operating diesel units. If the system operator determines the number of online diesel units by using the current unit scheduling criteria, the capacity of the *SR* may not be sufficient when the largest diesel generator trips offline. Therefore, it is suggested that the current unit scheduling criteria should be modified.

6. Novel Strategy for Modifying Existing Unit Scheduling Criteria

6.1. Effective Load-Carrying Capacity

Unlike conventional thermal power units that can be regulated directly, wind turbines always have unstable outputs. In a high-wind-power-penetration system, several key aspects must be considered, such as the sufficiency of the capacity of diesel units for compensating for changes in the wind turbine output, control ability of the frequency, which should be maintained within the required range for normal continuous operation by the system operator, and capability of the system to provide sufficient *SR* capacity. Furthermore, a change in the wind turbine output may increase the frequency of switching between diesel units, particularly when the proportion of wind turbines increases. According to the traditional unit scheduling criteria, wind power cannot be scheduled; hence, the management of system reliability mainly involves scheduling the diesel units. Nevertheless, the capacity credits contributed by wind turbines should be considered, particularly when the wind power penetration increases and distributes over a large area. Thus, the Electric Reliability Council of Texas (ERCOT) regards a fraction of total installed capacity of wind turbines as a firm-capacity contributor to the *SR* capacity. Therefore, an accurate formula for calculating the capacity value of wind power should include information on wind turbines.

The ELCC method is generally used to set the *SR* capacity. In this method, the required *SR* is estimated on the basis of the installed capacity of a reference unit. However, unlike traditional thermal units, wind turbines cannot be regulated; therefore, it is questionable whether the installed capacity of a wind turbine is equivalent to the reserve capacity. The relevant standards of ERCOT suggest that 10% of the installed capacity of wind turbines can be considered as the ELCC of wind power [30]. Although the *SR* capacity is calculated mainly on the basis of the margin capacity during peak-load hours, considering 10% of the installed capacity of wind turbines as the ELCC may lead to the overestimation of the ELCC because the wind power output in the Penghu power system is low during summer peak-load hours and may increase during winter off-peak hours. Furthermore, the Penghu grid system is a small island system. This study thus considered 10% of the monthly average of the total wind generation during the peak-load hours as the ELCC of wind power.

6.2. New Unit Scheduling Criteria Based on Spinning Reserve

The *SR* capacity specified in the relevant NERC standards exceeds 12.5% [31–33]. However, the Penghu power system is an island system and includes many commercial and residential loads. These loads can endure low-level power quality and are more tolerable to changes in the voltage and frequency. Furthermore, the diesel units in the Jiansan power plant have the capabilities of fast generation response and quick startup, in addition to high tolerance to considerable frequency variations.

The simulation results in Table 4 show that the wind power penetration in the Penghu power system may reach 53.4% (18.69 MW) during off-peak hours. To respond to such a high penetration, the Penghu power system requires 10 online diesel engines to be in operation at any time for providing sufficient *SR* capacity for a unit ramping up and down. The provision of sufficient *SR* also facilitates fulfilling ancillary requirements such as the regulation of the voltage and frequency. For the maintenance of a regular frequency during grid incidents, the diesel units must provide a sufficient *SR* capacity. Typically, the *SR* capacity should be greater than the maximum installed capacity of a single diesel unit. Therefore, the *SR* capacity in the Penghu power system should be greater than 11,000 kW. The calculation formula for *SR* is presented in Equation (1). In this equation, the ELCC of wind power is considered for determining the *SR*. Furthermore, to conservatively estimate Grmg (defined after Equation (1)), this study considered the average annual wind power output in the calculation formula:

$$SR = Source - Load - Grmg \tag{1}$$

where *Source* = installed capacity of online diesel units + ELCC of wind power, ELCC of wind power = monthly average wind generation during peak-load hours × 10%, *Load* = the maximum limit on the load (this parameter can be used to determine an appropriate number of online diesel units), *Grmg* = loss of *SR* capacity when the maximum online diesel unit trips offline = installed diesel unit capacity − average generation of online units = installed capacity – (*Load* – average annual wind output)/number of online units.

When a diesel unit trips, the loss of *SR* could be considerable. However, the calculation of the loss of *SR* capacity is generally imprecise. Therefore, a conservative method based on the average annual total power generated from wind turbines was used in this study to calculate the loss of *SR* capacity. For instance, when a diesel unit with the maximum power output trips offline, the loss of *SR* capacity in the system is defined as the difference between the value of the system load for a generation capacity of 11,000 kW and the average generating capacity of all the online diesel units (except the tripping unit); the average generating capacity of all the online diesel units is calculated as ((system load − average output of the wind turbines)/number of online diesel units). The calculation of the *SR* capacity by using Equation (1) is illustrated here; the *SR* capacity must be greater than the installed capacity of 11,000 kW. Let the number of online diesel units be 10 (three from Phase-I and seven from Phase-II). The *SR* capacity can then be calculated as:

$$SR = 10,443 \times 3 + 11,000 \times 7 + 157.13 - Load - \left(11,000 - \frac{Load - 7029.2}{10}\right) > 11,000\ \text{kW} \tag{2}$$

where 10,443 and 11,000 kW are the installed capacities of the Phase-I and Phase-II diesel generators, respectively. Furthermore, 157.13 kW is the ELCC of wind power, which is 10% of the monthly average of the total wind generation during peak-load hours, and 7029.2 kW is the average annual wind power output in Penghu. Because the *SR* in the Penghu system should be greater than 11,000 kW; that is, *SR* > 11,000 kW, the maximum load limit can be determined by solving the preceding inequality in Equation (2); that is, load < 95 MW. Therefore, the maximum load limit for 10 online diesel units in operation is 95 MW. The maximum load in the current Penghu system is approximately 72 MW, and therefore, 10 online diesel units can provide sufficient *SR* to the island system. In addition, according to the simulation results discussed in Section 4, the operation of 10 diesel units can enable achieving the maximum wind power penetration while attaining the lowest fuel cost. Therefore, to maintain high system reliability in the high-wind-power-penetration system, 10 online diesel units must be in operation at any given time.

7. Economic Benefit Obtained by Using Novel Unit Scheduling Strategy

This section discusses the economic benefit associated with using the proposed unit scheduling strategy and presents a comparison of the fuel costs between existing and novel unit scheduling strategies. If the existing unit scheduling strategy is used, wind power can be obtained only from the Zhongtun and Husi wind farms, and the total power generated from diesel generators and wind turbines is shown in Table 8.

Table 8. Generation from diesel generators and wind turbines when the existing unit scheduling strategy is used.

Month	Monthly Total Generation from Diesel Units (kWh)	Monthly Total Generation from Wind Turbines (kWh)
Jan.	29,797,227	2,834,156
Feb.	28,094,001	1,590,760
Mar.	30,288,281	2,039,128
Apr.	31,020,188	1,606,039
May	37,529,565	975,520
Jun.	41,289,457	504,872
Jul.	47,414,545	355,979
Aug.	44,773,049	833,183
Sep.	44,580,617	961,998
Oct.	33,853,882	2,228,634
Nov.	30,378,402	2,148,784
Dec.	29,803,820	2,464,157
Annual	428,823,034	18,543,210

Figure 5 shows the electricity portfolio for the diesel generators and wind farms when the existing unit scheduling strategy is used. In this case, the fuel cost for 1 year is new Taiwan dollars (NT$) 1,520,299,121. However, if the proposed unit scheduling strategy is used, the wind power from not only the Zhongtun and Husi wind farms but also the Jiangmei and Quito wind farms can be utilized; the total power generation from diesel generators and wind turbines is shown in Table 9.

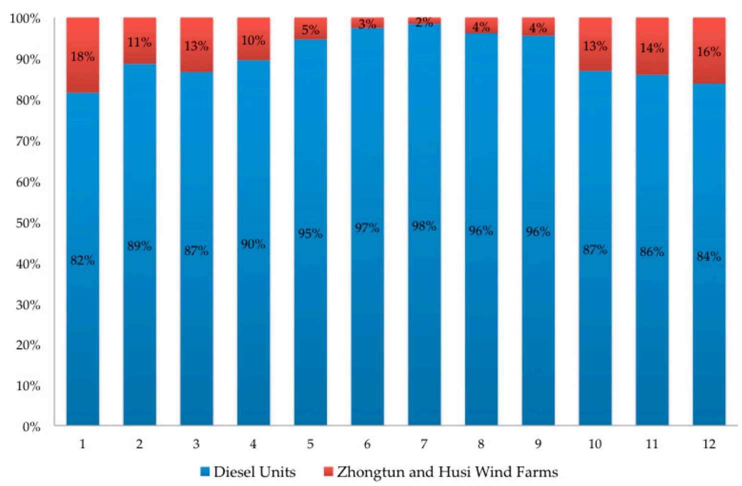

Figure 5. Electricity portfolio for diesel generators and wind farms when the existing unit scheduling strategy is used (blue: diesel generators; red: Zhongtun and Husi wind farms).

Figure 6 shows the generation ratio for the diesel generators and wind farms when the proposed unit scheduling strategy is used. In this case, the fuel cost for 1 year is NT$1,406,588,955. Specifically, savings in fuel cost in 1 year can reach 7.47%, which highlights the economic benefit of the proposed unit scheduling strategy.

Table 9. Generation from diesel generators and wind turbines when the novel unit scheduling strategy is used.

Month	Monthly Total Generation from Diesel Units (kWh)	Monthly Total Generation from Wind Turbines (kWh)
Jan.	23,244,080	9,387,309
Feb.	24,546,147	5,138,615
Mar.	25,421,976	6,905,435
Apr.	27,150,251	5,475,976
May	35,219,599	3,285,487
Jun.	40,096,953	1,697,377
Jul.	46,601,508	1,169,016
Aug.	42,993,271	2,612,962
Sep.	42,405,141	3,137,474
Oct.	28,774,180	7,308,338
Nov.	25,424,069	7,103,118
Dec.	23,625,555	8,642,422
Annual	385,502,730	61,863,527

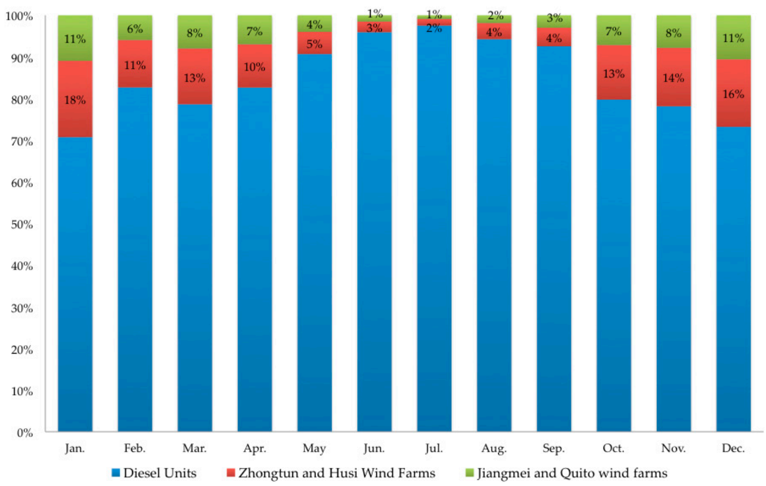

Figure 6. Electricity portfolio for diesel generators and wind farms when the novel unit scheduling strategy is used (blue: diesel units; red: Zhongtun and Husi wind farms; green: Jiangmei and Quito wind farms).

8. Conclusions

The share of wind energy in the global energy portfolio is increasing, and wind power penetration has increased sharply in certain regions of the world. The Penghu area has excellent wind resources, which are among the highest in the world, and the local government has planned to install a high number of wind turbines in this area. The intermittency of wind energy results in poor power quality and reliability of a wind power system. The current operation criteria on unit scheduling regard the output of wind turbines as corresponding to a negative load. When wind power penetration reaches a considerable level, the online diesel units must provide sufficient capacity to ramp up or ramp down to limit the variation of the system frequency to a reasonable range. Otherwise, a single serious fault can affect the reliability of the power supply.

This study aimed to determine the maximum wind power penetration permissible for the Penghu power system. In addition to the existing Zhongtun and Husi wind farms, Taipower plans to build two more wind farms, Jiangmei and Quito wind farms. The current operation criteria on unit scheduling use the net load to determine the number of online operating units. To evaluate the maximum wind power penetration, this study performed load flow analysis and stability analysis with five major criteria. Because current operation criteria on unit scheduling regard wind power as a negative load, the net load leads to a low number of online diesel engines and low *SR*. According to the simulation results, in cases D23M00, D24M00, D25M03, D26M05, and D27M08, the under frequency for load shedding relay is triggered when a serious fault occurs. When such a fault occurs, system outage would occur and wind power penetration would be limited. Therefore, the existing unit scheduling criteria should be modified. When the wind power of the Penghu power system increases in the future, this study suggests that the total load (without deducting wind power) and wind power outputs of the system should be the basis for determining the number of online diesel engines. When the number of wind turbines increases, sufficient *SR* can be achieved by increasing the number of online diesel engines and the ELCC of the wind turbines; to provide energy to the power system, the maximum wind power penetration would be promoted.

The result of a simulation of the proposed process for evaluating the maximum wind power penetration show that the maximum permissible installed capacity of wind power was 18.69 MW for 8, 6, 6 and 3 wind turbines at the Zhongtun, Husi, Jiangmei, and Quito wind farms, respectively; furthermore, the installed capacity of each of these wind farms was 4.8, 5.4, 5.4 and 2.7 MW, respectively. The total wind power capacity of 18.69 MW indicates a wind power penetration of 53.4%. For such high wind power penetration, the Penghu power system requires more than 10 online diesel generators to provide sufficient ELCC. Providing sufficient *SR* capacity to cope with grid accidents such as the tripping of a unit is also necessary. However, because many wind turbines are integrated into the power system, the online diesel generators will be operated with a low-load status. Sudden changes in the wind speed could cause an inverse power flow directed toward the power plant, resulting in the motoring of the diesel generators. To prevent motoring, reverse current protection relays can be installed in step-up transformers to detect reverse power and trigger wind turbines remotely. This can help prevent the diesel generators from absorbing large inverse power and thereby protect them from major damage. Finally, on the basis of our study, were commend that before the installation of a submarine cable between Taiwan and the Penghu grid, the total wind power of the installed capacity in the Penghu area should not exceed 18.69 MW, to maintain system reliability and security.

Appendix A

The models of governors, exciters, and wind inverter control used in the dynamic analysis were IEET2, ESAC8B, DEGOV1 and GGOV1, and they are shown in Figures A1–A4, respectively.

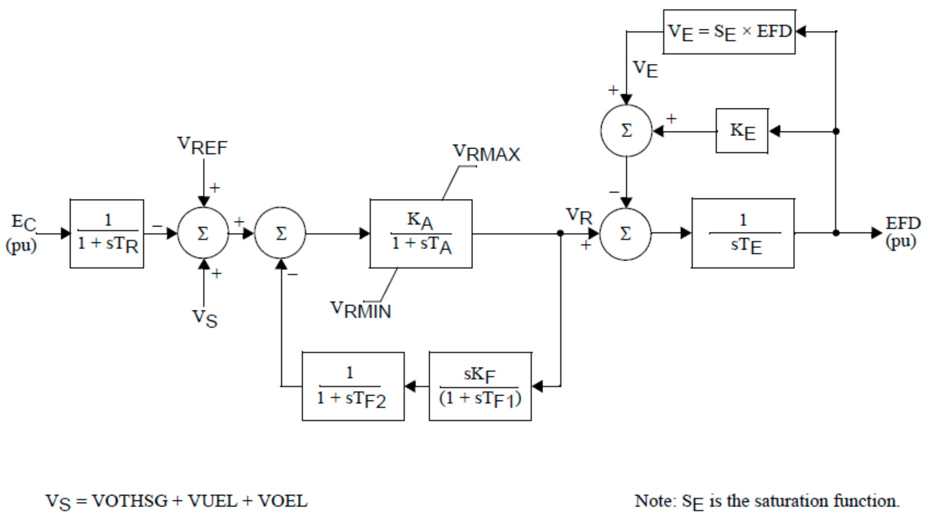

Figure A1. IEEET2 diagram of Phase-I units.

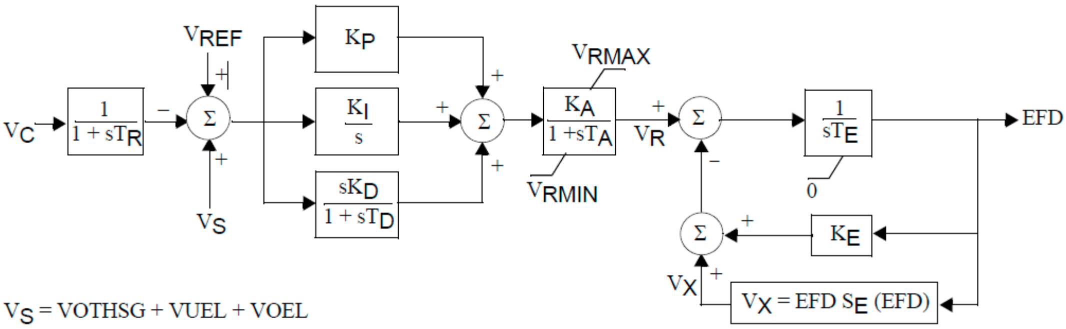

Figure A2. ESAC8B diagram of Phase-II units.

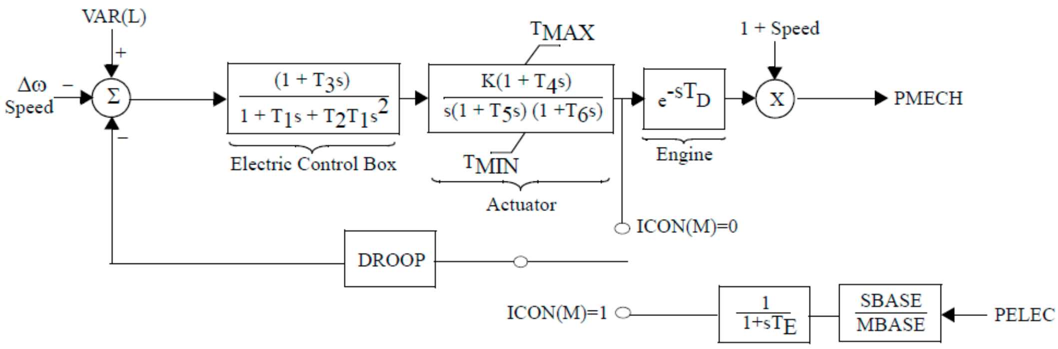

Figure A3. DEGOV1 diagram of the Phase-I and Phase-II units.

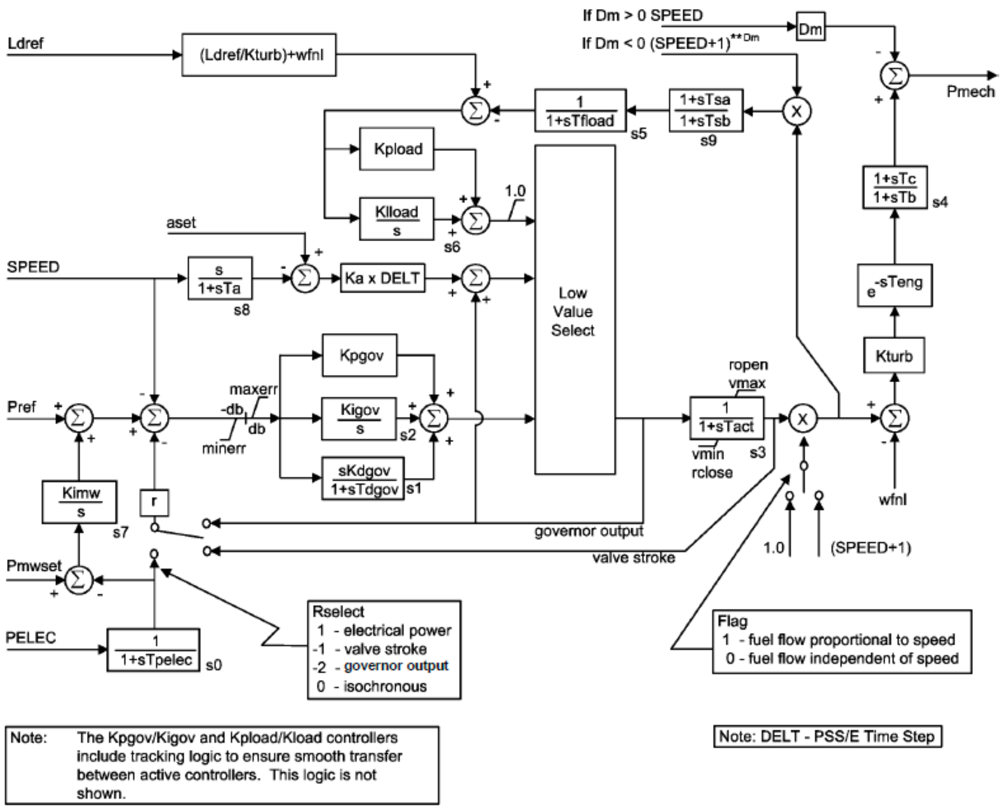

Figure A4. GGOV1 diagram of a wind governor/turbine model.

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