

A Stable Operation Strategy in Micro-grid Systems without Diesel Generators

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Abstract – Recently, as one of the countermeasures to reduce carbon dioxide(CO_2) for global warming problems, operation methods in micro-grid systems replacing diesel generator with renewable energy sources including wind power(WP) and photovoltaic(PV) system have been studied and presented in energetic manners. However, it is reported that some operation problems in micro-grid systems without diesel generator for carbon-free island are being occurred when large scaled WP systems are at start-up. To overcome these problems, this paper proposes an operation strategy in micro-grid systems by adapting control devices such as CVCF(constant voltage constant frequency) ESS(energy storage system) for constant frequency and voltage regulation, load control ESS for balancing demand and supply and SVC(static-var compensator) for reactive power compensation. From the simulation results based on the various operation scenarios, it is confirmed that the proposed operation strategy in micro-grid systems without diesel generators is a useful tool to perform a stable operation in micro-grid systems without diesel generator and also make a contribution to reduce carbon dioxide in micro-grid systems.

Keywords: Micro-grid systems, Diesel generators, Operation strategy, CVCF ESS, Load control ESS, SVC, PV systems, WP system, CO_2 reduction, PSCAD/EMTDC

1. Introduction

Global warming, environmental issues and critical situations of energy supply with oil prices have been emerged as worldwide problems. As one of countermeasure to overcome these problems, renewable energy sources such as PV system and WP systems, have been gradually interconnected with power distribution systems, and also micro-grid systems without diesel generators for carbon free island has been demonstrated as a power utility projects [1, 2]. Furthermore, optimal operation methods in micro-grid system have been presented to replace the diesel generators with renewable energy sources in order to reduce CO_2 emissions for the environmental and economic aspects [3, 4]. However, it is frequently reported that some operation and interconnection problems in island micro-grid systems without diesel generator are being occurred when some types of WP system with a large momentum power are at start-up, because ESS with CVCF function cannot supply the required active and reactive powers in a proper manner.

Therefore, this paper proposes a novel configuration in micro-grid systems without diesel generators and an operation algorithm in micro-grid system to perform a

stable operation and reduce CO_2 emission as much as possible, by introducing some control devices to existing micro-grid systems, which are CVCF ESS, load control ESS and SVC. Here, the CVCF ESS is designed for constant voltage and frequency control as a voltage source and the load control ESS is designed for power balancing between supply and load with the charging and discharging functions and SVC is also used for compensation of reactive power during start-up of WP system. From the simulation results based on the PSCAD/EMPDC modeling and operation algorithm, it is confirmed that they are practical tool for the reliability improvement and CO_2 emission reduction in micro-grid systems.

2. Operation Characteristics in Micro-grid System without Diesel Generators

For the purpose of CO_2 reduction and stable independent operation, the existing micro-grid system in Gapa-island is now being operated as shown in Fig. 1, which is consisted of three 150[kW] diesel generators, two 250[kW] WP systems, 1[MWh] ESS, 110[kW] PV system and customer loads including house, desalination facility, school and public building [5].

However, it is frequently reported that WP system in start-up stage causes problems in carbon-free operation because the diesel generator is not operated as a base power source and ESS with voltage source function cannot

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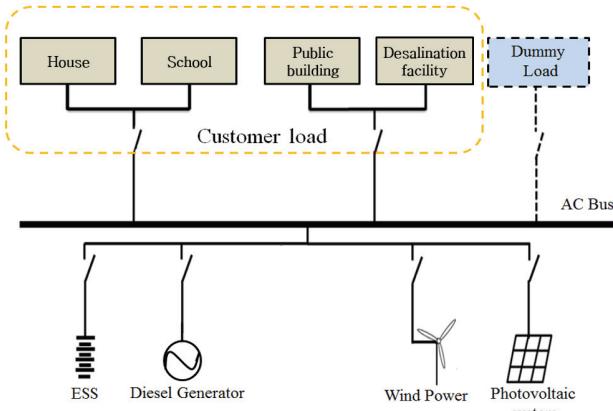


Fig. 1. Concept of micro-grid system in Gapa-island

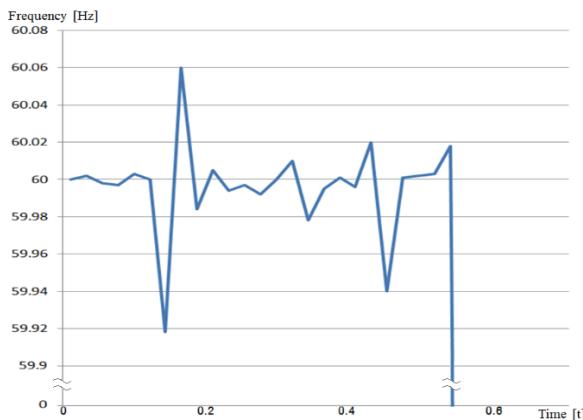


Fig. 2. Operation case in micro-grid system without diesel generators

Table 1. Operation characteristics at start-up of WP system

	Power	Frequency	Power factor
Apparent	495.9 [kVA]	60.11 [Hz]	0.834 (lagging)
Active	415.9 [kW]		
Reactive	270 [kVar]		

properly supply required reactive power in the torque control mode during the start-up of WP system, as shown in Fig. 2.

In order to analyze these problems in detailed manner, the measurement data at start-up stage in WP system has been collected in real micro-grid system. As shown in Table 1, 495.9[kVA] of apparent power, 415.9[kW] of active power and 270[kVar] of reactive power were measured at the start-up stage in WP system, respectively. This result shows that ESS with voltage source function in the micro-grid system without the diesel generator cannot properly compensate the required reactive power during the start-up in WP system. Therefore, it is clear that the micro-grid system with only renewable energy sources requires a proper control strategy for active and reactive power in order to perform a stable operation in micro-grid system.

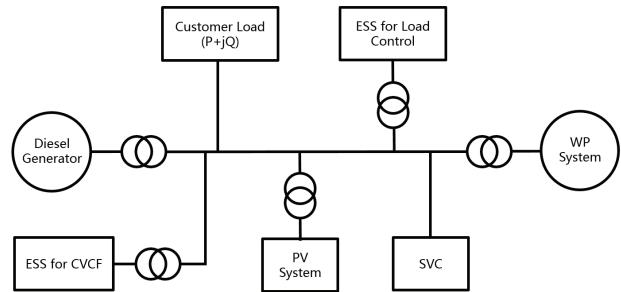


Fig. 3. Concept of novel micro-grid system without diesel generator

3. Operation Strategy in Micro-grid System without Diesel Generators

3.1 Novel configuration of micro-grid system

In order to overcome the operation problems as mentioned in Chapter 2, this paper adapts essential control devices such as CVCF ESS, load control ESS and SVC to existing micro-grid systems as shown in Fig. 3. Specifically, the CVCF ESS is designed for constant voltage and frequency control as a voltage source and the load control ESS is used for power balancing between supply and load with charging and discharging function and SVC is designed for reactive power compensation during the start-up in WP system.

3.2 Operation algorithm in novel micro-grid system

This paper presents an operation algorithm in novel micro-grid system with control devices including CVCF ESS, load control ESS and SVC in order to reduce CO₂ emission by replacing existing diesel generator with renewable energy sources for carbon-free island. The detailed process of the algorithm is categorized by 4 steps as follows.

- [Step 1] As an initial condition, CVCF ESS is operated for the constant voltage and constant frequency in the micro-grid systems without diesel generator as a base power source.
- [Step 2] Based on the daily load pattern, gaps between customer loads and outputs of renewable energy sources at each time interval are estimated.
- [Step 3] The load control ESS performs a charging operation when output of renewable energy source is bigger than customer load at each time interval, and also performs a discharging operation when output of renewable energy source is smaller than customer load at each time interval. If the output of renewable energy source is equal to customer load at each time interval, the operation of load control ESS is not required.
- [Step 4] During the start-up in WP system, SVC is

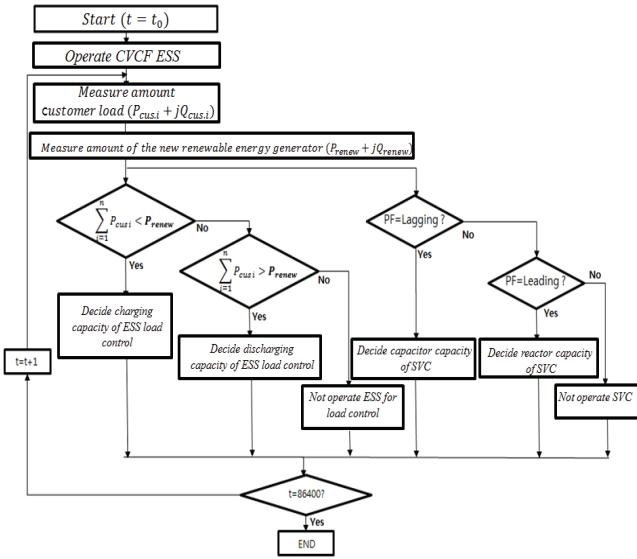


Fig. 4. Operation strategy for carbon-free island micro-grid system

scheduled to compensate a required reactive power depending on the power factor conditions. Where, the capacity of SVC should be properly designed for desired power factor of 1.0 and SVC is operated as a reactor at leading power factor and as a capacitor at lagging power factor.

Based on the above procedure, the operation algorithm of micro-grid systems without diesel generators for carbon free island can be illustrated as shown in Fig. 4.

4. Component Modeling of Micro-grid System based on the PSCAD/EMTDC

4.1 DFIG WP system

In order to figure out the operation characteristics of the WP system interconnected with island micro-grid system, this paper proposes the modeling of DFIG which is double fed-induction generator, based on the PSCAD/EMTDC. Fig. 5 shows the modeling of the DFIG which is composed of electrical section to control active and reactive powers and mechanical section to control wind power energy. Where, the electrical section in the WP system is consisted of a machine side converter(MSC) to estimate a flux of stator according to the current and voltage of stator and a grid side converter(GSC) to control active and reactive powers and phase-locked-loop(PLL) [6-8].

Furthermore, wind power energy provided by wind velocity of blade in mechanical section of WP system can be expressed by the kinetic energy of wind as shown in Eq. (1) and output coefficient of blade can be illustrated in Eq. (2). Also, λ of tip speed ratio is determined by angular velocity of blade, wind velocity and diameter of the turbine,

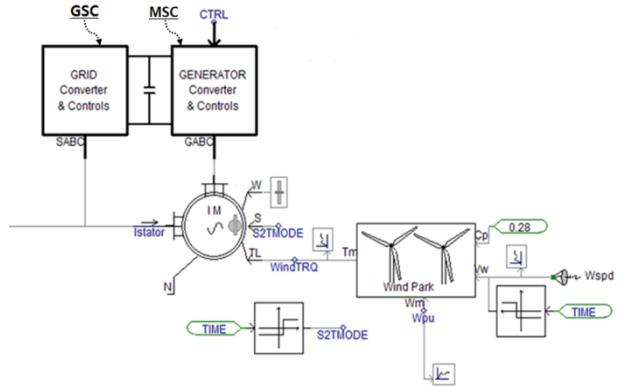


Fig. 5. DFIG WP system modelling

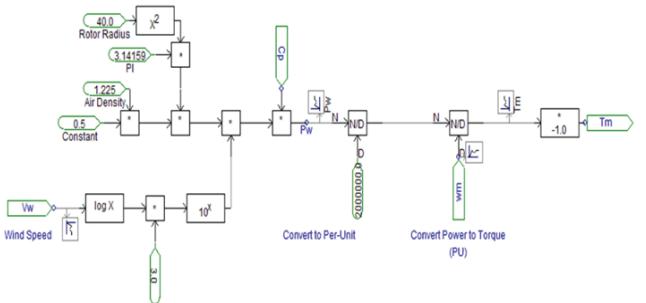


Fig. 6. Modeling of wind power energy

as shown in Eq. (3).

$$P_{wind} = \frac{1}{2} \rho A V_{wind}^3 C_p \quad (1)$$

$$C_p = \frac{1}{2} (\lambda - 0.022\beta^2 - 5.6) e^{-0.17\lambda} \quad (2)$$

$$\lambda = \frac{R \times \omega}{V_{wind}} \quad (3)$$

where, P_{wind} is a wind power energy, ρ is an air density, A is an area of rotating blade, V_{wind} is a wind velocity, C_p is an efficiency of energy conversion, λ is a tip speed ratio, β is a pitch angle of blade, ω is an angular velocity and R is a diameter of turbine.

Therefore, by substituting Eq. (2) and Eq. (3) with Eq. (1), a wind power energy from the blade can be obtained in Eq. (4).

$$P_{wind} = \frac{1}{2} \rho A (V_{wind})^3 C_p(\lambda) = \frac{1}{2} A \rho \left(\frac{\omega R}{\lambda} \right)^3 C_p(\lambda) \quad (4)$$

The modeling of wind power energy in mechanical section of WP system using Eq. (4) can be illustrated by using the PSCAD/EMTDC, as shown in Fig. 6.

4.2 PV system

The desired instantaneous active power(P) and reactive

power(Q) of PV system are generally decided by d-q axis variables which are converted to DC values from 3-phase AC values based on the stationary and synchronous coordination system. Exactly, instantaneous active power and reactive power in balanced 3-phase system can be expressed as shown in Eq. (5) based on the concept of the d-q coordinate method [9, 10]. Because the output voltage of V_q in d-q axis rotating at synchronous speed is equal to instantaneous voltage magnitude of the output terminal and also output voltage of V_d is 0, Eq. (6) can be obtained from Eq. (5).

$$P = \frac{3}{2} (V_d I_d - V_q I_q), Q = -\frac{3}{2} (V_d I_d - V_q I_q) \quad (5)$$

$$P = \frac{3}{2} |V_0| I_q, Q = -\frac{3}{2} |V_0| I_d \quad (6)$$

where, V_d , V_q are output voltages of d-axis and q-axis, I_d , I_q are output currents of d-axis and q-axis and $|V_0|$ is a magnitude of instantaneous voltage.

In order to control the desired active and reactive power in a grid-connected inverter, current control algorithms with PI controller can be expressed as shown in Eq.(7) and Eq.(8). In this process, active and reactive power of PV system can be controlled in an independent manner, because there is a decoupling circuit in a current control equation.

$$V_d = (I_{ref-d} - I_d) \cdot \left(k_p + \frac{k_i}{s} \right) - I_q \cdot \omega L + V_{sq} \quad (7)$$

$$V_q = (I_{ref-q} - I_q) \cdot \left(k_p + \frac{k_i}{s} \right) - I_d \cdot \omega L \quad (8)$$

where, I_{ref-dq} is a reference current of inverter and V_{sq} is an instantaneous voltage of output terminal.

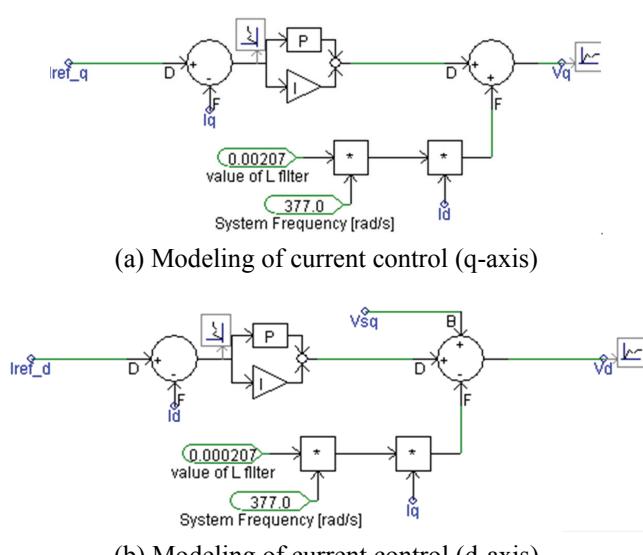


Fig. 7. Modeling of current control in PV system

Based on the Eq. (7) and Eq. (8), modeling of the PI current control can be demonstrated by using PSCAD/EMTDC, as shown in Fig. 7. Where, Fig. 7(a) represents current control modeling in q-axis and Fig. 7(b) is current control modeling in d-axis.

4.3 Load control ESS

The desired instantaneous active power and reactive power of ESS in balanced 3-phase system can be obtained with the same procedures in Eq. (5) and Eq. (6). Where, reference currents of I_{q-bref} and I_{d-bref} of load control ESS can be expressed as shown in Eq. (9) and Eq. (10). Eq. (9) represents a q-axis reference current for desired active power in ESS and Eq. (10) is a d-axis reference current for desired reactive power in load control ESS.

$$I_{q-bref} = \frac{2}{3} \times P \times \left(\frac{1}{V_0} \right) \quad (9)$$

$$I_{d-bref} = -\frac{2}{3} \times Q \times \left(\frac{1}{V_0} \right) \quad (10)$$

This paper adapts an idea that reference current ($I_{dq-bref}$) with negative value(-) is defined as a state of charging operation in ESS, and also reference current with positive value(+) is a state of discharging operation in ESS. Therefore, based on the reference currents for desired charging and discharging power of ESS, the modeling of load control ESS can be designed by using PSCAD/EMTDC as shown in Fig. 8.

4.4 CVCF ESS

In order to supply constant voltage and frequency in micro-grid system without diesel generator as a voltage source, CVCF ESS with a control loop to maintain output voltage and frequency in a constant manner is introduced to micro-grid system. Where, circuit equations related to the control loop for constant voltage and frequency in voltage source inverter is formulated by Eq.

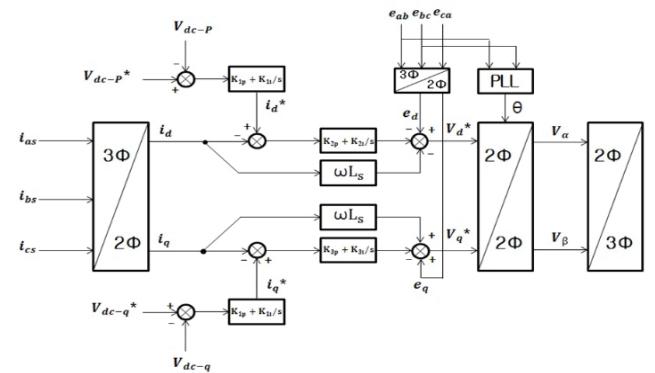


Fig. 8. Modeling of ESS for load control

(11) and Eq. (12).

$$L \frac{dI_{inv}}{dt} = V_t - V_c \quad (11)$$

$$C \frac{dV_c}{dt} = I_{inv} - I_{load} \quad (12)$$

where, V_t is an inverter voltage, V_c is a capacitor voltage, I_{inv} is an inverter current, I_{load} is a load current, L is an inductance for output filter and C is a capacitor for output filter.

By converting the Eq.(11) and Eq.(12) to a synchronous coordinate system, a desired DC output can be obtained as shown in Eq. (13).

$$V_{dc} I_{dc} = \frac{3}{2} (v_{cq} i_{lq} + v_{cd} i_{ld}) \quad (13)$$

where, V_{dc} is a DC link voltage, I_{dc} is a DC link current, v_{cq} is a q-axis voltage of capacitor, i_{lq} is a q-axis output current in a power source, v_{cd} is a d-axis voltage of capacitor and i_{ld} is the d-axis output current in a power source.

Furthermore, in order to perform voltage control in Eq. (13), $v_{cq} = V_m$ (desired output voltage) and $v_{cd} = 0$ should be set by properly adjusting a stationary coordinate axis, when the three-phase system is a balanced condition and also a power factor is controlled by 1.0. Based on these concepts, CVCF ESS using PSCAD/EMTDC can be designed as shown in Fig. 9.

4.5 Diesel generator

A diesel generator controller is generally composed of an exciter to regulate output voltage and a governor to control active power. By controlling the field voltage and current of the rotary machine, the protective function of generator is performed. The modeling of exciter can be illustrated by using the PSCAD/EMTDC, as shown in

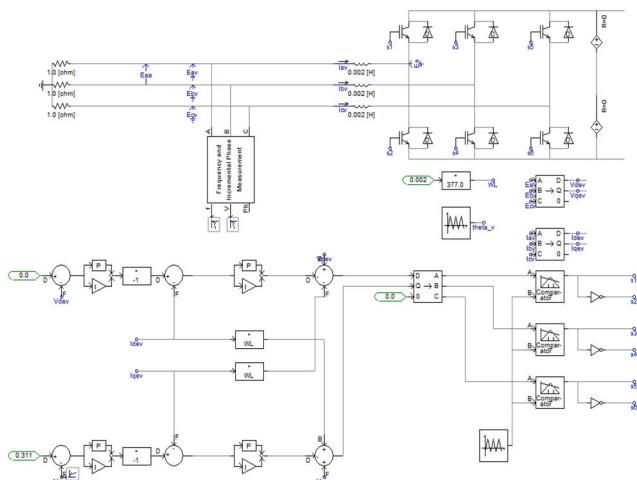


Fig. 9. Modeling of CVCF ESS

Fig. 10. Furthermore, the governor of diesel generator to control the rotational speed with constant value is composed of active power control section to follow demand power in the micro-grid system and speed control section to follow system frequency of 60[Hz]. The modeling of governor can be expressed by the PSCAD/ EMTDC as shown in Fig. 11.

4.6 SVC modeling

In order to compensate the reactive power during the start-up in the WP system, SVC is introduced to micro-grid system. Depending on various power factors in micro-grid

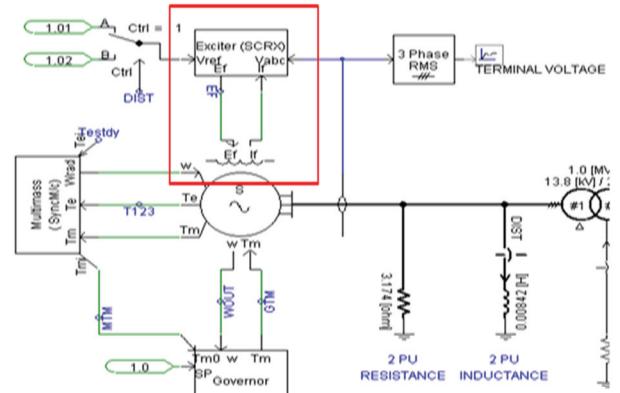


Fig. 10. Exciter modeling of diesel generator

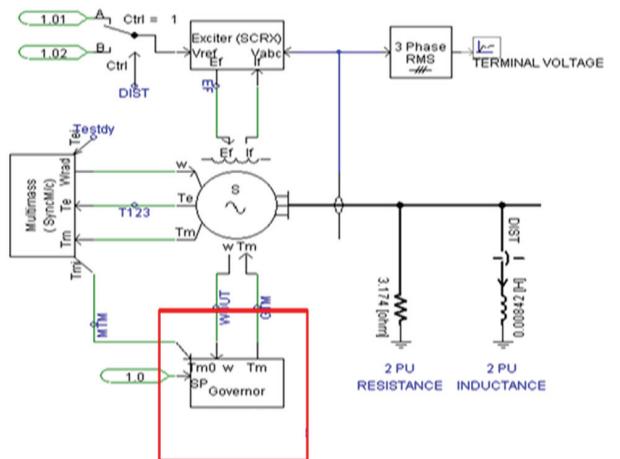


Fig. 11. Governor modeling of diesel generator

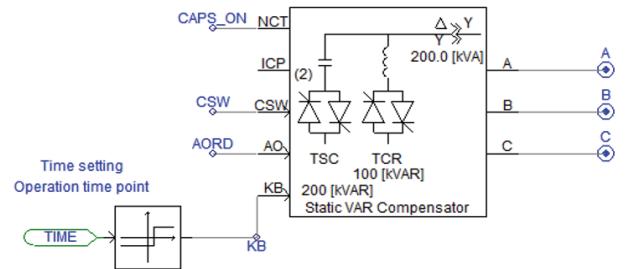


Fig. 12. Modeling of SVC

system, SVC which is composed of reactor and capacitor taps is operated to compensate required reactive power. The modeling of SVC is designed by using PSCAD/EMTDC, as shown in Fig. 12. Where, SVC is composed of TCR(Thyristor Controlled Reactor) for lagging reactive power and TSC(Thyristor Switched Capacitor) for leading reactive power.

4.7 Total system modeling

Based on the modeling mentioned earlier, the modeling of novel micro-grid system including diesel generator, double fed induction generator(DFIG) of WP system, PV system, load control ESS for active power control, CVCF ESS for constant control of voltage and frequency, and SVC for reactive power control can be illustrated as shown in Fig. 13.

5. Case studies

5.1 Simulation conditions

5.1.1 Configuration of the micro-grid system

In order to confirm the effectiveness of proposed algorithm and modeling for novel micro-grid system without diesel generator, some control devices such as CVCF ESS to supply constant voltage and constant frequency, load control ESS to perform charging and discharging operation, and SVC to compensate reactive power are introduced to existing micro-grid system which is composed of diesel generator, WP system, PV system and customer load as shown in Fig. 3. Where, the capacity for each power source and customer loads are assumed as initial conditions which is the field operation data in Gapa-island, as shown in Table 2 [11, 12].

5.1.2 Operation scenarios of the micro-grid system

In order to validate proposed operation algorithm in the micro-grid system, this paper classifies 3 operation scenarios, namely existing operation method in the micro-grid system with diesel generator(Case I), existing operation method in micro-grid system without diesel generator considering only CVCF ESS(Case II), and proposed method in novel micro-grid system without diesel generators considering load control ESS, CVCF ESS and SVC (Case III), as shown in Table 3.

5.2 Performance evaluation for PSCAD/EMTDC modeling

In order to analyze the frequency and reactive/active power characteristics during the start-up in the WP system, the operation time in the torque control mode is set by 1

Table 2. Capacity of each component in micro-grid system

Power source	Capacity
Diesel generator	450[kVA]
PV system	110[kW]
WP system	500[kVA]
SVC	100[kVar]
ESS for load control	864[kWh]
ESS for CVCF	1080[kWh]
Customer load	270[kVA]

Table 3. Operation strategies of micro-grid system

	Case I	Case II	Case III
Diesel generator	O	X	X
PV system	O	O	O
WP system	O	O	O
SVC	X	X	O
Load control ESS	O	X	O
CVCF ESS	X	O	O

(*)Note: Operation stands for O and no operation for X

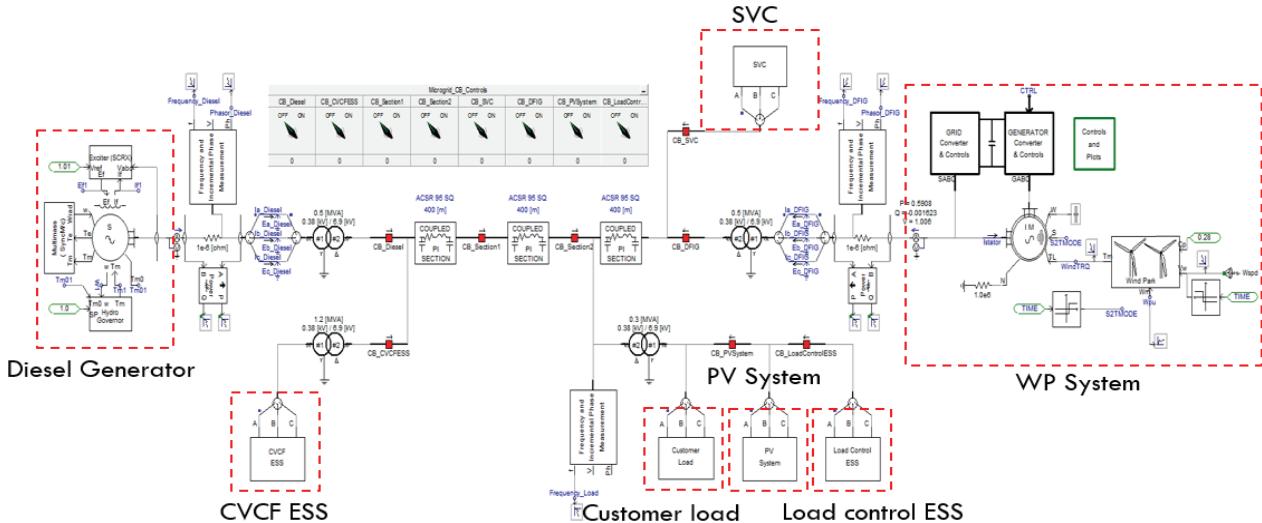


Fig. 13. Modeling of total system

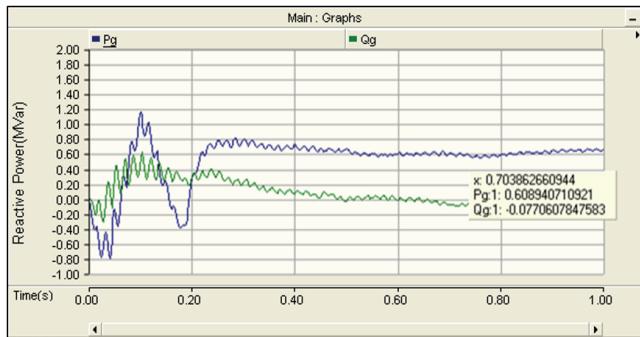


Fig. 14. Characteristic of active and reactive powers during start-up in WP system

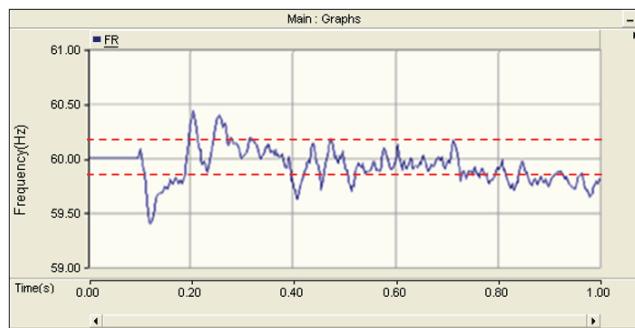
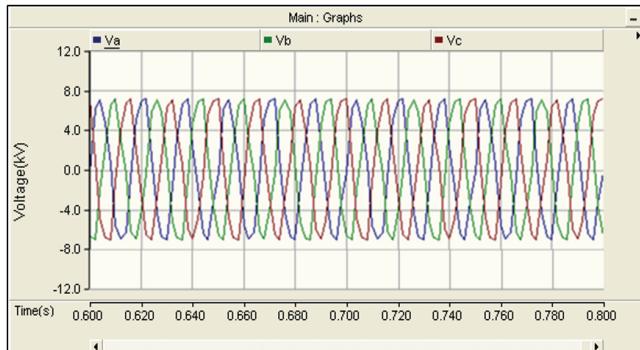
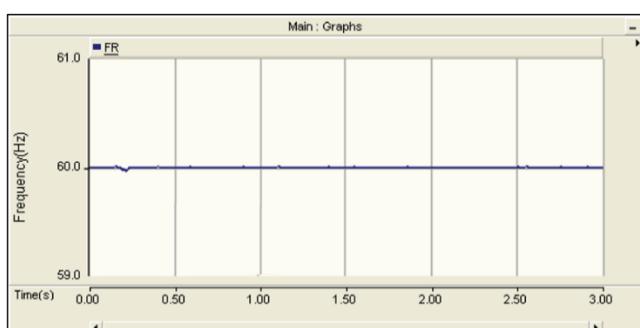


Fig. 15. Frequency characteristic during startup in WP system



(a) System voltage



(b) System frequency

Fig. 16. Voltage and frequency characteristics in micro-grid system with CVCF ESS

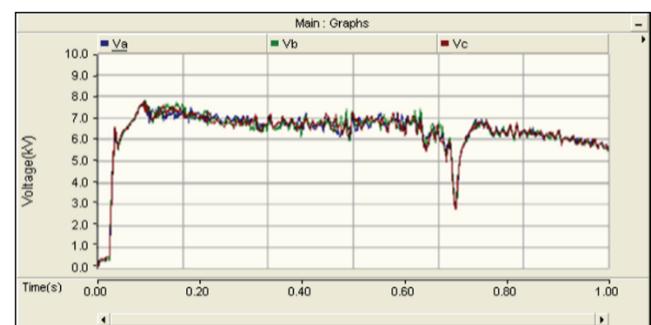
[sec] and the wind velocity is assumed by 12[m/s]. Based on the PSCAD/EMTDC modeling, it is found that active and reactive powers required in the torque control mode of the WP system are 900[kW] and 500[kVar] as shown in Fig.14, respectively, and also it is confirmed that system frequency in the micro-grid system violates the allowable limits(60 ± 0.2 Hz) in the torque control mode as shown in Fig. 15.

Furthermore, CVCF ESS is introduced to supply constant voltage and constant frequency in micro-grid system instead of diesel generator as a base voltage source. Under this operation conditions, it is found that the system voltage and frequency by the CVCF ESS can be maintained within allowable limits as shown in Fig. 16(a) and Fig. 16(b), respectively.

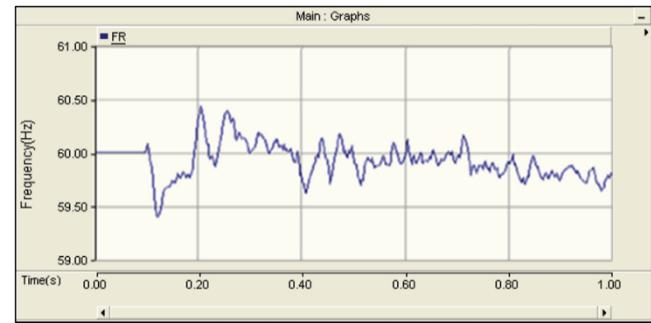
5.3 Operation characteristics of the micro-grid system

5.3.1 Existing micro-grid system with diesel generator (Case I)

In order to analyze operation characteristic in existing micro-grid system with diesel generator, it is assumed that WP system is at start up after 0.3[sec] of initial point and total output of renewable energy sources including WP system is bigger than load capacity after 2[sec] of initial point. Under these conditions, it is confirmed that system voltage has rapid variation characteristics as shown in Fig.



(a) System voltage



(b) System frequency

Fig. 17. Voltage and frequency characteristics in existing micro-grid system

17(a) and system frequency also violates the allowable limits in Fig. 17(b) due to over-supply with the reverse power flow of renewable energy sources. Therefore, when total output of renewable energy is bigger than customer load, it is clear that the existing micro-grid system with diesel generator may have a possibility of unstable operation condition.

5.3.2 Existing micro-grid system without diesel generator (Case II)

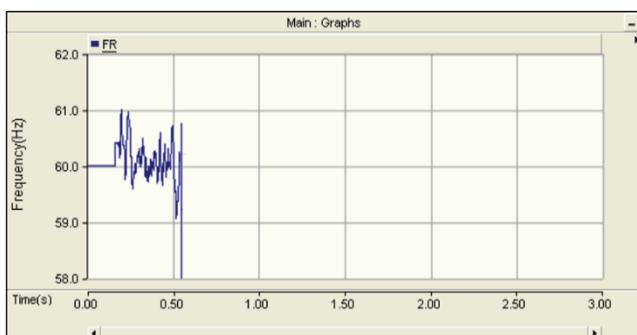
When WP system is at start-up by the torque control mode in existing micro-grid system without diesel generator, the system voltage is rapidly dropped and also system frequency violates allowable limits as shown in Fig. 18(a) and Fig. 18(b), respectively, because only CVCF ESS cannot compensate required active and reactive powers during start-up of the WP system. Therefore, in order to solve this problem, it is clear that active and reactive power control devices such as load control ESS and SVC to help out the function of CVCF ESS should be required to perform a stable operation in micro-grid system without diesel generator.

5.3.3 Proposed micro-grid system without diesel generator (Case III)

In order to overcome the operation problems of existing

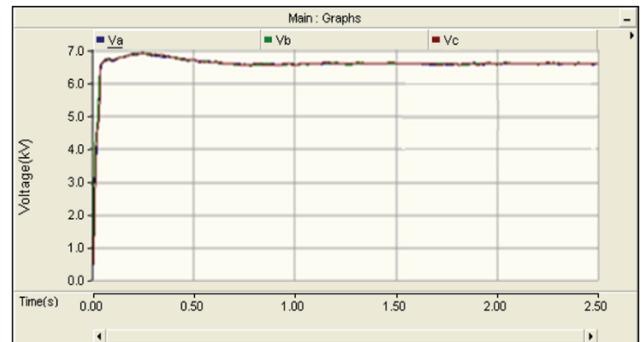


(a) System voltage

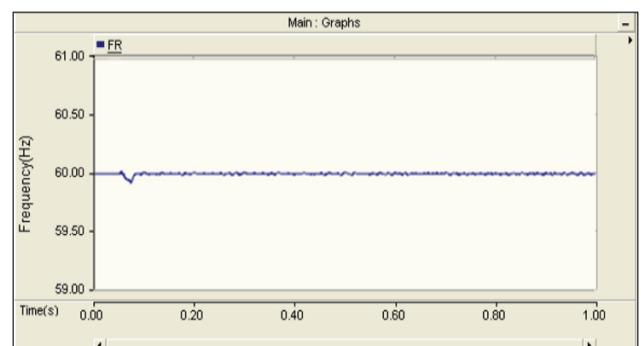


(b) System frequency

Fig. 18. Voltage and frequency characteristic in existing micro-grid based on CVCF ESS



(a) System voltage



(b) System frequency

Fig. 19. Voltage and frequency characteristic by proposed method

micro-grid system without diesel generator as mentioned earlier, this paper proposes new approach (Case III) which adapts control devices such as load control ESS to balance demand and supply in normal operation mode and SVC to compensate reactive power in start-up mode of WP system. From the simulation results based on the proposed modeling and operation algorithms, system voltage can be maintained within the allowable limits due to reactive power properly supplied by SVC during the start-up of WP system as shown in Fig. 19(a). And also system frequency can be kept within allowable limits by using load control ESS even if the total power supply is bigger than load demand at each time intervals in Fig. 19(b). Therefore, it is found that proposed method can improve system reliability in existing micro-grid system and then reduce CO₂ emission produced by diesel generator.

6. Conclusion

This paper proposes the operation algorithm and modeling of the micro-grid system with CVCF ESS, load control ESS and SVC for the purpose of the stable operation and CO₂ emission reduction. The main results are summarized as follows.

- (1) In the case of existing micro-grid system with diesel

generator(Case I), it is found that system voltage has rapid variation characteristics and system frequency also violates the allowable limits due to oversupply with the reverse power flow of renewable energy sources when total output of renewable energy sources is bigger than customer load.

- (2) In the case of existing micro-grid system without diesel generator considering only CVCF ESS(Case II), it is found that the system voltage is rapidly dropped and also system frequency violates the allowable limits, because only CVCF ESS cannot compensate enough active and reactive powers during start-up of the WP system.
- (3) In novel micro-grid system with control devices such as load control ESS, CVCF ESS and SVC, it is confirmed that system voltage can be maintained within the allowable limits due to reactive power properly supplied by SVC during the start-up of WP system, and also system frequency can be kept within allowable limits by using load control ESS even if the total supply is bigger than demand at each time intervals.

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