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A Wind-Solar-Energy Storage System Leading to High Renewable Penetration in the Island System of Kinmen

Yuan-Kang Wu[1], Ching-Yin Lee[2], Bo-Shiung Jan[1], Yong-Qing Huang[3]

[1]Department of Electrical Engineering, National Chung-Cheng University
[2]Department of Electrical Engineering, Tungnan University
[3]Green Energy and Environment Research Laboratories, Industrial Technology Research Institute
Email:allenwu@ccu.edu.tw, cylee@mail.tnu.edu.tw, itri960611@itri.org.tw

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Abstract

Kinmen Island lacks fossil-fuel energy, However, it has rich potential for solar and wind energy resources because of its excellent climate and geographical location. Therefore, a large scale utilization of the renewable energy sources is favoured. In June 2004, the Kinmen County government published the Strategic Plan for the Sustainable Development of Kinmen, which focuses on maintaining the ecology of the islands. In the near future, a high penetration of renewable power can be predicted to be installed in this island. However, a large renewable energy penetration into a diesel power system would face technical and economic problems. Therefore, this study intends to discuss the system operation of the Kinmen system and investigates the original unit commitment scheduling. Based on the simulation results, a new unit commitment scheduling will be proposed in this work.

Keywords: Kinmen; Renewable Energy; Unit Commitment Scheduling

1. Introduction

There are many instances where renewable energy sources have been developed including: 100% RES project for El Hierro, Spain; Crete Island in Greece; Gotland in Sweden; Rhode Island and the Hawaiian Islands of the United States; Australian King Island, and the island country of Saint Lucia and so on. Additionally, there are more than 40 islands around the world that have either proceeded with or plan to carry out the construction of independent renewable energy sources. Kinmen Island, Taiwan, has also obtained support and subsidies from the central government and has installed two wind turbine generator systems [1].

Located on the southeast coast of mainland China, Kinmen Island lacks many natural resources. Therefore, this island is deeply affected by the natural ecosystem and tourism. With the economy moving from military rule to tourism, the island has seen a lot of new construction. Tashan power plant in Kinmen burns an average of 42,000,000 l of fuel oil annually. However, its annual power generation capacity was 250,000,000 kWh and this required 50,000,000 l of fuel oil. Meanwhile, the plant produces approx. 150,000-170,000 metric tons of carbon dioxide yearly. The current cost of conventional diesel generation in Kinmen is NT$7.2 per kWh. This is expected to rise to somewhere between NT $11 and NT$14 by 2020. In order to make Kinmen more sustainable, it focused on issues such as how to effectively use Kinmen's natural resources, sunlight and wind power, and how to develop renewable energy sources through a distributed power supply system instead of the concentrated power one now in use. Kinmen hopes it can play a role in preventing global warming, take advantage of new technologies and create sustainable development.

Wind turbine technology has significantly improved over the last 20 years, allowing for the rapid growth of the wind penetration. Large-scale wind power penetration impacts the electricity supply industry in many aspects and leads to fundamental changes in electric power systems. Integration of wind power into power systems presents challenges to power system planners and operators [2-3]. These challenges stem primarily from the stochastic nature of wind; power systems have to incorporate for first time a source of high uncertainty, high volatility, and low predictability. The expected large wind energy penetration impacts the electricity supply industry both technically and economically. Energy storage is a viable solution to suppress the fluctuation of wind power [4-5]. It can act as a buffer that isolates the rest of the grid from these frequent and rapid power changes caused by renewable resources. In this study, a simulation analysis will be carried out by adding energy storage systems to the high wind penetration system in Kinmen.

The interconnection of large amount of renewable generation resources would result in a lower amount of inertia on the electric system and a potential frequency control problem [6-8]. That is, if more synchronous machines are displaced by wind generation, the system inertia will decrease, making the power system more sensitive to generation-load imbalances. Generally, the small size and lack of external support of isolated power systems could result in severe voltage dips due to disturbances and frequency stability issues [9-10]. The weaker is the system the larger and are longer voltage dips. Additionally, in isolated systems with high renewable energy penetration, they have low inertia constant and insufficient primary frequency regulation; therefore, frequency stability issue should be taken care.

In this work, the development strategies of renewable energy sources and future renewable energy planning in Kinmen will be introduced. Additionally, system impacts of large-scale integration of renewable energy in Kinmen and corresponding system simulation analyses are implemented in this study. Finally, a revised unit commitment scheduling in Kinmen system is proposed.

2. The Development Strategies of Renewable Energy Sources in Kiemen

2.1. Current Electricity Power System of Kinmen Island

The power system in Kinmen area is a typical islanding system with the highest voltage rating at 22.8kV. Kinmen Power Company constructed a new power plant at Tashan and also expanded the electricity capacity of Xiaxing power plant already in use. Therefore, today, Kinmen Island has two power plants. It can be divided into Tashan and Xiaxing thermal power plants, Jinsa wind parks, Tashan, Juguang, Qushan, and Xiaxing substations. Tashan thermal power plant has phase 1 and phase 2 diesel generator units, including 4 diesel generator units for phase 1 with an installed capacity of 7.91 MVA for each unit and 4 diesel generator units for phase 2 with an installed capacity of 8.25 MVA for each unit. Therefore, the total installed capacity of thermal power plants is 84.94 MVA. These 8 diesel generator units are grid connected through the 13.2kV/22.8kV step-up transformers. Each generator unit has two control modes: droop and isochronous controls. For the two Type-C wind power generator units in Jinsha wind park, each unit has a rated output of 2MW. After the step-up transformer to convert the voltage to 11.4KV, each set of four units is connected to the bus of Qushan substation. The single line diagram of the whole Kinmen system is shown in Fig.1.

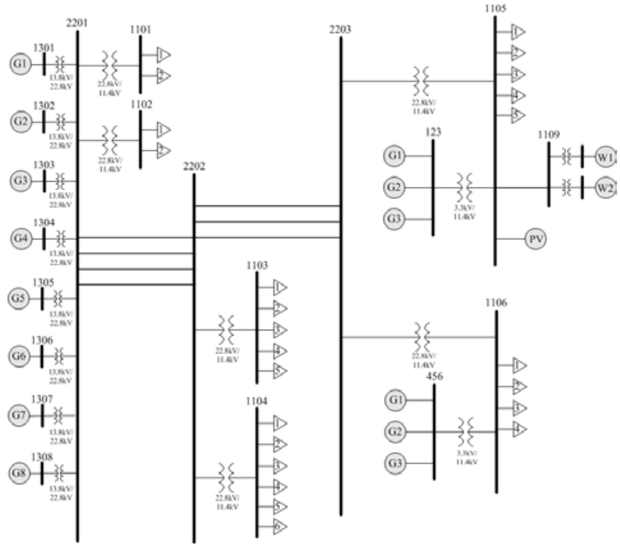

Figure 1 Single line diagram of the Kinmen system

2.2. Survey and Analysis regarding the Potential for Renewable Energy Sources

The climatic statistic data for Kinmen region during 2004 to 2012 is shown in Table 1. In recent years, sunlight duration in Kinmen has averaged 154.77 h per month. This is higher than past records which indicate an average of 138.8 h per month. In fact, the monthly average sunlight duration in July and August is over 200 h and can sometimes reach up to 251.49 h. In Kinmen July and August have the longest sunlight duration and also have the highest temperatures. Thus, it might seem that Kinmen has optimum conditions for the development of solar energy, whether that be solar PV systems or solar thermal water heater systems.

The wind from June to August in Kinmen is from the southwest while in winter months it blows from the northeast. In recent years, the maximum 10 min wind speed has ranged from 8.29 m/s to 12.24 m/s. The maximum instantaneous wind speed has ranged from 16.8 m/s to 31.9 m/s. Most winds blow from the ENE, NE, and N directions. Based on the statistical data from Table 1, Kinmen Island is also suitable for the development of wind power generation systems to replace concentrated power plants.

2.3. Current Protection Scheme in Kinmen Power System

The under-frequency load shedding scheme is currently used in Kinmen to prevent incidents from causing system crashes and blackout; its detail is shown in Table 2. Taiwan Power Company (TPC) uses automatic under-frequency load shedding relays on the feeders at Tashan and Xiaxing substations as the main power defense strategy for Kinmen's power system. The shedding op

Table 1. Climatic statistic data for Kinmen region during 2004-2012.

Month	Max. 10min Wind speed (m/s)	Max 10 min Wind direction	Sunlight duration (hr)
Jan.	8.77	58.89	104.04
Feb.	9.13	67.78	97.93
Mar.	9.57	91.11	105.94
Apr.	10.46	108.89	107.37
May	9.87	134.44	134.31
Jun.	11.10	227.78	150.31
Jul.	10.36	226.67	251.49
Aug.	12.24	250	219
Sep.	11.34	143.75	186.81
Oct.	10.16	123.75	193.55
Nov.	9.23	95	152.98
Dec.	8.29	58.75	153.51
Avg.	10.04	132.23	154.77

Table 2. Load Shedding Protection Scheme in Kinmen.

Stage	Frequency (Hz)	Shedding Load (kW)	Load Shedding feeders
Satge I	57.3	3951	Brewery I, Gugang, Guning, Sayang
Satge II	57	4083	Brewery II, Brewery III, Hightec, DongKung, Gingang
Satge III	56.5	3997	MinSang, Minchu, Jin-shan, Jindong, Taoci
Satge VI	56	5996	Jinmengcheng, chengxi, Minchuang, Wuder, Taiwu, Huanghai, Xian-gyang

eration is divided into four stages: The first stage is set at 57.3Hz; the second stage is set at 57.0Hz; the third stage is set at 56.5 Hz, and the fourth stage is set at 56Hz. The operating time of each relay and circuit breaker is 3 cycles and 45ms respectively.

2.4. Current Unit Commitment Rule in Kinmen Power System

Diesel generators in an isolated-island system plays a significant role. The diesel units can follow the load variations by means of their speed/power control mechanism. The power that the diesel plant must supply at a certain time equals the load demand minus the available generation of renewable sources and energy storage systems. Also, if a diesel unit operates at a small fraction of its nominal power output, its efficiency is considerably reduced. For these reasons, the diesel plant output must never undershoot a certain value. Table 3 shows the current unit commitment scheduling in Kinmen. If the net load (minus wind power) is less than 16MW, then only four units are ON and all other units are OFF; in that situation, power penetration for each diesel generator is 25% and system spinning reserve is large than 12MW. For load in the interval (16MW~17.6MW), the suitable unit scheduling is obtained if 5 diesel units are ON. As the net load is increased, the number of ON units is also increased. However, this unit scheduling in Table 3 is designed under low wind power penetration. Once the wind power penetration is increased, this unit scheduling has to be revised.

Table 3. Current Unit Commitment Scheduling in Kinmen.

Net System Load (MW) (subtract wind power generation)	Xiaxing Power Plant		Tashan Power Plant		Ratio of each diesel generator (%)	Spinning Reserve (MW)	Ratio of Spinning Reserve (%)
	Generation (MW)	No	Generation (MW)	No			
<16	2	0	4	4	25	>12	>75
16 ~ 17.6	2	1	3.9	4	22.2	>13.2	>75
17.6 ~ 20.6	2.6	1	4.5	4	21.8	>10.8	>52.4
20.6 ~ 24.0	2.6	2	4.7	4	19.6	>10.5	>43.8
24.0 ~ 31.9	2.2	2	5.5	5	17.2	>11.4	>35.7
31.9 ~ 43.6	2.6	2	6.4	6	14.7	>8.6	>19.7
43.6 ~ 55.4	2.6	3	6.8	7	12.3	>8.1	>14.6
55.4 ~ 62.2	2.6	3	6.8	8	10.9	>9.3	15

2.5. Future Renewable Energy Planning in Kinmen

The Industry Technology Research Institute (ITRI) has implemented wind and solar energy potential in Kinmen region, which considers available public land and area, climate statistical data (wind speed and solar radiation), and other important factors. In addition to the current 2 wind turbines at Jinsa wind park, other two regions are also suitable for wind turbine installation: one is located at Housa area and the other is at the area between Tianpu and Hukotun (the East of Kinmen Island); in the former area, five 850kW wind turbines would be installed. In the latter area, there is a potential for building 20MW wind generation capacity. In addition to wind energy resource, there is also a large amount of solar generation capacity that can be installed in Kinmen Island. Three locations have been planned to install PV panels, including Kinmen airport (272kW), tourist service center (865kW), and Kinmen university (86kW). If all of the planning renewable energy capacity is installed in Kinmen Island, the installed capacity of wind and solar generation is 28.25MW and 1.223MW respectively. Furthermore, energy storage system with 2.5MW capacity is also planned to install in this system.

3. System Impacts of Large-Scale Integration of Renewable Energy

3.1. System Inertia and Spinning Reserve

Real time system inertia and spinning reserve are the main parameters having influence on operation limits. In particular, the issue of inertia is important for high wind penetration in synchronized systems. System inertia can be defined as the total amount of kinetic energy stored in all spinning turbines and rotors in the system. When an unbalance occurs between generation and demand, the inertia would limit the rate of change of frequency. For a given network condition replacing the diesel generation by wind power generation would lead to a reduction in global inertia and spinning reserve. This translates directly into lower operation limits to cope with the frequency stability criterion. Therefore, system operators should review the system inertia performance to adjust the frequency control scheme on seasonal or annual bases. As wind power penetration increases, the system inertia information becomes more important for system operators.

Sudden loss of supply or demand will result in frequency deviation from the nominal frequency. The rate of change in frequency due to imbalance depends on the system inertia. System inertia is directly proportional to synchronously rotating mass in the system. The general equation for calculating rate of change of frequency using system inertia constant (H) is illustrated in (1) below:

$$\frac{df}{dt} = \frac{\Delta P}{2H} \cdot f_0 + \frac{D}{2H} \cdot \Delta f \quad (1)$$

where H is the system inertia constant on system base; D is the power system load dampening value; f_0 is the frequency at the time of disturbance; ΔP = (PL-PG)/PG; PL indicates the load prior to generation loss; PG indicates system generation after loss; Δf is the change in frequency. Assuming load dampening D to be zero, (1) results in a simplified equation as below:

$$\Delta f = \frac{df}{dt} = \frac{\Delta P}{2H} \cdot f_0 \quad (2)$$

Therefore, the inertia constant H and frequency change Δf presents an inverse proportion; that is, as system disturbance occurs, a larger H value would result in smaller frequency change.

3.2. Limit Criterions of Wind Power Penetration

In addition to system inertia, the number of on-line diesel generator units and the corresponding spinning reserve margin may also affect the lowest system transient frequency. The more diesel generator units running, the larger the corresponding spinning reserve margin is, and the less the drop of the lowest system transient frequency would be. In other words, to prevent low transient frequency from triggering an under-frequency load shedding relay as a principle during an incident, the number of running diesel generator units should be increased appropriately. However, the issue of low power generation efficiency and accelerated depreciation when power output of each single generator unit is too low should also be considered. Therefore, a set of appropriate operating modes for diesel generators to meet the system reliability and economic is important. Generally, the determination of the maximum wind power penetration will be determined by the following limit criterions: minimal and maximum power production criterion of the conventional diesel plants, ramp rate of the diesel plants, dynamic penetration limit for transient frequency and voltage stability, power quality impact, and protection schemes and load management.

In the case of small island systems, the sudden loss of all available wind power is quite probable. This may happen due to generator trips, grid faults, and voltage sags that exceed the fault ride through capability of the wind turbine generators, and even due to fast increases of the wind speed that exceeds the wind turbine cut out speed. Tripping wind turbines or diesel units will impose a substantial frequency excursion in the Kinmen system. Therefore, the transient frequency stability becomes a significant criterion to evaluate the maximum wind power penetration.

3.3. Case Study - the Impact of System Incidents Limit Criterions of Wind Power Penetration

In Kinmen's case, this dispatch and output arrangement was chosen by mainly considering the tolerance of the reserve margin of the system and the minimum acceptable output of the generator units. In the transient simulation, six systematic perturbations were assumed separately, including N-1 diesel generator units at Tashan Power Plant (the maximum output of generator units), trip-off of the Jinsha wind farm, trip-off of the distribution line from Bus 2201 to Bus 2202, trip-off of the distribution line from Bus 2202 to Bus 2203, trip-off of PV generators, trip-off of the transformer at Juguang Substation, and the occurrence of three-phase short-circuit ground faults of important buses, so as to analyze the effects on the system frequency and voltage.

Table 4 shows the Transient Frequency and Voltage in Kinmen Power System under various incidents. In this study, system load is assumed as 20MW and the minimal power production of the conventional diesel plants is assumed to be 50% install capacity. Table 5 concludes the simulation results at the similar operation conditions but the system load is increased to 50MW. We can find from Tables 4 and 5 that the transient stability impact is limited if distribution lines, transformers, or PV generators trip offline. However, once one of the diesel units at Tashan or the Jinsha wind farm trips offline, then transient frequency dip increases, which would activate low-frequency load shedding relay. Therefore, in this study, we focus on the transient analyses based on the trip-off of a diesel unit at Tashan Power Plant or the Jinsha wind farm.

Table 4. Transient Frequency and Voltage in Kinmen Power System under various incidents (System Load=20MW).

Type of System Incidents		Bus 2201		Bus 2203		Bus 1104		Bus 1105	
		Frequency (Hz)	Voltage (V)	Frequency (Hz)	Voltage (V)	Frequency (Hz)	Voltage (V)	Frequency (Hz)	Voltage (V)
Line trip (from 2201 to 2202)	max	60.01	1.003922	60.01	0.99	60.01	1.00	60.01	0.998
	min	59.99	0.997364	59.99	0.99	59.99	0.99	59.99	0.991
Line trip (from 2202 to 2203)	max	60.01	1.00	60.01	0.99	60.01	1.00	60.01	0.99
	min	60	0.99	60	0.98	60	0.99	60	0.98
PV generators trip (bus 1101)(0.865MW)	max	60.16	1.01	60.16	1.01	60.16	1.00	60.16	1.00
	min	59.51	1.00	59.51	0.99	59.51	1.00	59.51	0.99
Transformer trips (Juguang Substation MTR2)	max	62.57	1.02	62.56	1.02	60	1.00	62.56	1.01
	min	59.25	1.00	59.25	1.00	60	0	59.25	0.99
Tashan Unit N-1 trips (4.125MW)	max	61.15	1.01	61.15	1.00	61.15	1.01	61.15	1.00
	min	56.86	0.99	56.86	0.99	56.86	0.99	56.86	0.99
Jinsha wind farm trips (2.09MW)	max	60.41	1.00	60.41	0.99	60.41	1.00	60.41	0.99
	min	58.81	1.00	58.81	0.99	58.81	0.99	58.81	0.99

Table 5. Transient Frequency and Voltage in Kinmen Power System under various incidents (System Load=50MW).

Type of System Incidents		Bus2201		Bus 2203		Bus 1104		Bus 1105	
		Frequency (Hz)	Voltage (V)	Frequency (Hz)	Voltage (V)	Frequency (Hz)	Voltage (V)	Frequency (Hz)	Voltage (V)
Line trip (from 2201 to 2202)	max	60.01	1.00	60.01	0.99	60.01	0.99	60.01	0.99
	min	59.99	1.00	59.99	0.99	59.99	0.99	59.99	0.99
Line trip (from 2202 to 2203)	max	60.006	1.00365	60.01	0.99	60.01	1.00	60.01	0.99
	min	59.99	1.00	59.99	0.99	59.99	0.99	59.99	0.99
PV generators trip (bus 1101)(0.865MW)	max	60.07	1.00	60.07	0.99	60.07	1.00	60.07	0.99
	min	59.76	1.00	59.76	0.99	59.76	0.99	59.76	0.99
Tashan Unit N-1 trips (4.125MW)	max	60.44	1.00	60.44	1.00	60.44	1.00	60.44	1.00
	min	**58.71**	1.00	**58.71**	0.99	**58.71**	0.99	**58.71**	0.99
Jinsha wind farm trips (2.09MW)	max	60.37	1.01	60.37	0.99	60.37	1.00	60.37	1.00
	min	58.90	1.00	58.90	0.99	58.90	0.99	58.90	0.99

4. System Simulation Analyses

In this paper, the modeling and simulation study has been carried with the PSS/E software. PSS/E is composed of a comprehensive set of programs for studies of power system transmission network and generation performance in both steady-state and dynamic conditions. Both steady-state and dynamic simulations have been carried out to assess the power grid behavior of the Kinmen Island system under study. The main goal of this study is to analyze the impact of wind generation on the stability of the grid. Two main aspects have been covered: the impact of wind generation on frequency stability and on transient stability.

4.1. Load Flow Studies

It is important to undertake load flow studies in the design phase to ensure the voltage distribution over the network will remain within statutory limits. In addition, cables and transformers must be also dimensioned adequately to handle the thermal loadings. In this study, load flow studies were performed for several scenarios in order to simulate the range of anticipated load demands and generation mixes on the island. According to load flow analysis results, the load ratio of each line is in the range of 16-77% after wind power is integrated into the system.

4.2. System Transient Analyses

In this study, the off-peak system in Kinmen is considered, including 18.2MW load, 4MW wind power output, and 0.528 PV output. This adopted system condition is under the maximum renewable generation penetration (24.8%) in Kinmen region currently. Based on the current unit scheduling at the Tashan Power Plant, four diesel units have to be operated at least.

Due to the low PV penetration (2.89%), this study ignores the effect of PV and discusses the system impact from three-phase short circuit fault, trip-off of a diesel unit, and trip-off of the Jinsha wind farm respectively. Further, the original unit commitment scheduling will be revised based on the simulation results.

Case 1: Three-phase short-circuit grounding fault at Bus 2201 for 6 cycles

In this case, the most severe symmetrical three-line-to-ground fault is considered as a network disturbance; it is assumed that wind speed is constant and equivalent to the rated speed for the wind turbines. Figure 2 shows the dynamic response of one wind generator at Jinsha when a three-phase short circuit fault occurs at 22.8kV Tashan Bus 2201. The fault occurs at 1 sec and is cleared after 1.1sec. During the transient process, each wind turbine will decrease its active power but support additional reactive power to try to maintain its voltage output. The reactive power of 0.974 MVAr is produced during the fault for each wind turbine. After the fault is cleared, the wind turbine returns to support stable active power to the grid. Figure 3 shows the system transient voltage curves at bus 2201 during the event; it is noted that the voltage drop is obvious and the recovery voltage returns to the normal system voltage after the fault. In this case, the system minimum frequency is 59.86Hz therefore the low frequency relay would not be activated.

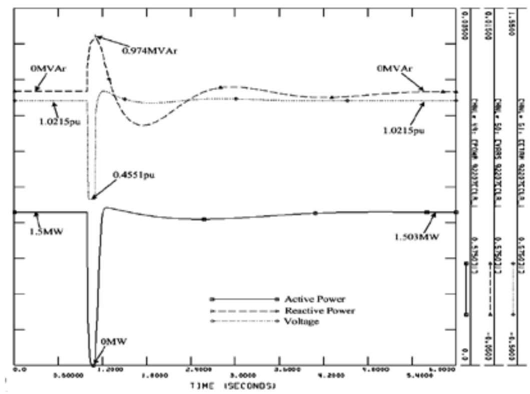

Figure 2 Power output of a wind turbine at Jinsha (Case1)

Case 2: One of the diesel generators trips off for 6 cycles

It is assumed that one of the diesel generators at Tashan Power Plant trips instantaneously to be offline, and the voltage and frequency curves at bus 2201 are shown in Figure 4. It is observed that the transient frequency is decreased to 57.41Hz and there is an oscillation phenomenon on recovery voltage and frequency curves.

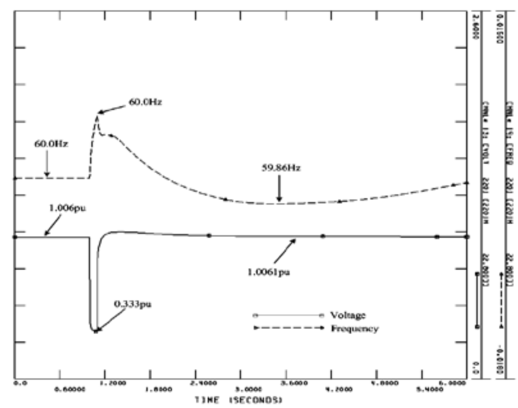

Figure 3 Transient voltage and frequency curves at Bus 2201 in the Kinmen system under case1

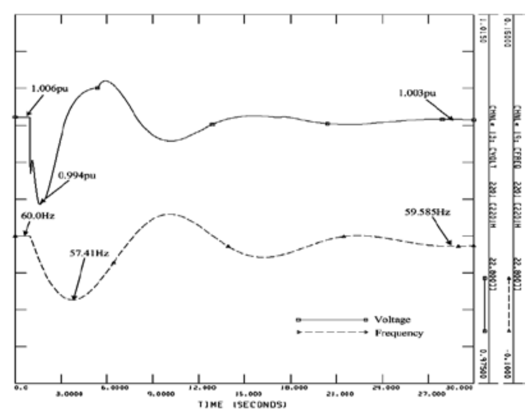

Figure 4 Transient voltage and frequency curves at

Bus 2201 in the Kinmen system under case 2

Figure 5 shows the transient active power, reactive power, and output voltage from a wind turbine at Jinsha wind farm. It can be observed that the transient voltage dip is small. Therefore, the impact of this fault case on the transient voltage is limited.

Case 3: Jinsha Wind Farm trips offline

It is assumed that all wind turbines in the Jinsha wind farm trip instantaneously to be offline, and the transient voltage and frequency curves at bus 2201 are shown in Figure 6. It is observed that the transient frequency is decreased to 57.78 Hz and there is an oscillation phenomenon on recovery voltage and frequency curves. However, the frequency dip is less than that in Case 2.

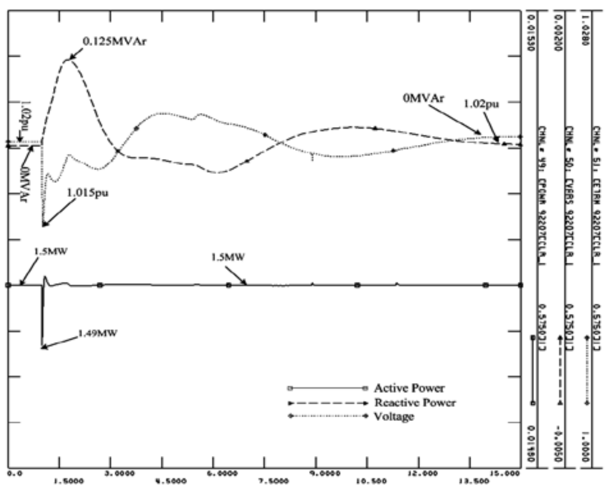

Figure 5 Power output of a wind turbine at Jinsha (Case 2)

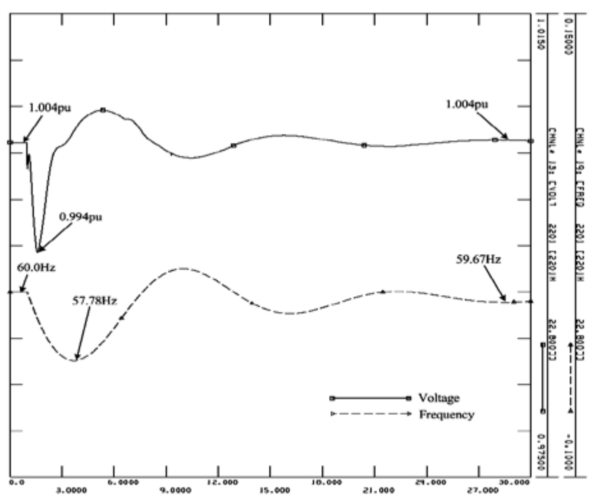

Figure 6 Transient voltage and frequency curves at Bus 2201 in the Kinmen system under case 3

5. Revised Unit Commitment Scheduling in Kinmen System

In this study, the current install capacity of renewable energy generation in Kinmen region is considered; that is, the total renewable generation is 4.528MW. Then system transient analyses under the load between 18MW and 50MW are implemented. The analyzed system incidents include the trip-off of Jinsha wind farm and the trip-off of one diesel unit. Based on the simulation results, a revised unit commitment scheduling is suggested.

In order to make sure the operation safe, the spinning reserve has to maintain the maximum capacity of a diesel generator. Additionally, it should be noticed that the diesel generators should be avoided to operate under low or medium load. Finally, the system operation should be maintained not to activate the low frequency load shedding relay. Table 6 shows the suggested new unit commitment scheduling based on our simulation results.

6. Conclusions

The power system on the Kinmen Island is presented. The renewable generation is sited at various locations around the Kinmen network, and includes wind turbines and inverter-connected PV systems. Several simulations were performed in this research to study the impact of the wind farm and PV generator integration on the dynamic behavior of the Kinmen's power system. The considered grid disturbances are the trip-off of a diesel generator and the wind farm. Simulations have shown that deviations of the power system frequency and voltage would be unacceptable under several system incidents. However, it is still possible to operate the power system of Kinmen with a high level of renewable penetration maintaining a high level of security if adequate spinning reserve and unit commitment scheduling are available. Therefore, this study has proposed a new unit commitment scheduling to cope with the high renewable energy penetration.

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Table 6. New Proposed Unit Commitment Scheduling in Kinmen.

Net System Load (MW) (subtract wind power generation)	Xiaxing Power Plant		Tashan Power Plant		Ratio of each diesel generator (%)	Spinning Reserve (MW)	Ratio of Spinning Reserve (%)
	Generation (MW)	No	Generation (MW)	No			
<=13	2	0	4	4	25.0	>12	>75.0
13~14	2	1	3.9	4	22.2	>13.2	>75.0
14~22	2.6	1	4.5	4	21.8	>10.8	>52.4
22~26	2.6	2	4.7	4	19.6	>10.5	>43.8
26~36	2.2	2	5.5	5	17.2	>11.4	>35.7
36~47	2.6	2	6.4	6	14.7	>8.6	>19.7
47~55	2.6	3	6.8	6	12.3	>8.1	>14.6
55 ~	2.6	3	6.8	7	10.9	9.3	15.0

