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Autonomous Micro-grid Design for Supplying Electricity in Carbon-Free Island

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Abstract – In island and backcountry areas, electrical power is usually supplied by diesel generators. It is difficult for small scale diesel generators to have an economy of scale owing to the usage of fossil fuels to produce electricity. Also, there is a problem of carbon dioxide emissions that brings some environmental pollution to the entire region of the area. For solving those, this paper proposes a design method of autonomous micro-grid to minimize the fossil fuels of diesel generator, which is composed of diesel generator, wind turbine, battery energy storage system and photovoltaic generation system. The proposed method was verified through computer simulation and micro-grid operation system.

Keywords: Micro-grid, Hybrid generation, Autonomous operation, Photovoltaic generator, Wind turbine, Diesel generator, Carbon-Free Island

1. Introduction

Micro-grid or Hybrid generation system has been considered as a countermeasure for electricity power supply in island and backcountry areas. In this regard, the paper proposed to date are references [1-5], as in ESS (Energy Storage System), photovoltaic generator, DFIG (Doubly-Fed Induction Generator), and PMSG(Permanent-Magnet Synchronous Generator) adopted in various forms. However, the most of hybrid system is actually installed and operated as a wind-diesel-hybrid power generation system.

To date, in the case of Australia, USA and Europe 200 to 600kW-class hybrid power systems are installed and are operating. [6-8] In domestic island, so does the same class wind-diesel hybrid power systems. But most of the diesel hybrid power generation system independent of power quality and economic have a challenge problem.

On the other hand, such a hybrid power generation system is configured in DC link type and AC link type. The DC link type is relatively simple and the cost is low, but the efficiency is low and the DC voltage level affects the entire system. The AC link type has many control elements and relatively difficulties to control systems owing to the difference of voltage phase and magnitude between them. But the efficiency is higher and the development of control techniques is carried out.

In most current hybrid generation systems, diesel generators control the hybrid system voltage and frequency to keep constant and ESS supports the role of the frequency adjustment. But in this case the diesel generator with CVCF function has greater capacity and fuel consumption. [9-11]

This paper presents a method of solving this by BESS with some coordination rules which the frequency and voltage maintains to be constant and photovoltaic and wind generators work to maximize its output. As a result, the fuel consumption of a diesel generator can be minimized through its emergency operation in spite of changes in the weather and wind speed.

At first, we consider a AC bus type of micro-grid which consists of BESS, diesel generators, photovoltaic and wind generators. And then, a coordination rule of the hybrid generation system is proposed under considering the charging state of BESS. The operation rule is applied to the micro-grid design in Jeju Gapa island through modeling and simulation by PSCAD / EMTDC software package. The result is compared with the operation data of the micro-grid.

2. Structure and Coordination Rule of Micro-grid

2.1 Structure of micro-grid

The structure of the micro-grid with BESS, two diesel generators, photovoltaic generator, and Squirrel-Cage Induction Generator (SCIG) with wind turbine is shown in Fig. 1.

2.2 Coordination rule of micro-grid

In hybrid power generation system such as micro-grid, a

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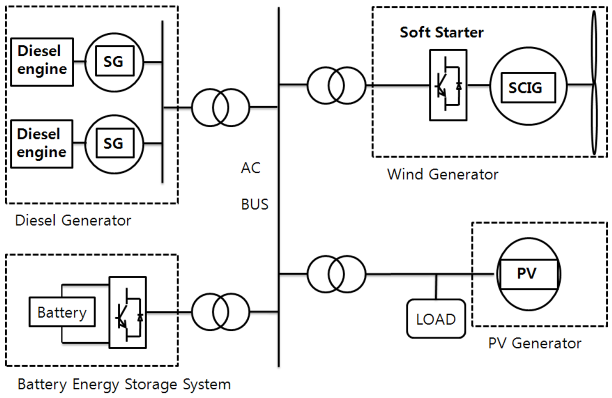


Fig. 1. Structure of Wind-Diesel-BESS-PV Micro-grid

coordination rule for reliable power supply and minimum operation cost is essential. That is, photovoltaic and wind power generators according to weather changes produce maximum power; BESS performs the CVCF function under proper state of charge(SOC); diesel generator works based on the SOC such as repair or abnormal charging state of BESS.

The decision of the operation range of BESS is very important. Because the instantaneous charging and discharging kW output is different according to the SOC of battery. This gives an impact on the proper operation and the life cycle of BESS in micro-grid. Depending on battery manufacturers and specifications, the SOC value enough to produce the rated kW charging or discharging output of BESS is suggested from 20-30% as minimum to 70-80% as maximum.

This paper proposes a coordination rule for hybrid power generation system considering the SOC of BESS as shown in Fig. 2.

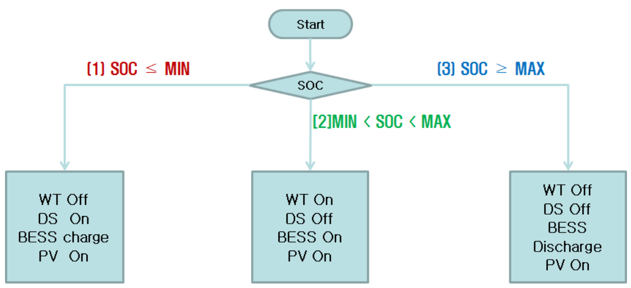
The operation method is divided into three categories according to the SOC of BESS as follows.

In normal state defined as SOC is between MIN and MAX, BESS operates in CVCF mode; WT and PV in MPPT(Maximum Power Tracking Point) mode. Then, changes in the load and the output of WT and PV are compensated. by the CVCF operation of BESS.

In state of SOC under MIN, DS operates in synchronous connection to the hybrid power system in droop operation mode and supplies electric power to loads and charges BESS. Then, BESS still operates in CVCF mode; fixed speed WT is off for stable charging of BESS; variable speed WT is on; Small size of PV can be on.

In state of SOC over MAX, DS stops. BESS still operates in CVCF mode; fixed speed WT is off; variable speed WT is off; Small size of PV can be on.

The normal state of micro-grid as (2) shown in Fig. 2 can be transferred to the state of SOC under MIN as (1) shown in Fig. 2 or the state of SOC over MAX as (3) shown in Fig. 2 according to changes of loads, WT and PV output. The transition decision from state (1) to state (2) depends on the generation state of WT and PV or the weather.



MIN, MAX: Minimum, Maximum Value of SOC
WT: Wind Turbine Generator
PV: Photovoltaic Generator DS: Diesel Generator

Fig. 2. Coordination rule for hybrid power generation system considering the SOC of BESS

3. Design and Modeling of Micro-grid

As design and modeling target, the micro-grid of Jeju Gapa island is considered. The Gapa island is in 5.5km away from the land and has been supplied power by diesel generators since 1995. Jeju special self-governing province plans to build a carbon free island in entire Jeju region by 2030. Accordingly, Gapa island was selected as target area of micro-grid pilot project and power supply technique using only renewable energy such as PV, WT, and ESS without diesel generation. Design and modeling method is described in the following.

3.1 General status and power facility

Gapa island is a small island of 0.85㎢ and 281 people, 193 customers live there. Tourism, agriculture, fisheries processing is the main industry. Power supply facility consists of diesel generators and distribution facility as shown in Table 1.

Table 1. Electrical facility and load status in gapa island

Diesel generator	Feeder	Peak load	Power consumption
150kW×3	6.6kV×2D/L	224kW	1,045MWh('10)

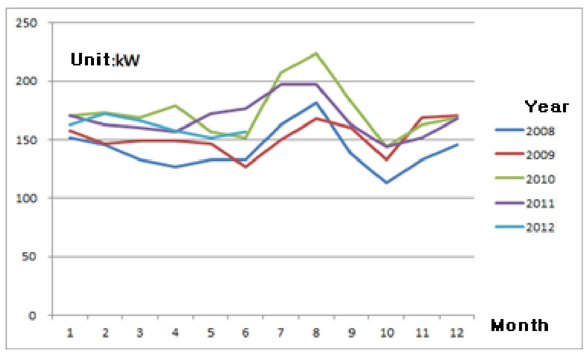


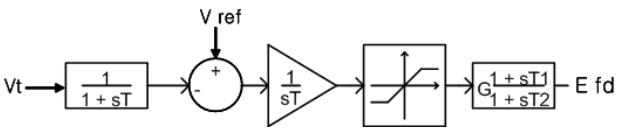
Fig. 3. Peak power consumption per month

3.2 Peak load power consumption

As a characteristic of the islands, peak power appears at 13:00 in the daytime and at 21:00 at night, and monthly peak power of distribution facility appears in August every year.

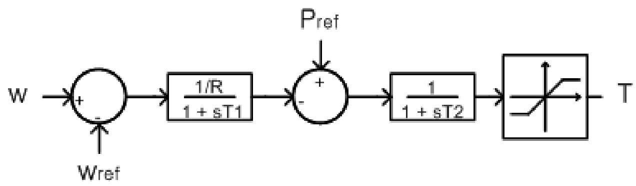
3.3 Diesel generator

The specification of existing diesel generator is three phase 380V 150 kW. The parameters of DG are modeled by values provided by PSCAD/EMTDC software package. But the exciter and governor are used with generalized controller. [12]



Vt: terminal voltage Vref: reference terminal voltage
Efd: field voltage T2: time constant (0.2)
G: gain (10)

Fig. 4. DG exciter model



T: turbine output Pref: reference output
w: turbine speed wref: reference turbine speed
R: droop coefficient (0.1) T2: time constant (0.6)

Fig. 5. DG governor model

3.4 Wind generator

Gapa island's 250kW WT generation system is fixed speed type and squirrel-cage induction generator with soft starter. The specification is as Table 2.

The WT is modeled as follows: [12]

$$P_{blade} = \frac{1}{2}A_p V^3 Cp = \frac{1}{2}A_p V^2 Cp\, \omega \frac{V}{\omega}$$
$$= \frac{1}{2}A_p V^2 Cp\, \omega\gamma = T\omega$$

A: blade area[m^2] ρ : air density [kg/ m^3]
ω : blade speed[rad/sec] V : wind speed [m/sec]
T: torque [Nm] $Cp : 0.5(\gamma - 0.022\beta^2 - 5.6)e^{-0.17\gamma}$

Table 2. Specification of wind generator

Output (kW)	Height (m)	Startup wind speed (m/s)	Stop wind speed (m/s)
250	30	4	25

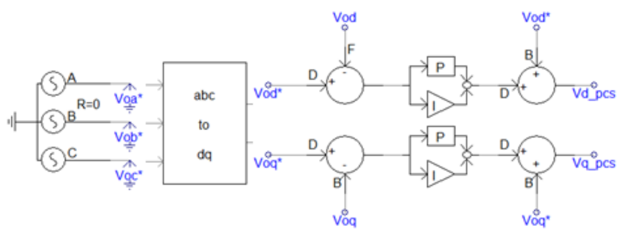
3.5 BESS

BESS is composed of lead acid battery and power conditioning system(PCS) of CVCF operating and charging the PV and WT. Capacity of lead acid battery is 850kWh and 8-hour power supply to Gapa Island is possible without other power supply after full charge and its life time is 17 years. Its internal resistance is 0.086Ω .

Table 3. Data of lead acid battery

Nominal voltage (v)	Unit capacity (Ah)	Desired life time (25℃)	SOC
8	1,500	3,150Cycle	30～90%

As a device to convert AC to DC and vice versa, back-to-back PCS is considered for CVCF operation. It uses IGBT device and PWM switching is applied. The specification is three phase 220V 350kVA. The CVCF controller is used as simplified model in Fig. 6.

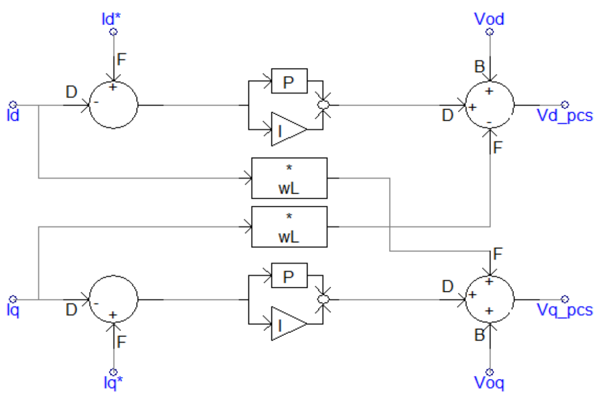


Vd, Vq: d-q transformed value of the PCC voltage
Voa*, Vob*, Voc*: rated reference CVCF voltage
Vod*, Voq*: d-q transformed value of Voa*, Vob*, Voc*
Vod_pcs, Voq_pcs: d-q voltage command of PCS

Fig. 6. CVCF controller of PCS

3.6 Photovoltaic generator

3kW photovoltaic generation modules were installed for 21 households at their roofs. The PV generator is modeled as simplified current controller shown in Fig. 7.



Id*, Iq*: PV reference output d-q current
Id, Iq: PV output d-q current
Vd_pcs, Vq_pcs: d-q voltage command of PV
ω : frequency[rad/sec] L: output filter

Fig. 7. Controller of PV generator

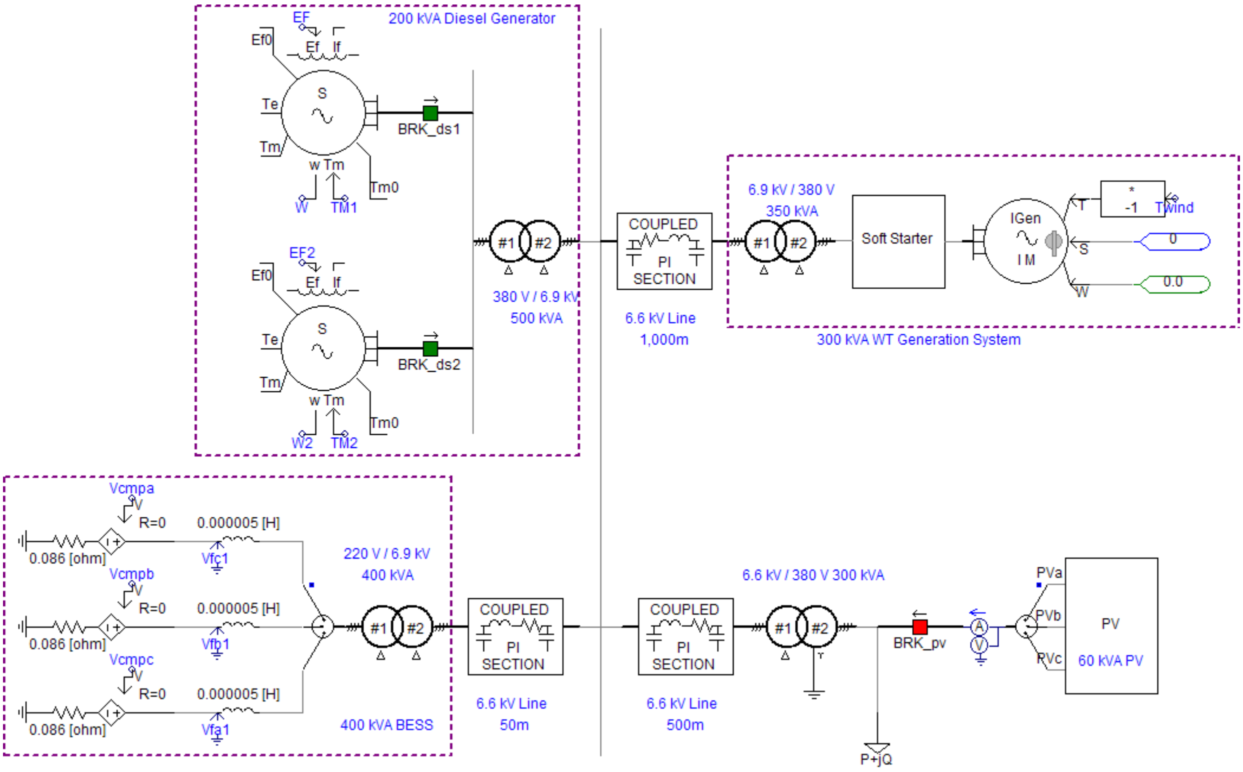


Fig. 8. Overall micro-grid modeled by PSCAD/EMTDC for gapa island

Table 4. Simulation scenario for micro-grid model

Time (sec) / state	10	20	30	40	50	60	70	80	90	100	110	120
Actions		DS On			WT On	Wind speed 14m/s		Wind speed 8m/s		WT Off		
Load Change	210kW+130.15kVar			140kW+86.76kVar			60kW+37.19kVar				140kW+86.76kVar	

: the state (1) of SOC < MIN　: the state (2) of MIN < SOC < MAX　: the state (3) of SOC > MAX

4. Simulation Results and Discussions

For verifying the proposed coordination operation rule, the target Gapa micro-grid was composed of two 200 kVA diesel generators, 300 kVA WT, 60 kW PV, 400 kVA BESS, PQ loads(210 kW + j130 kVar) with power factor 0.85. The overall micro-grid model by PSCAD/EMTDC is depicted in Fig. 8.

4.1 Simulation procedure considering the proposed cooperation operation rule

The simulation scenario was considered so sufficiently that the proposed cooperation operation rule can be applied to all operation states. At 0 second, BESS with CVCF mode operates in the normal state (2) of MIN<SOC<MAX in Fig. 2. Then no wind continues. At 10 second, the situation changes from the state (2) to the state (1) of SOC<MIN. DS connects synchronously to the hybrid power system and operates with maximum output in droop mode and supplies electric power to loads and charges BESS. At 30 second, loads changes from 210 kW to 140 kW and the situation transfers from the state (1) to (2) owing to sufficient charging of BESS. Hence DS stops at 40 second. At 50 second, wind speed changes from 0 to 14 m/s. At 60 second, loads changes from 140 kW to 60 kW. At 70 second, wind speed changes from 14 to 8 m/s. At this time the situation goes from the state (2) to the state (3) of SOC>MAX. At 90 second, WT stops. At 100 second, loads changes from 60 kW to 140 kW.

The scenario during 0 second to 120 second is as follows:

0 sec : BESS CVCF operation under the state (2)
10 sec : DS's maximum operation, BESS charging under the state (1)
30 sec : Load change from 210 kW to 140 kW under the state (1)

40 sec : DS off under the state (2)
50 sec : Wind speed change from 0 to 14 [m/s] under the state (2)
60 sec : Load change from 140 kW to 60 kW under the state (2)
70 sec : Wind speed change from 14 to 8 [m/s] under the state (2)
90 sec : WT stops under the state (3)
100 sec: Load change from 60 kW to 140 kW under the state (3)

4.2 Simulation results and discussions

4.2.1 Results

The simulation results for the scenario from 0 to 120 second is shown as follows:

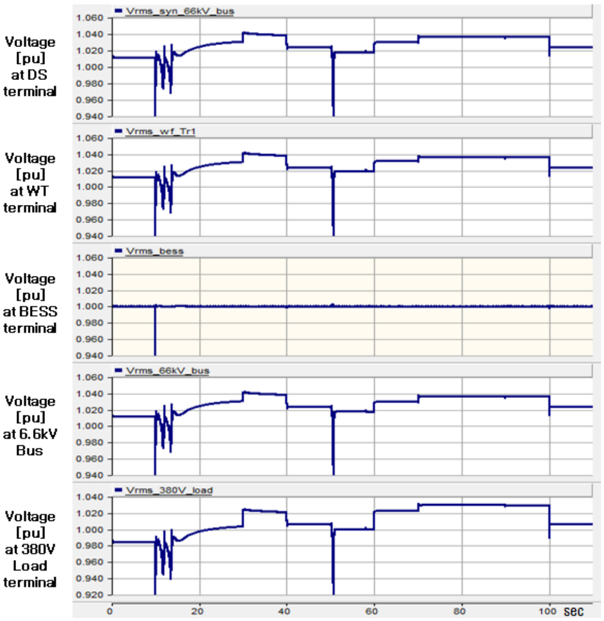


Fig. 9. Voltage variations at each terminal

Fig. 9 describes the voltage variations at each terminal. The steady state voltage maintains within ±3%, but not around 10 sec. and 50 sec. The abrupt voltage change at 10 sec. occurred owing to DS paralleling without synchronizing. The severe voltage drop at 50 sec. occurred owing to WT start operating through soft starter.

Fig. 10 depicts the real and reactive power output variations at each terminal. The abrupt power change at 10 sec. occurred owing to DS paralleling without synchronizing. Also, the severe change at 50 sec. for the WT and BESS terminal occurred owing to WT start operating. Especially, the reactive power change is remarkable.

Fig. 11 shows the frequency variations at each terminal.

The abrupt frequency change at 50 sec. occurred owing to WT start operating. But the frequency maintains within ±1%.

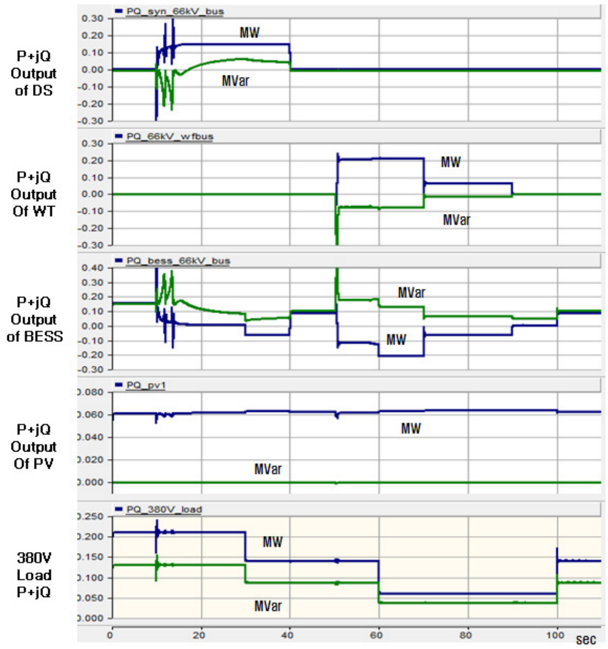


Fig. 10. Real and reactive power variations at each terminal

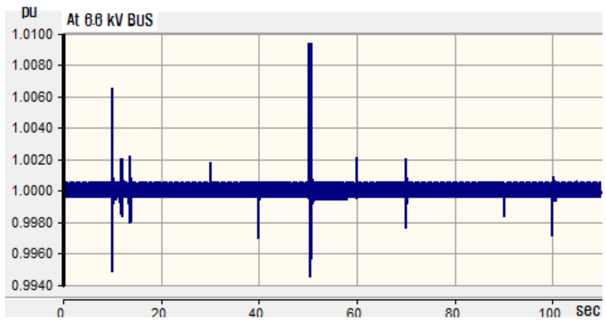


Fig. 11. Frequency variations at 6.6 kV BUS

4.2.2 Discussions and countermeasure

When considering the simulation results for the proposed coordination rule applied to all possible situations, voltage and frequency variations maintains very well within the domestic permissible voltage range ±6% and frequency range±1%. But the severe voltage change owing to start operating of WT such as the fixed speed type should be noted. On the other hand, it is necessary to monitor and manage the SOC of BESS. Because that is critical to operate the micro-grid with high reliability, carbon-free and fossil fuel minimization.

Therefore, control center is installed to integrated management of micro-grid component and it is composed to collect data and manage by connecting all systems.

As area of control center is 66m^2, generation source, distribution system, operation status of smart meter, Also, monitoring power quality and fault status of facility remotely, quick correspondence are possible for every fault.

For operator's convenience, it is made that generation and load information can be confirmed at the same time.

For generation information, each generation power's status is displayed, and the SOC of BESS is presented as numerical value. In addition, communication status of each device as well load sharing by distribution line and power quality is presented by color, so it is easy to recognize.

We monitor production/supply power of WT, PV, DS in a week, and confirm output change of frequency, voltage and total generation power statics.

Monitoring two 250kW wind generators' power production status, active/reactive power and voltage/current is possible.

Fig. 12. Main screen of integrated operation system

Fig. 13. ESS management system

Fig. 14. Power quality monitoring system

Fig. 15. Power quality management of wind generator

Remote startup/stop is also possible and at that time, we can confirm power quality, connection of communication network.

Micro-grid provides daily results of monitoring of ESS's charging status, voltage and power of distribution lines and current of diesel generator to operator in order to monitor generating and distributing facility at once, and respond unexpected status.

Besides, we will connect EV charging system and water conversion facility to improve operation efficiency.

5. Conclusion

This paper proposes a design method of micro-grid with some coordination rules which the frequency and voltage maintains to be constant and photovoltaic and wind generators work to maximize its output. The proposed operation rule is applied to target model, namely Gapa island micro-grid. Through simulation results for scenario considering the coordination rule applied to all possible situation, voltage and frequency variations maintains very well within the domestic permissible voltage range ±6% and frequency range ±1%. But the severe voltage change owing to start operating of WT such as the fixed speed type should be noted. On the other hand, it is necessary to monitor and manage the SOC of BESS. Because that is critical to operate the micro-grid with high reliability, carbon-free and fossil fuel minimization.

As a result, the fuel consumption of a diesel generator could be minimized through its emergency operation in spite of changes in the weather and wind speed.

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