공학석사 학위논문

Modeling and Control Strategy of the Small-scale Hybrid AC/DC Standalone Microgrid based on the Real Application Network

실 계통에 기반한 소규모 하이브리드 AC/DC 독립형 마이크로그리드 모델링 및 제어전략 수립

2017 년 8 월

서울대학교 대학원

전기 · 정보공학부

나 준 화

Modeling and Control Strategy of the Small-scale Hybrid AC/DC Standalone Microgrid based on the Real Application Network

지도 교수 문 승 일

이 논문을 공학석사 학위논문으로 제출함
2017 년 7 월

서울대학교 대학원
전기 · 정보공학부
나 준 화

나준화의 공학석사 학위논문을 인준함
2017 년 7 월

위 원 장 ______박 종 근______ (인)

부위원장 ______문 승 일______ (인)

위 원 ______윤 용 태______ (인)

Abstract

Modeling and Control Strategy of the Small-scale Hybrid AC/DC Standalone Microgrid based on the Real Application Network

Junhwa Ra
Department of Electrical and Information Engineering
The Graduate School
Seoul National University

Hybrid AC/DC standalone microgrid(MG) is considered as the prominent formation that can be a major type of MG which is essential to realize small scale, distributed and decentralized power system in the future. Based on the two MG projects performed in the same island located near the west-south coast of Korea, Geocha-island has become the place to be able to provide the meaningful opportunity to realize the test-bed project of hybrid AC/DC MG for the first time in the world as far as the author is aware of.

As a first step to implement hybrid AC/DC MG configuration in Geocha-island, the modeling work has been done based on the design information of pre-existing AC MG and DC MG. In the process of the combining two MGs, interlinking converter (ILC) is only added at the point of connection to transfer the proper amount of active power between MGs required to achieve system control purposes such as system voltage control in DC MG, system frequency control in AC MG and constant active power transfer.

Secondly, the control strategy of hybrid AC/DC MG in Geocha-island is established based on the modeling result performed in this paper. It is composed of five types of control mode in normal operation and two types of control mode in contingency operation. Each of mode has individualized control scheme in order to guarantee the reliable operation of the whole system at most cases.

At last, the effectiveness of the proposed control strategy is verified through the simulation using Matlab/Simulink for several normal and contingency operation cases. The simulation results clearly show that hybrid AC/DC MG in Geocha-island can be operated reliably while satisfying the given grid codes and performing better than individual MG operation case.

Consequently, developing the control strategy for hybrid AC/DC MG in Geocha-island and verifying its usefulness for the future application are the main contributions of this dissertation.

Keywords : Hybrid AC/DC microgrid, Standalone microgrid, Interlinking converter, Battery energy storage system, State of charge, Distributed generations

Student Number：2015－22783

Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1 Backgrounds

Environmental effects provoked by the conventional activities in power industries to produce and distribute electricity have drawn much public attention all over the world. One of the major issues related to these effects is a fine dust problem, which is particularly severe in some Asian cities such as Seoul and Beijing that have many fossil-fueled power plants nearby. The emissions from these plants are highly likely to be major sources of air pollutants including fine particles.

In order to solve the above-mentioned problem regarding an air quality, replacing a traditional electric power system sustaining more than century with a clean, safe and cost-effective system that suits modern environment policies is inevitable and is only possible when a revolutionary form of power grid is seamlessly developed and extensively adapted. This new type of grid has been commonly referred to as "smart grid" in many literatures and explosive research efforts have been made on this concept more than a decade.

Towards small scale, flexible and decentralized grid : Microgrid

The key element composing of smart grid in the future is going to be a sub-grid that has characteristics such as geographical proximity of generation sources and loads, simple expandability and independent operation ability from the main utility grid. This localized form of power grid mostly named as "Microgrid" (MG) [1] is essential for the transformation from long distance, large-scale generation to distributed, small-size, decentralized generation because it can maximize the power capacity generated from distributed energy resources(DERs) such as solar photovoltaic (PV) module, wind turbines (WTs) and so on.

Typically, microgrid is considered as an partial entity from the utility's view of main grid that can be operated in two modes : grid connected and islanded [2]. In grid-connected mode, major issues to maintain a power quality inside MG can be reasonably handled by the adequate energy transfer between main grid and MG. However, keeping voltage and frequency stable in islanded mode is more technically challenging issue that has been mainly studied in many literatures. Previous MG projects in Korea also have been progressed in small islands without the connection to the main grid because it makes sense enough for the verification of MG research as a case of the islanded situation that is more important in the perspective of research topic. The term "standalone microgrid" will be used for the indication of MG type which can be operated autonomously but not possible to be connected to the main grid due to mostly geographical limitations [3]. Here in this dissertation, standalone microgrid is the base structure to perform modeling and simulation studies.

Surge of DC-grid and evolution to hybrid AC/DC microgrid

Most of studies in the early stage of MG research had been done aimed at the development of control and operation methods in AC MG [4]. On the other hand, recent massive integration of renewable energy sources (RES) with rapid emergence of consumer electronics and expansion of electric vehicle (EV) markets has DC microgrids and DC distribution systems attracting significant interests from research community as DC grid performs better in terms of higher conversion efficiency, more reliable stability and scalability [5].

In the perspective of conventional power utility company, changing the existing AC grid into new DC grid does not seem to be a possible option owing to some physical and economic constraints even though there are clear advantages of DC grid over AC grid in modern power system environments. DC grids will be spread centering around the application of DC MG as an independent form of a small-size power system entity in the region of remote islands, independently operating factories and so on. The increasing installations of such DC MGs naturally leads to the integration of AC MG and DC MG for the sake of the maximization of benefits obtained from the utilization of both AC and DC grids.

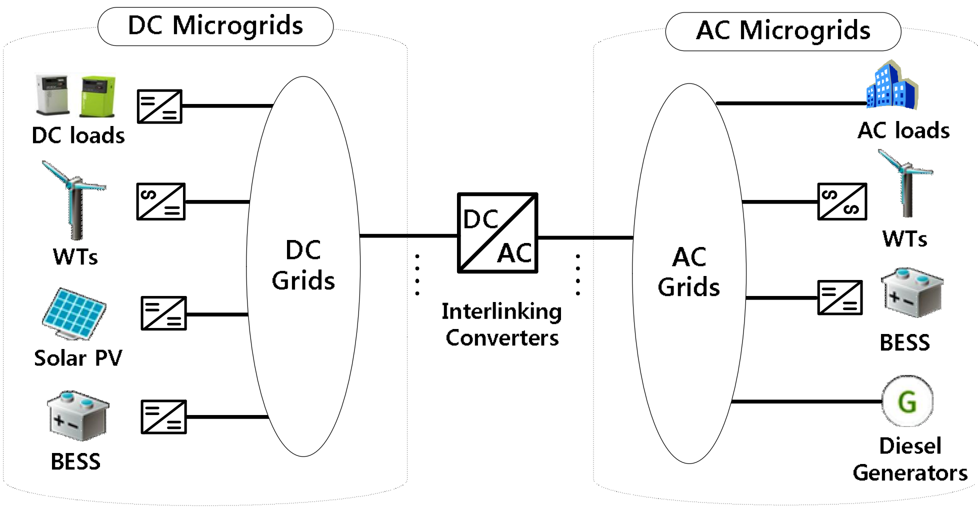


Fig. 1.1 Schematic diagram of hybrid AC/DC MG

In this context, the concept of hybrid AC/DC microgrid has been proposed [6]. Simplified structure of hybrid AC/DC MG using an interlinking converter(ILC) which will be described in detail in chapter 2 is shown in Figure 1.1. It is the most promising type of MGs in the future power systems capable of most efficiently reducing the AC/DC conversion processes and facilitating the connection of various AC/DC sources and loads to power system. As mentioned before, standalone operation of hybrid AC/DC microgrid will be the main target of the research in this thesis.

1.2 Review of the research progress in MG

Since the concept of MG was first introduced in the technical literature about 15 years ago [1], several papers have discussed the controls and operations aspects of AC MGs. In the early stage, control strategies for DERs, power and energy management strategies (PMS) for a MG and MG supervisory control methods were categorized and analyzed based on a comparison between MGs and conventional large power systems in [4]. After accumulating research results to solve technical issues caused for integrating more intermittent RES into MGs, the state-of-the-art control strategies and recent trends in MG were introduced including an overview of three-level hierarchical control systems applied to MG in [7].

Significantly increasing interest to DC microgrids

While remarkable progress has been made for the improvement of the performance of AC MGs during more than a decade [2], [4], [7], DC MGs have been considered as more attractive alternative due to higher efficiency, natural interface to many types of RES and energy storage systems(ESS) and better compliance with consumer electronics, etc [8]. In this vigorous research activities on DC MG, new system operation and control methods for the DC MG with primary nondeterministic RES and variable loads have been proposed in [9]. It developed the strategies for close coordination among wind generation, energy storage, variable load and AC grid connection based on DC voltage measurement. After a few years of research efforts, general control strategies and stabilization techniques for DC MGs were reviewed in [5]. Local and coordinated control levels depending on the communication method were classified and explained in addition to the discussion of properties related to DC MG dynamics and stability. As another aspect of research direction, the practical design features of DC MG technology were reviewed in terms of system hardware topologies, applications in future smart grids (SG), grounding and protection issues and standardization matters in [10]. Furthermore, as a few key issues of future DC MG research, the design of fast acting dc devices such as breakers and the development of new converter topologies for interfacing different types of sources or were pointed out.

Proposing an advanced structure : Hybrid AC/DC microgrid

Even in DC grids, AC sources have to be converted into DC before the connection and DC/AC inverters are required for conventional AC loads. With the proposal of a hybrid AC/DC microgrid in compliance with the demand of the advanced structure that can facilitate the connections of various AC/DC sources & loads and ESSs with optimal operation efficiency, the models and coordination control schemes among various converters have been suggested for smooth power transfer between AC and DC links and for stable system operation under various generation and load conditions in [6]. Also, a new droop control scheme has been proposed in order to investigate power-sharing issues of an autonomous hybrid AC/DC MG in [11]. Proportional power sharing throughout the hybrid MG was able to be enforced with the interlinking converters (ILC) knowing precisely the amount of active power to transfer between the sub-grids. The other type of decentralized control strategy based on the two-stage modified droop method for the control of the ILC was proposed in the context of same purpose in [12]. In [13], various structures of hybrid AC/DC MGs were discussed with the presentation of real-world examples of different types (AC-coupled, DC-coupled, AC/DC-coupled). Different control schemes and power management strategies of these types of hybrid MGs under contrasting operation and loading conditions have been also thoroughly reviewed.

1.3 Review of MG projects in Korea

Research and development of MGs technologies in Korea have progressed focusing on the demonstration of standalone microgrids in remote islands. Table 1.1. is the list of major MG projects performed in several domestic islands [14].

Table 1.1 Major standalone MG projects in domestic islands [14]

Items	Generation type & cap. (kW)	ESS type & cap.(kWh)

Islands	WT	PV	Diesel	Types	Cap.
Gasa- island	100 * 4	314	100*3	Li	3,000
Gapa- island	250 * 2	114	150*3	Pb-Li	1,800
Geocha-island	100 * 1	110	150*3	Li	500

** By Dec. 2015 performed by KEPCO

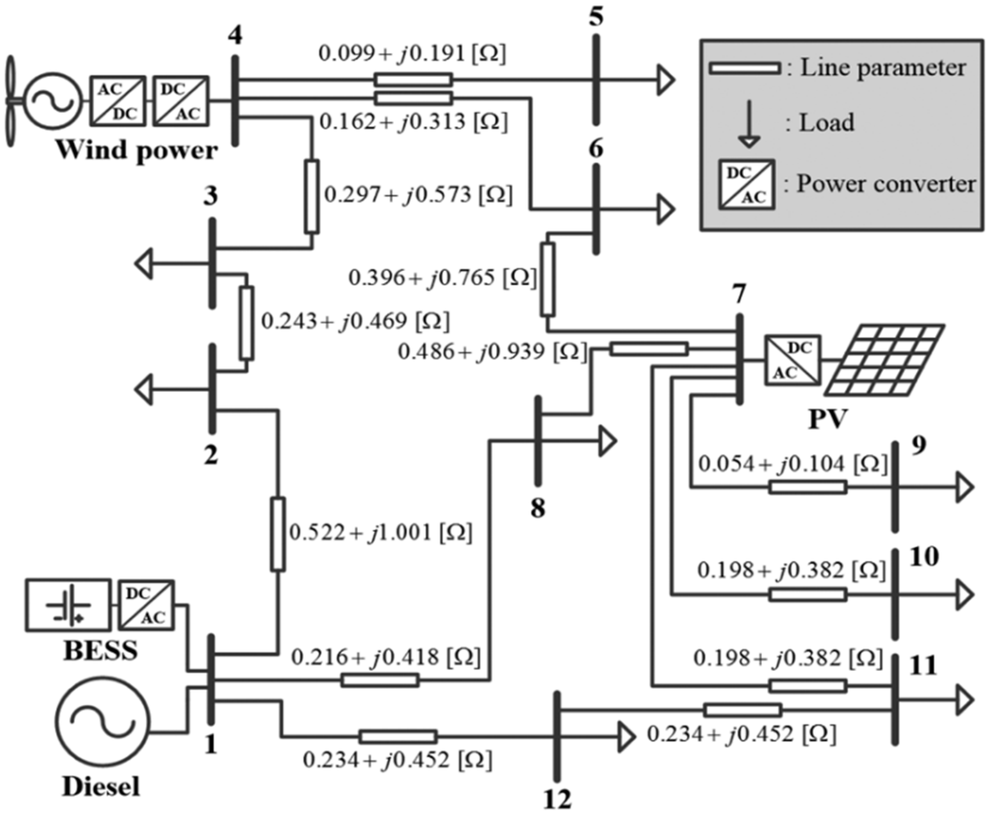


Fig. 1.2 Ulleungdo power system configuration [15]

Since the first test–bed project of carbon–free island constructed in Gapa–do, Jeju island in 2012, operational performance and the size of components in MGs have been improved and increased over a couple of follow–up projects implemented in Gasa–do and Samma–do islands belonging to Jeollanam–do Province. As the latest and biggest project, Ulleung–

do MG project being progressed and expected to be completed in 2020 is targeting to construct the world largest energy self-sufficient island (capacity around 20MW) based on the usage of various distributed generations (DGs) and distributed storages (DS) as shown in Fig 1.2 [15]. On the other hand, there also have been another type of on-going MG project which aims to construct a grid-connected microgrid in Seoul national university to improve the efficiency of energy consumption in the campus and save the energy cost by providing an energy solution model [16].

While all of MG projects stated above have been designed as the form of AC standalone MG, one of recently launched MG projects by Korea Electric Power Corporation (KEPCO) has a goal of the installation of islanded low-voltage DC distribution network similar to DC MG in Geocha-do where AC MG was already installed in 2016 as part of standalone MG project facilitating 100kW WTs, 100kW solar PVs and 500kWh BESS in island areas. This timely and regional duplication of two different characteristic MG projects, constructions of both AC MG and DC MG around the same time in the same islands, has led the author of this thesis to have an idea of integrating two MGs into a new combined form of MG which can be called as hybrid AC/DC standalone MG.

1.4 Motivations and purposes

Considering the two AC and DC MG projects being progressed in Geocha-island from the perspective of one primary power system operator of the island was the direct motivation of the whole idea of this thesis. By combining two MGs properly and operating them as one MG entity through an interlinking converter, the improvement of total grid reliability and energy efficiency can be easily expected.

Meaningful benefits from the combination of two MGs

At the stage of the design of two MG projects, AC MG has not taken into account the existence of DC MG and neither have DC MG reversely because of different project agents and implementation period (More details related to the existing MG projects in Geocha-island in Appendix A). As a result, individual design of two MGs cannot fully harness the potential performance of the installed DG and DS in the island in terms of maximization of generation from RES and the development of more flexible control strategy. These limitations can be addressed in detail through the modeling and simulation of hybrid AC/DC MG performed in this thesis. Moreover, newly suggested combined MG suggested in this thesis will be able to prove the feasibility for itself to be the test-bed project for the implementation of hybrid AC/DC standalone MG in the near future for the first time in Korea. If feasible, this work can be done at the same site using the existing AC MG and DC MG infrastructures. Needless to say, it is a quite valuable opportunity for utility company and researchers to save lots of time and efforts on the way to achieving technical advancements in the field of hybrid AC/DC standalone MG.

Purpose of this thesis

There are three key points that this thesis intends to accomplish through remaining chapters.

1. Modeling of hybrid AC/DC standalone MG based on the

real application network composed of AC MG and DC MG at the same island

2. Establish control strategy of hybrid AC/DC standalone MG considering reliability and operation cost reduction
3. Verification of the suggested control strategy through the simulation on Matlab/Simulink

1.5 Thesis outline

Chapter 1 presents the background of this research and reviews the research progress in the field of MG. After also reviewing the completed or on-going MG projects in Korea, the motivations and purposes of this thesis are followed.

Chapter 2 provides the general information regarding design structure and types and characteristics of DGs and converters used in hybrid AC/DC standalone MG discussed in this thesis. And, configuration of hybrid AC/DC standalone MG is modeled with control schemes of interlinking converters based on the existing AC MG and DC MG projects in Geocha-island.

Chapter 3 establishes the control strategy of hybrid AC/DC standalone MG newly modeled in chapter 2. Seven types of control modes in normal and contingency operation are described in detail.

Chapter 4 shows the simulation results of various cases which need several mode transitions according to the given operation scenarios to verify the effectiveness of the control strategy established in chapter 3 . The simulation of contingency cases is also performed.

Chapter 5 concludes the whole contents of this thesis and briefly comments the contributions made through this work.

Suggestions for the improvements of upcoming MG projects in Geocha−island and future works about some additional technical issues related to the control and operation of hybrid AC/CD MG are proposed.

Chapter 2. Modeling of Hybrid AC/DC MG

In this chapter, hybrid AC/DC standalone MG is going to be modeled based on the modeling results of existing AC MG & DC MG. Because the modeling and field construction of AC MG in Geocha-island has been already completed in another exquisitely performed project [17], modeling of RESs(PVs, WTs) and other DGs (diesel generator , BESS) in AC MG are employed from that work. Meanwhile, some of RESs components modeling works in DC MG have been performed using the form of the equivalent circuit under the given rating values because they are not installed in the site yet and details of component design are not finally determined. Modeling of hybrid AC/DC MG in Geocha-island is composed of the direct combination of two existing MG modeling works through interlinking converter without any change of the components model inside two MGs.

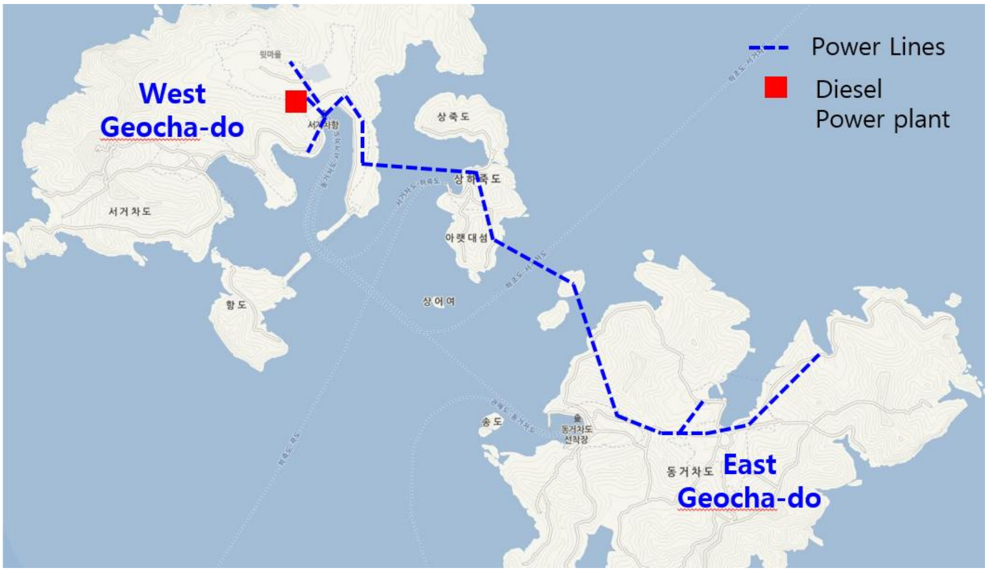


Fig. 2.1 Map and power distribution lines of Geocha-island

Before checking on each of both MGs modeling, it is necessary to look up the brief information about Geocha-island island to help understanding the configurations of MGs followed. Fig. 2.1 is the map of Geocha-island with a simple one-line drawing of main power distribution lines. As seen in the map, Geocha-island is composed of geographically two small islands, west Geocha-island and east Geocha-island. Unlike its physical separation, there is only one power plant located in west Geocha-island which generates electric power from three 150kW-size diesel generators and supplies it over the entire island through two distribution lines of 6,900V level. Fig. 2.2 is the distribution system diagram of Geocha-island before the components installation to configure MGs. More details and characteristics about Geocha-island and its pre-existing power system can be found in Appendix A and B.

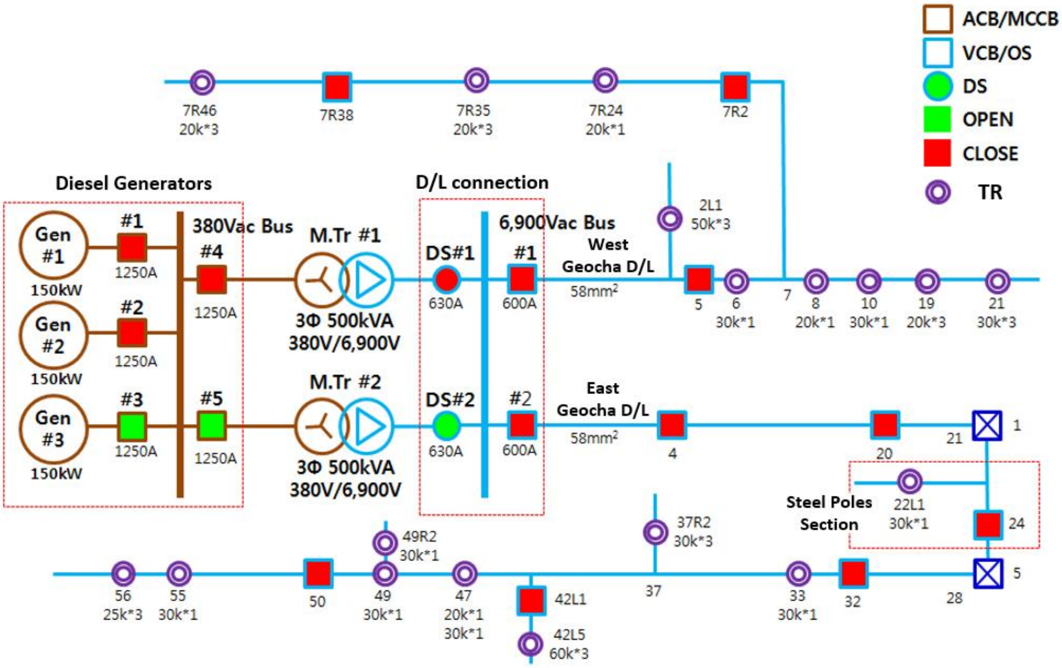


Fig. 2.2 Distribution system diagram of Geocha-island before MG projects [17]

2.1 Modeling of existing MGs in Geocha-island

2.1.1 Configurations and components

AC microgrids

The configuration and parameter values of AC MG in Geocha-island is shown in Fig 2.3. Electric powers are delivered to residents in Geocha-island mainly by two main distribution lines as seen in Fig 2.3. They are extracted from one diesel power plant, which is located in west Geocha-island and compose of three 150kW (total 450kW) diesel generators. Two of three generators are in parallel operation at all times and the other one is for the use of emergency conditions. The output power of generators (AC, 380V) are connected to the two 3-phase main transformers which increase the voltage to the level of main grid voltage, 6,900V and change the type of line connection from wye to delta. The capacity of a main transformer is 500kVA.

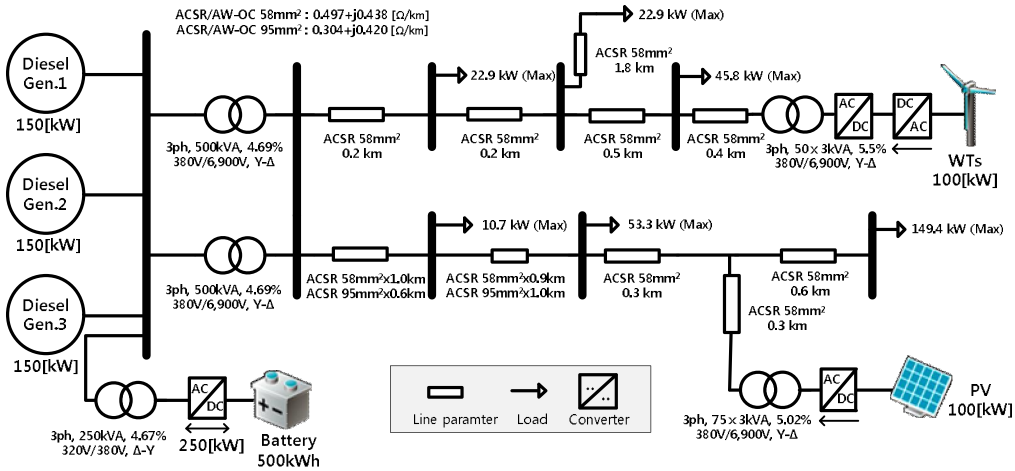


Fig. 2.3 AC MG configuration in Geocha-island

The type of distribution lines are Aluminum wire typically used in overhead power lines. ACSR stands for Aluminum conductor steel-reinforced cable. ACSR/AW-OC is the type of ACSR suitable for outdoor weather using sheath layer with a water-tight characteristic. Two types of wire conductor thickness of wires, 58mm^2 and 95mm^2, are used for the overhead power grid in Geocha-island. 95mm^2 thickness wires are only installed on the steel poles used for the section crossing the sea.

The main load points in west & east Geocha-island are similarly located in three geographic points. The total sum of peak loads in the islands are 305kW, 124kW on average. The specific load information is given in Fig 2.3.

There are four types of distributed generations installed in AC MG : diesel generators, solar PVs, wind turbines and BESS. Brief explanation about diesel power plants is already given above. In case of PV system, it is located in east Geocha-island and composed of solar panels, AC/DC converter and three 75kVA step-up transformer. The capacity of PV system is 100kW. WT system is located in west Geocha-island and composed of back-to-back(AC/DC/AC) converter and 3phase 50kVA linking transformer. The capacity of WT is also 100kW. At last, BESS system is located inside the diesel power plant of west Geocha-island and composed of Li-ion battery and power conversion system (PCS). The capacities of batteries and PCS are 500kWh and 250 kVA.

In real AC MG installation, 200kW emergency diesel generator has been installed parallel to PV system in east Geocha-island for the isolated operation of east Geocha-island in case that east Geocha-island has to be separated from the main diesel power plant located in west Geocha-island. In the analysis of this thesis, however, this emergency diesel generator is not reflected on the simulation model because the isolated operation of east Geocha-island has no direct relationship with the study of modeling and operation in hybrid AC/DC standalone MG.

DC microgrids

A partial map of west Geocha-island and power lines & components forming DC MG is shown in Fig 2.4. And, detail configuration of DC MG with specific component parameters is also given in Fig 2.5. While AC MG cover the entire region including west and east Geacha-do, DC MG is being constructed in part of west Geocha-island. Unlike AC MG, DC MG has no direct connection with existing diesel generators or main transformers.

Fig. 2.4 Map and DC power lines of west Geocha-island[18]

The type of distribution line for DC power supply and RES-generated power delivery is 0.6/1.0kV CV 3core 120mm^2 cable. CV cable is the standard type of power cable normally used as a low-voltage distribution line in the underground power supply region by utilities. The distribution voltage level is 750V and 190V. The power lines for DC MG is newly constructed from various DGs to new DC type loads and some of AC/DC multi-mode houses without the removal of existing AC distribution lines for the reliable electricity supply even in abnormal situations such as DC MG maintenance.

Most of loads in DC MG is newly constructed (EV charger 20kW and LED 2kW) or transformed from AC loads to DC loads (Drying racks and village DC homes) using AC/DC distribution panels in the process of components construction like DC homes. In our modeling, all of DC loads are assumed that they are newly installed in DC MG and compose DC distribution grid independently from AC MG.

There are three types of DGs installed in DC MG : Solar PV, WT and BESS. Both PV system and WT are located near the seawall and directly connected to DC main grid through their own inverter. Compared to PV and WT in AC MG, there is no need to install step−up transformers to the points of PV and WT connection. The capacity is 100 kW for WT and 100 kW for PV system. In the modeling of PV and WT in DC MG, as mentioned earlier in the beginning of this chapter, equivalent circuit models are applied instead of the exact model of converters and generation sources because the specific designs can be changed in the stage of field construction and equivalent circuit models are also still enough to verify the performance of hybrid AC/DC MG. Lastly, BESS in DC MG is also located inside diesel power plant site in the same way of BESS in AC MG. But, PCS of DC BESS is differently designed because it is connected to DC grid. The capacities of Li−ion battery and PCS are 1.5MWh and 200kVA.

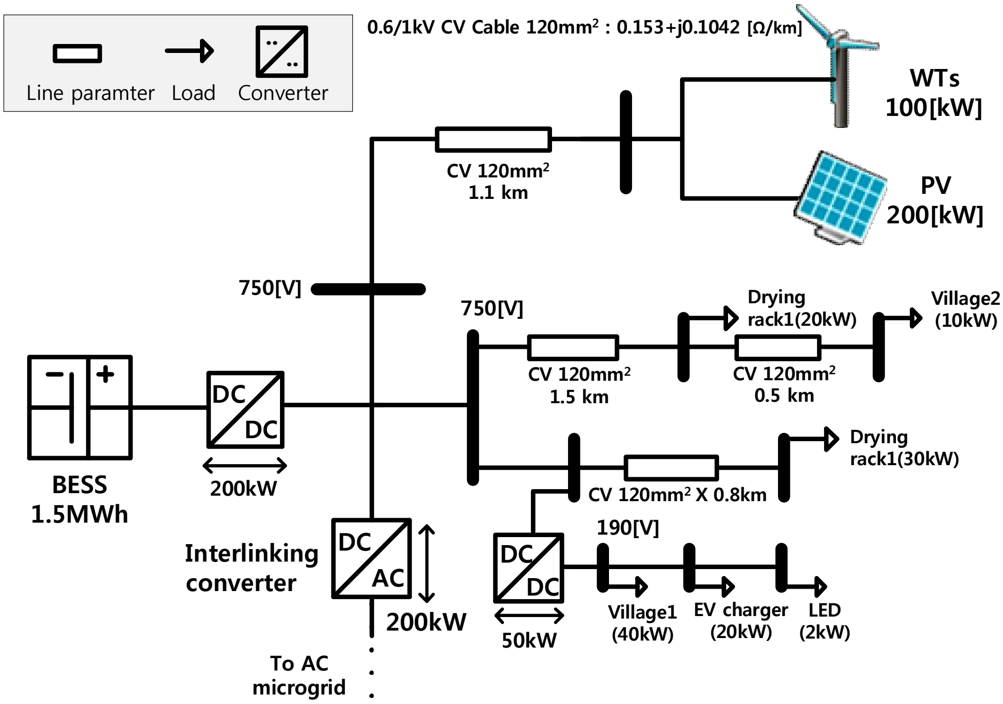


Fig. 2.5 DC MG configuration in west Geocha-island

In the design of original DC MG field construction, one variable-speed diesel generator is planned to be installed in the power plant site in west Geocha-island. But, there is no use operating a new diesel generator when DC MG is connected to AC MG where the existing diesel generators are already in operation. The purpose of this new generator is to charge batteries installed in DC MG for the case of low state of charge (SOC) or to supply AC power to DC MG using the same distribution line in order to compare the energy efficiency between AC power system and DC power system. As charging DC BESS by a diesel generator can be done by AC MG and the comparison of energy efficiency in AC and DC grids is not the scope of this thesis, this variable-speed diesel generator is excluded in the modeling of DC MG. On the other hand, some part of distribution lines to deliver electric power to dispersed loads in DC MG has been designed to form bipolar-type dc microgrid [18]. In this figure, DC power is distributed through three-wire lines composed of 3 level voltages (+750V, -750V, 0V). Even though this bipolar-type design is generally helpful for power lines to satisfy high efficiency and high-quality power supply, it is not included in the modeling of DC MG because it is not directly related to the analysis of hybrid network.

2.1.2 Modeling of DGs

All types of distributed generations in AC MG and DC MG are listed with their control schemes and controllability in Table 2.1.

Table 2.1 Types of DGs in hybrid AC/DC MG

Items / Units	**Types of control scheme**	**Controllability**
$BESS_{AC}$	Grid forming or Constant P output	Controllable
$BESS_{DC}$		
WT_{AC}	MPPT (Maximum power point tracking)	Uncontrollable
WT_{DC}	Constant Power	
PV_{AC}	MPPT	
PV_{DC}	Constant Power	
Diesel Generator (D.G.)	Grid-supported grid forming (Droop control mode)	Controllable

In this paper, the generation systems including BESS, WT and

PV have been modeled using the average model instead of switched model to save time and efforts required to run simulations [22].

*Battery energy storage system in AC MG (**$BESS_{AC}$**)*

The model of $BESS_{AC}$ is composed of mainly 2 parts : circuit model part and control block part as seen in Fig. 2.6. Modulating signal is generated from the control block and the signal goes into the converter in the circuit model. According to control mode signal of $BESS_{AC}$, it can be able to perform two types of purpose. One is to form the system voltage and frequency (CVCF control, Constant Voltage and Constant Frequency) of the grid that BESS is connected to. And, the other is to make constant power output (PQ control) without considering voltage or frequency variation of the connected grid.

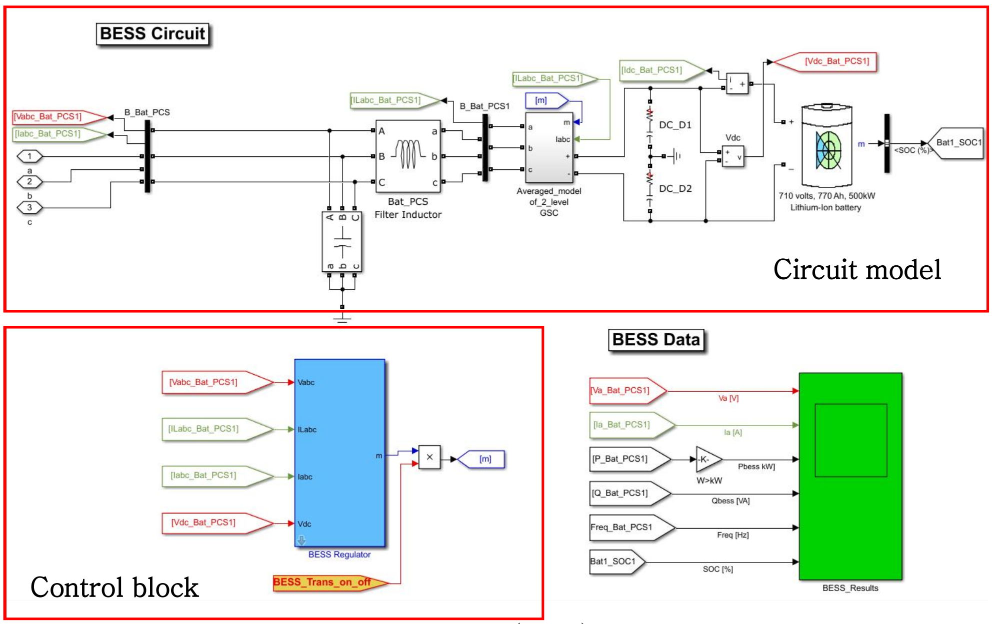


Fig. 2.6 Power conditioning system (PCS) model of $BESS_{AC}$

*Battery energy storage system in DC MG (**$BESS_{DC}$**)*

BESS in DC MG is doing a very important role. As other generation sources in DC MG are uncontrollable renewable units like WT and PV, $BESS_{DC}$ is the only component that can maintain DC system voltage (+750V) as constant by controlling its output properly. In case of PCS attached to the battery, there are two types of controllers (Fig. 2.7). The first one is the voltage controller to keep V_{DC} stable when DC grid is in operation independently. The other one is the output controller that makes BESS being charged or discharged until it returns to the designed SOC range regardless of the system voltage condition. Finally, the modulating signal from the chosen controller goes into the DC-DC converter in PCS of $BESS_{DC}$.

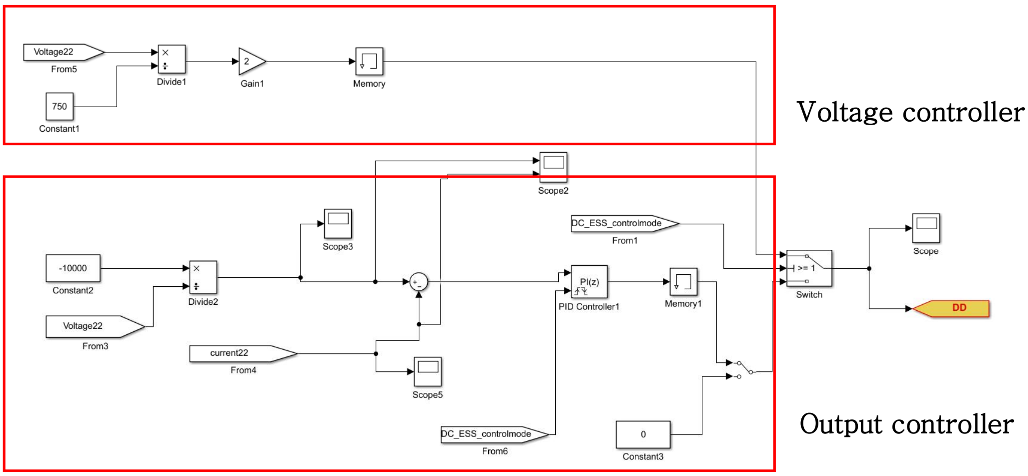


Fig. 2.7 Controller model of $BESS_{DC}$

*Wind turbine in AC MG (**WT_{AC}**)*

WT in AC MG is connected to the grid by the use of back-to-back converter which is composed of two AC/DC converters sharing DC-link terminal as shown in Fig. 2.8. Therefore, grid-side converter does the role of maintaining D-link voltage while machine−side converter controls the power output of wind turbine.

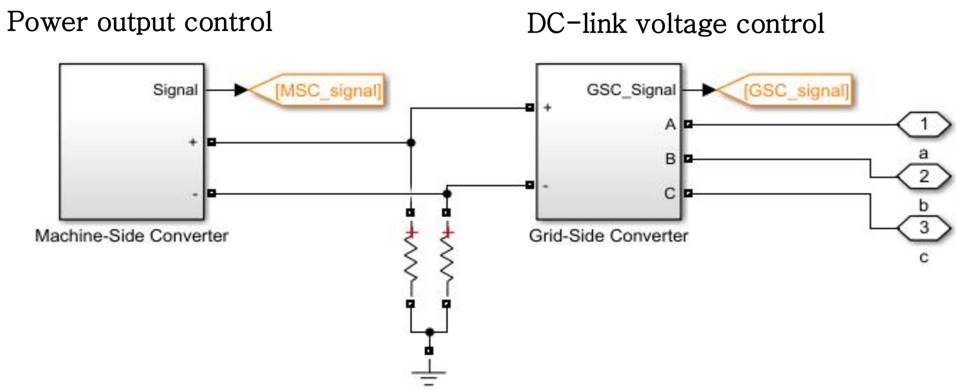


Fig. 2.8 Aspect of back-to-back converter in wind generation system

WTs are operated in the control mode of MPPT(Maximum power point tracking) to maximize the extracted power output from the source. Details of MPPT algorithms which are well−studied in many previous literatures are out of scope in this paper [23]. WTs are uncontrollable sources, which means they cannot participate to form or maintain system voltage or frequency.

*Solar photovoltaics in AC MG (**PV_{AC}**)*

In order to model PV generation system, PV module is the first part to be expressed in the circuit model. Fig. 2.9 shows the equivalent circuit of PV module including the consideration of parallel and series resistances [24].

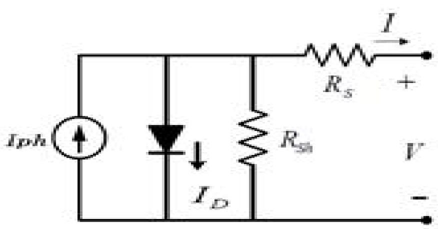


Fig. 2.9 Realistic equivalent circuit of PV module

Therefore, V−I characteristic equation obtained from the circuit model is represented as Eq (2.1) based on the diode characteristic equation.

$$I = I_{ph} - I_0 \left[exp\left(\frac{qV}{kT_{cell}A}\right) - 1 \right] - \frac{V+IR_s}{R_{sh}} \qquad (2.1)$$

I	PV output current [A]
V	PV output voltage [V]
I_{ph}	Photocurrent [A]
I_o	Reverse saturation current [A]
k	Boltzmann's constant [1.38X$\mathbf{10^{-23}}$J/k]
q	Charge of electron [16X10−19 C]
E_G	Band gap energy in the solar cell [1.12~1.15eV]
A	Ideality factor
T_{cell}	Cell temkperature (temparature of the pn-junction) [K]
R_s	Series resistance [Ω]
R_{sh}	Shunt resistance [Ω]

The power generated from PV module is delivered to the system with the voltage level required in the grid through the attached PCS. The structure of PCS in PV system used in the dynamic analysis is shown in Fig. 2.10. PV system also extracts the maximum power according to the amount of solar radiation by operating itself at the maximum power point (MPPT algorithm).

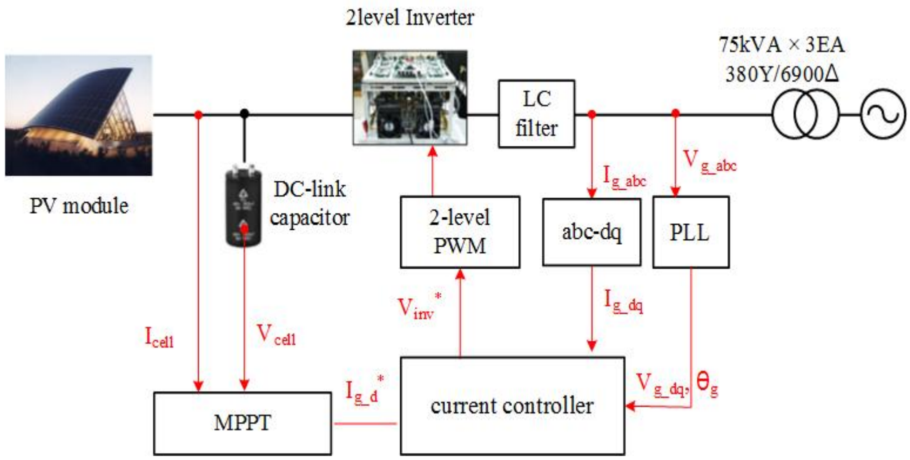


Fig. 2.10 The structure of PCS in PV system

*Wind turbine (**WT**$_{DC}$) and Solar photovoltaics (**PV**$_{DC}$) in DC MG*

Unlike the modeling of WT and PV in AC MG, WT and WT in DC MG are expressed as controlled current sources as shown Fig. 2.11 because they just produce the arranged power output according to the input data (wind velocity and solar irradiation) based on the applied MPPT algorithm. PV system sets to generate 150kW steadily and WT sets to generate 60~80kW according to the variation of wind velocity.

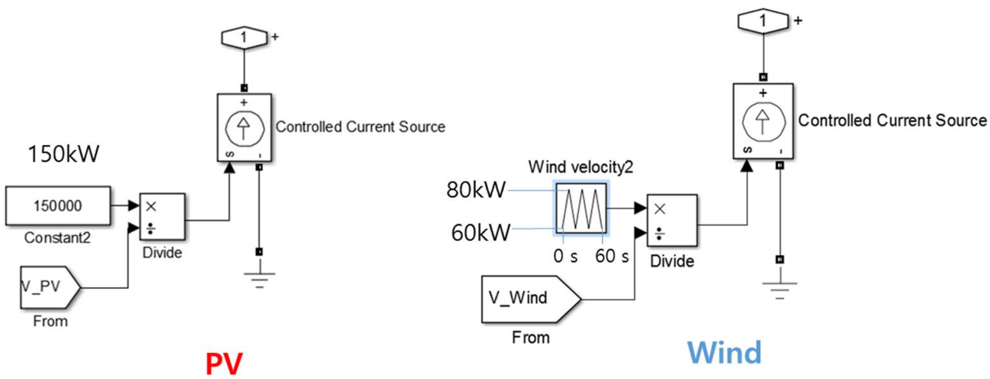


Fig. 2.11 The equivalent modeling of PV and WT in DC MG

Diesel generators (D.G.)

Diesel generators in Geocha−island are physically installed in west Geocha−island and are electrically connected only to AC MG. As explained before, an additional variable−speed diesel generator in DC MG is not included in the modeling work.

Diesel generators in AC MG have modeled to be able to run in two different modes, which are droop mode and isochronous mode. In this paper, diesel generators are fixed to be operated under the droop mode. Eq. (2.2) and Fig 2.12 shows the basic algorithm of droop control mode applied to the diesel generation system. [21]

$$f_{system} = \frac{f_{FL} - f_{NL}}{P_{FL} - P_{NL}} P_{system} + f_{NL} \qquad (2.2)$$

f_{system} : System frequency

f_{FL} : Frequency at full−load condition

f_{NL} : Frequency at no−load condition

P_{FL} : Output active power at full−load condition

P_{NL} : Output active power at no−load condition

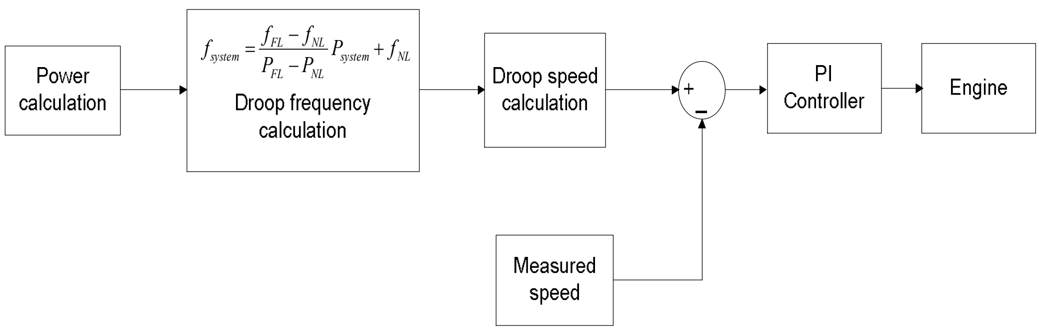


Fig. 2.12 Algorithm block of droop control mode

As seen in Fig 2.12, the system frequency under droop control mode is calculated using the active power output from diesel generators. And, the difference between calculated speed and measured speed becomes the inputs of PI controller and is controlled to be zero. (System frequency follows the reference frequency obtained from droop frequency calculation). In the grid of Geocha-island, three diesel generators have been installed in the plant site and two of three are operating in parallel under the droop control mode. Table 2.2 & 2.3 describes the parameter values used in the synchronous machine and exciter modeling of diesel generators.

Table 2.2 Parameter values of synchronous machine

Parameters		Values
Stator	stator resistance R_s	0.0166 [Ω]
	stator leakage inductance L_l	0.0001684 [H]
	d-axis magnetizing inductance L_{md}	0.005856 [H]
	q-axis magnetizing inductance L_{mq}	0.005052 [H]
Field Winding	field winding resistance $R_{f'}$	0.005245 [Ω]
	leakage inductance $L_{lfd'}$	0.0006816 [H]
Dampers	d-axis resistance $R_{kd'}$	0.1526 [Ω]
	d-axis leakage inductance $L_{lkd'}$	0.003404 [H]
	q-axis resistance $R_{kql'}$	0.04057 [Ω]
	q-axis leakage inductance $L_{lkql'}$	0.0006079 [H]

Machine	inertia coefficient J	3.354 [kg.m^2]
	friction factor F	0 [N.m.s]
	number of pole pairs P	2

Table 2.3 Parameter values of exciter and PI controller

Parameters		Values
Exciter	amplification gain K_e	70
	time constant τ_e	0.002
PI Controller	proportional gain K_p	5
	integral gain K_i	13

2.2 Modeling of a hybrid AC/DC MG in Geocha-island

The idea and method to form a hybrid AC/DC MG in Geocha-island are very simple. Combining two grids having different voltage characteristics by adopting a proper converter commonly called as interlinking converter(ILC) in many literatures is the whole concept as shown in Fig. 2.13. When the number of connected MGs are becoming more than 2, this co-operating power network composed by multi-MGs can be emerged under the name of MG cluster or community MG. The community MG would coordinate some cluster of the interconnected AC and DC MGs located in neighboring areas while a hybrid MG mostly means single AC/DC blended MG entity to reduce the power conversion processes and facilitate the integration of AC/DC sources and loads to a main power system [19]. The extensive study about community MG is out of scope in this thesis. Consequently, the method of forming hybrid AC/DC MG in Geocha−island as a kind of beginning stage to move forward for the development of community MG in the future would be mainly studied in this paper.

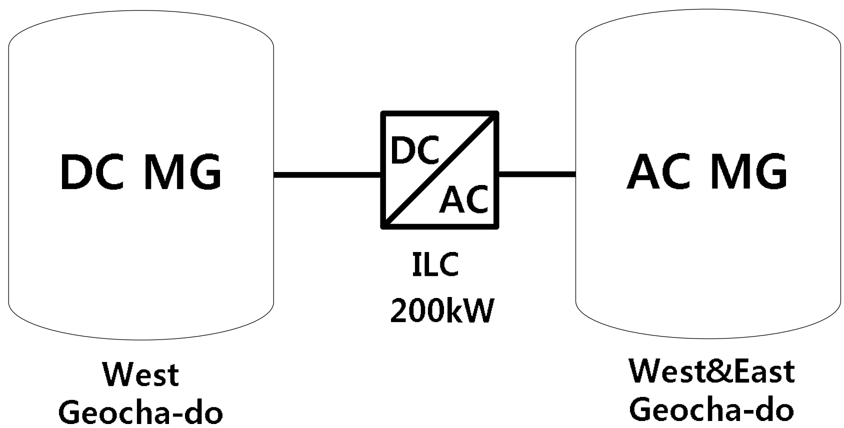


Fig. 2.13 Concept of forming a hybrid MG in Geocha-island

2.2.1 Configuration

In the configuration of hybrid AC/DC MG in Geocha−island, only change made through the process of combining two MGs is the addition of single interlinking converter at the point of connection. All of components types and parameter values remain unchanged as shown in Fig. 2.14. The development of hybrid MG in Geocha−island is planning to be naturally implemented by installing DC MG components on the base of AC MG configuration because both MGs have been implemented at the different time without the consideration of the another MG existence. The design of components have been done only based on the conditions inside its own MG. Therefore, The bidirectional interlinking converter that interfaces the AC sub-grid to the DC sub-grid should plays a critical role in the operation of a hybrid MG in case for the generation and load imbalances, low SOC level of batteries, grid faults and etc. The interlinking converter modeled in this hybrid AC/DC MG in Geocha-island has been designed to be capable of 200kW power conversion from AC(DC) to DC(AC) and deliver the power directionally according to its control mode. More detail roles and control schematics will be explained minutely in the following section of this chapter.

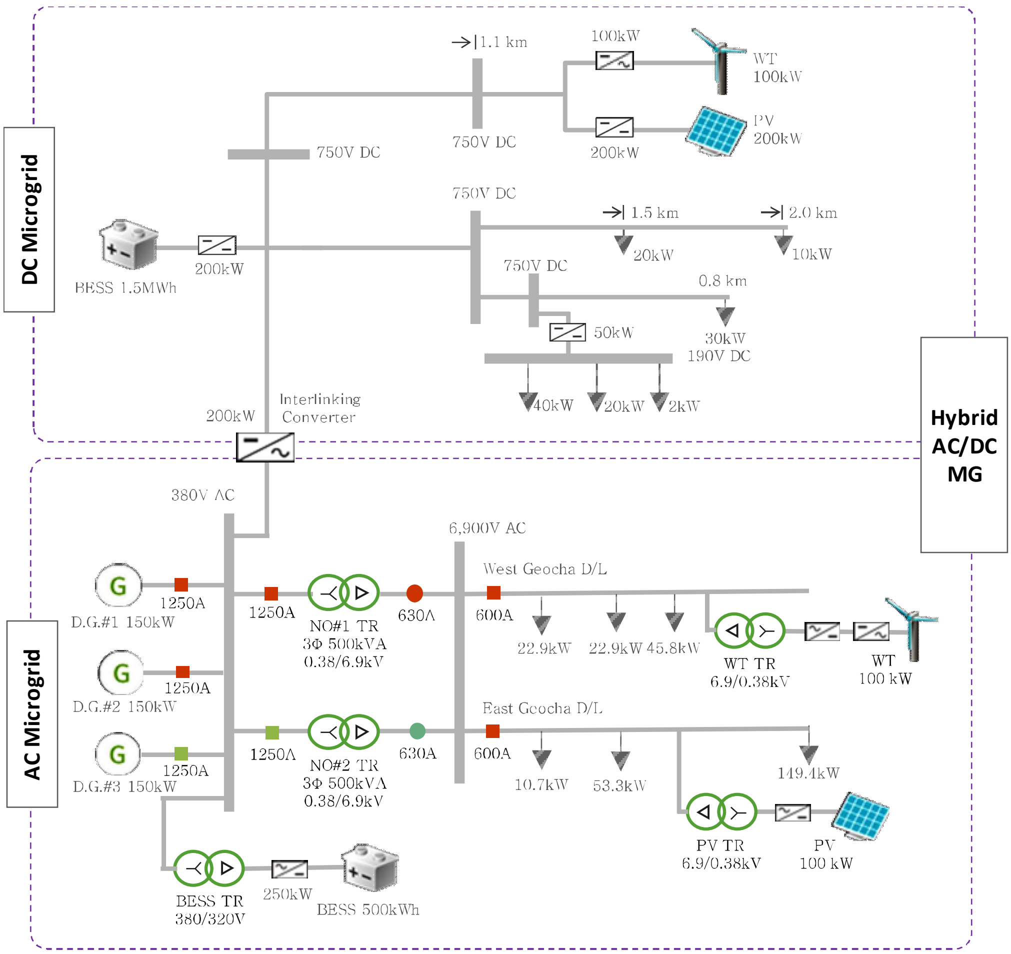


Fig. 2.14. Hybrid AC/DC MG configuration in Geocha-island

2.2.2 Modeling of interlinking converter

Interlinking converter (ILC) can be seen as source or load depending on where it is seen from, which means ILC can control its active power flow bi-directionally between MGs. There are three control functions that ILC can take part in. First two are to maintain system voltage in DC MG or system frequency in AC MG using the feed-back error signal through PI controller between rated value and present value. The other is just transferring the dispatched constant amount of active power to the target grid as intended by high-level operator. To realize these three functions, ILC fundamentally uses the same type of 2-level AC/DC converter used in other DG units. But, it has a different configuration of its controllers. First of all, it uses the same output controller (PQ control) used in ESS' PCS and gives this output to the current controller (inner loop). Secondly, ILC provides the output of the different outer loop with inner loop as the reference current values (I_d,I_q) in order to control DC grid voltage. Finally, ILC uses the indirect method to control the frequency of AC MG, which means that it supplies additional active power to AC MG according to the current system frequency.

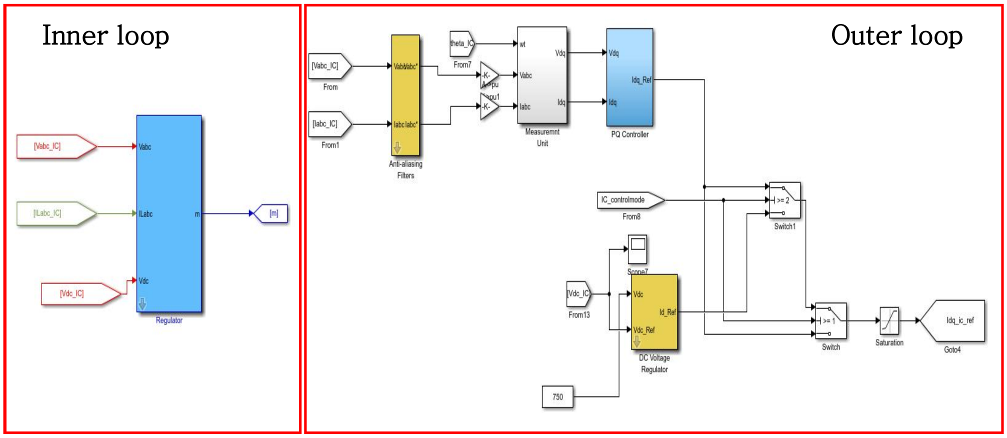


Fig. 2.15. The controller structure of ILC

Chapter 3. Control strategy of Hybrid AC/DC MG

Here in chapter 3, the operation strategies of hybrid MG would be described according to the mode categorization of normal & contingency cases based on the specific model of hybrid AC/DC standalone MG in Geocha-island performed in chapter 2.

First of all, all of operation cases can be classified into two groups: normal and contingency cases. Normal cases means that the configuration of hybrid AC/DC MG remains without disconnecting two MG in varying generation and load conditions. Normal cases are also divided into 5 different modes mostly based on which component is forming AC or DC grid voltages in several SOC limit cases of BESSs. In the contrast, contingency cases are defined as the unusual conditions which need an intentional separation of hybrid AC/DC MG into AC MG and DC MG, respectively for the purposes of grid maintenance works and etc. Therefore, reliable operation of each MG and smooth recovery to hybrid AC/DC MG by the connection through interlinking converter have to be available when contingency occurs. These contingency cases will be handled in mode 6 and 7. The whole system operation procedure of hybrid AC/DC MG in Geocha-island is graphically depicted in Fig 3.1. In the figure, $\mathbf{BESS_{DC}}$ and $\mathbf{BESS_{AC}}$ indicate battery energy storage systems in DC MG and AC MG, respectively. And, $\mathbf{SOC_{BESS_{DC}}}$ and $\mathbf{SOC_{BESS_{AC}}}$ mean status of charge of $\mathbf{BESS_{DC}}$ and $\mathbf{BESS_{AC}}$. More specific conditions of each mode and its control strategy will be given in the following sections of this chapter.

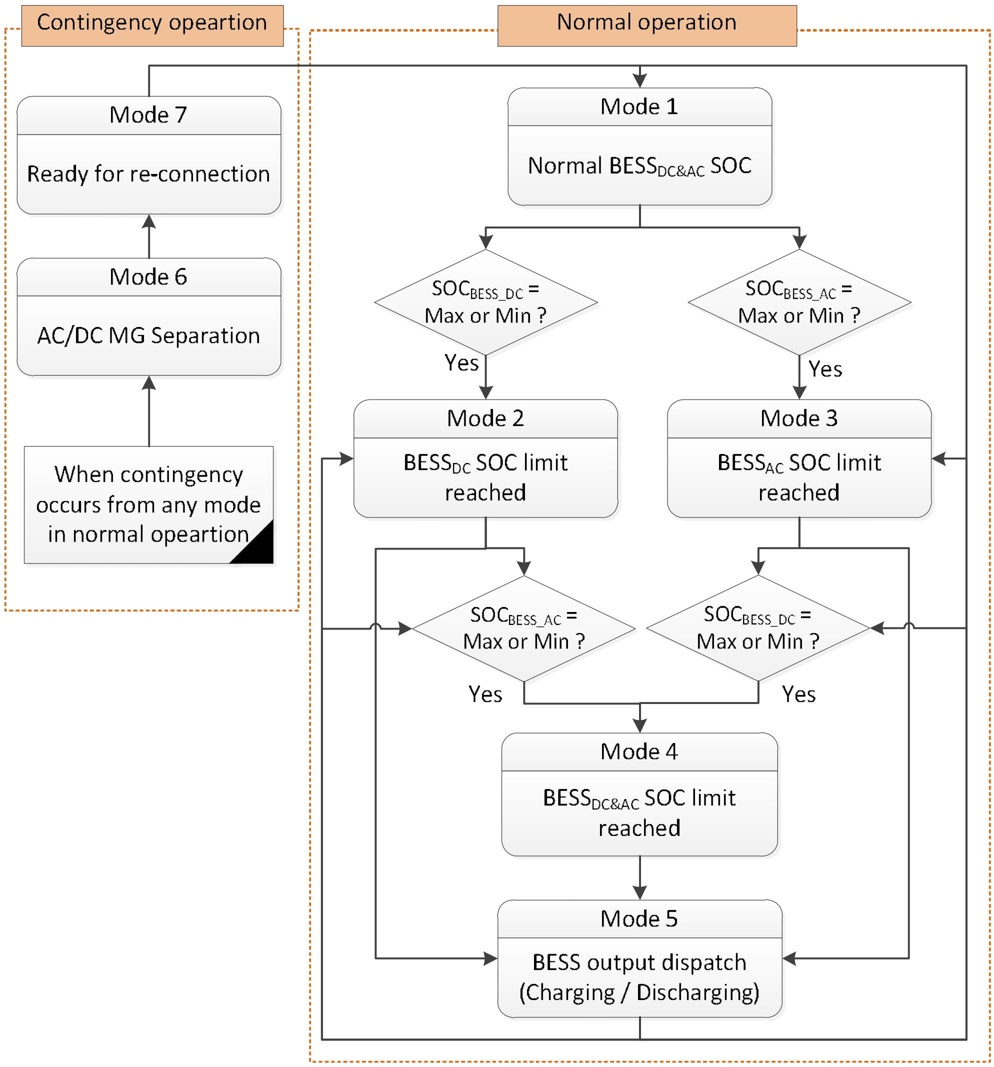


Fig. 3.1 Control mode flow of hybrid AC/DC MG in Geocha-island

Secondly, as examined in chapter 2, there are only four DG components that are able to form AC or DC grid voltage in hybrid AC/DC MG in Geocha-island : $BESS_{DC}$, $BESS_{AC}$, diesel generators in AC MG and interlinking converter. RESs (WT and PV systems) in

AC MG or DC MG are not able to participate in the formation of a grid voltage because they are only operated in MPPT mode to maximize the power generation from sources as explained in chapter 2. The operating modes to control voltage and the voltage control targets of the controllable units are summarized in Table 3.1. V_{DC} indicates the system voltage of DC MG and V_{rated} means the pre−defined nominal voltage of its target grid. $V_{AC,}$ f_{AC} and f_{rated} indicate the system voltage system frequency and the rated frequency of AC MG. The detailed roles of controllable units in each mode would be provided in the next sections.

Table 3.1 Controllable units and their operating mode & targets

<table>
<tr><th>Items / Units</th><th colspan="2">Operating modes when controlling voltage</th><th>Control target</th></tr>
<tr><td>BESS_{DC}</td><td colspan="2" rowspan="2">Grid forming</td><td>V_{DC}</td></tr>
<tr><td>BESS_{AC}</td><td>V_{AC}, f_{AC}</td></tr>
<tr><td rowspan="2">Interlinking Converter (ILC)</td><td rowspan="2">Grid feeding with PI signal</td><td>$(V_{DC} - V_{rated})$</td><td>V_{DC}</td></tr>
<tr><td>$(f_{AC} - f_{rated})$</td><td>f_{AC}</td></tr>
<tr><td>Diesel Generator (D.G.)</td><td colspan="2">Grid supported - Grid forming</td><td>V_{AC}, f_{AC} with droop change</td></tr>
</table>

3.1 Normal operation

3.1.1 Mode 1 : Constant P (active power) transfer

In mode 1, each BESS in DC and AC MGs controls its own grid voltage whereas ILC only transfers the specific amount of power from one side of hybrid MG to the other energy−insufficient side according to pre−dispatched value by higher level of operating system in order to keep the energy balance in the entire hybrid MG. Diesel generators installed in AC MG are operated in the droop mode which is also able to participate in the control of V_{AC}/f_{AC} with the proper adjustment of operating point responding to the variation of frequency and voltage magnitude in AC grid. But, there would be no change of diesel generator's operating point in mode 1 because $\mathbf{BESS_{AC}}$ makes AC grid's voltage and frequency stay in nominal values. Instead, diesel generators are assumed to be running at the proper operation point defined by the imaginary system operator to minimize the fuel cost used for diesel generators in the given circumstances.

Eq.(3.1) and (3.2) are the active−power balance equations in DC MG and AC MG . Since the reactive−power balance equations in DC MG and AC MG are bound to be similarly stated in case of active power, only active power cases are to be discussed here.

In DC MG,

$$P_{WT_{DC}} + P_{PV_{DC}} + P_{ILC_{Trans}} + P_{BESS_{DC}} = Load_{DC} + Loss_{DC} \tag{3.1}$$

In AC MG,

$$P_{WT_{AC}} + P_{PV_{AC}} + P_{D.G.} - P_{ILC_{Trans}} + P_{BESS_{AC}} = Load_{AC} + Loss_{AC} \tag{3.2}$$

where,

$P_{WT_{DC}}$, $P_{WT_{AC}}$: Active power output of wind turbines in DC and AC MG, respectively.

$P_{PV_{DC}}$, $P_{PV_{AC}}$: Active power output of solar PVs in DC MG and AC MG, respectively

$P_{BESS_{DC}}$, $P_{BESS_{AC}}$: Active power output of BESS in DC and AC MG, respectively.

$P_{ILC_{Trans}}$: Active power transferred from one MG to the other MG through interlinking converter

$P_{D.G.}$: Active power output of diesel generators running in pre-defined operating point in AC MG

$Load_{DC}$, $Load_{AC}$: Total amount of loads in DC MG and AC MG, respectively

$Loss_{DC}$, $Loss_{AC}$: Total amount of losses in DC MG and AC MG, respectively

Table 3.2 shows the summarized roles of the controllable units in case of mode 1.

Table 3.2 Controllable units and their roles in Mode 1

Items / Units	**Roles in Mode 1**
$BESS_{DC}$	Form the rated V_{DC}

$BESS_{AC}$	Form the rated V_{AC}/f_{AC}
ILC	Deliver the dispatched power from one MG to the other MG
D.G.	Output the dispatched power (minimized as best as possible) with droop control

3.1.2 Mode 2 : SOC limit of $BESS_{DC}$ reached

During the operation of hybrid AC/DC MG in mode 1, BESS in AC or DC MG cannot control its grid voltage anymore if SOC of BESS ($\mathbf{SOC_{BESS_{DC}}}$ and $\mathbf{SOC_{BESS_{AC}}}$) reaches its own limitation (Max. or Min.). Mode 2 is the operating state when $\mathbf{SOC_{BESS_{DC}}}$ reaches its limitation. As seen in Fig. 3.1, mode 1 is changed into mode 2 when a high level operator detects the reaching of $\mathbf{SOC_{BESS_{DC}}}$ limitation.

As a result, in mode 2, $\mathbf{BESS_{DC}}$ is operated to make no output power ($P_{BESS_{DC}} = \mathbf{0}$) instead of controlling V_{DC} in mode 1 until a system operator dispatches new output value of $\mathbf{BESS_{DC}}$. According to this dispatched value, $\mathbf{BESS_{DC}}$ will be charged or discharged, which is going to occur in mode 5. In this situation, ILC carries out the role of maintaining V_{DC} unlike the role of dispatched power delivery in mode 1 between AC MG and DC MG. In case of AC MG, $\mathbf{BESS_{AC}}$ still controls V_{AC}/f_{AC} and diesel generators produces the dispatched amount of power at its operating point with droop control like as the case of mode 1.

Eq. (3.1) and (3.2) are also valid in mode 2. Only changes from mode1 to mode 2 in the equations are that $P_{BESS_{DC}}$ sets to 0 and $P_{ILC_{Trans}}$ is not the constant dispatched power but a varying power transfer between MGs corresponding to the energy unbalance in DC

MG to maintain V_{DC}. Table 3.3 summarizes the roles of the controllable units in mode 2.

Table 3.3 Controllable units and their roles in Mode 2

Items / Units	**Roles in Mode 2**
$BESS_{DC}$	No power output ($P_{BESS_{DC}} = 0$)
$BESS_{AC}$	Form the rated V_{AC}/f_{AC}
ILC	Maintain the rated V_{DC}
D.G.	Output the dispatched power (minimized as best as possible) with droop control

3.1.3 Mode 3 : SOC limit of $BESS_{AC}$ reached

In mode 3, hybrid AC/DC MG behaves very similarly to the case of mode 2 only except that ILC maintains f_{AC} , not V_{DC}. When $SOC_{BESS_{AC}}$ reaches its limitation and it is detected by a high level system operator, mode 1 is switched into mode 3 as shown in Fig. 3.1.

Contrary to the zero output power of $BESS_{DC}$ in mode 1, $BESS_{AC}$ is set to make no power output ($P_{BESS_{AC}} = 0$) in mode 2. Now that $BESS_{AC}$ is not able to form V_{AC}/f_{AC} any longer, ILC becomes in charge of maintaining the rated value of f_{AC}. But, diesel generators still behaves identical to the operation of mode 1 & 2 because there is no dramatic change of f_{AC} (maintained by ILC). On the other hand, in DC MG, $\mathbf{BESS_{DC}}$ forms the rated value of V_{DC} even if there are variations of RES generation outputs or loads.

In Eq. (3.1) and (3.2), $P_{BESS_{AC}}$ becomes zero and $P_{ILC_{Trans}}$ has a varying transfer power value according to the MG's energy balance. Table 3.4 summarizes the roles of the controllable units in mode 3.

Table 3.4 Controllable units and their roles in Mode 3

Items / Units	**Roles in Mode 3**
$\mathbf{BESS_{DC}}$	Form the rated V_{DC}
$\mathbf{BESS_{AC}}$	No power output ($P_{BESS_{AC}} = 0$)
ILC	Maintain the rated f_{AC}
D.G.	Output the dispatched power (minimized as best as possible) with droop control

3.1.4 Mode 4 : SOC limit of $\mathrm{BESS_{AC\&DC}}$ reached

Mode 4 can be reached from mode 2, mode 3 and mode 5. The transition from mode 2 to mode 4 occurs when $\mathbf{SOC_{BESS_{AC}}}$ reaches its limit under the mode 2 operation and the transition from mode 3 to mode 4 occurs when $\mathbf{SOC_{BESS_{DC}}}$ reaches its limit under the mode 3 operation. Transition from mode 5 to mode 4 occurs only when the one of BESS needs to be dispatched for charging/discharging while the other BESS is already being charged/discharged. All of three cases indicate that no BESS among two cannot participate in the control of system voltage in MGs. Because two BESSs in mode

4 cannot actively react to the variation of generations and loads, their power outputs are fixed to be zero ($P_{BESS_{DC}} = 0$ and $P_{BESS_{AC}} = 0$, when transited directly from mode 2 or mode3) or one of two are fixed to make no power while the other one is being charged or discharged.

Therefore, the rest of controllable DGs except $\mathrm{BESS_{DC}}$ and $\mathrm{BESS_{AC}}$ among four units in hybrid AC/DC MG has to be responsible for maintaining V_{DC} and V_{AC}/f_{AC} at the rated system voltage value. As there is no controllable DG other than $\mathrm{BESS_{DC}}$ in DC MG and there should be at least one controllable source in one MG to be able to keep the nominal grid voltage, ILC must be the one that can maintain V_{DC}. Meanwhile, AC MG has only diesel generators to form V_{AC}/f_{AC} in this mode. As diesel generators are being operated as a function of grid-supported grid forming (GSGfm) with droop control, there will be slight frequency deviation from the rated value based on the droop coefficient and the amount of diesel-generated power variation from its existing operating point.

In Eq. (3.1) and (3.2), both $P_{BESS_{DC}}$ and $P_{BESS_{AC}}$ becomes zero or the dispatched output and $P_{ILC_{Trans}}$ becomes the varying power output of ILC to maintain V_{DC} similar to the situation of mode 2. Table 3.5 shows the summarized roles of the controllable units in case of mode 4.

Table 3.5 Controllable units and their roles in Mode 4

Items / Units	**Roles in Mode 4**
$\mathrm{BESS_{DC}}$	No power output ($P_{BESS_{DC}}$ = 0) or Dispatched previously

$BESS_{AC}$	No power output ($P_{BESS_{AC}} = 0$) or Dispatched previously
ILC	Maintain the rated V_{DC}
D.G.	Form the rated V_{AC}/f_{AC} with small variation according to droop characteristic

3.1.5 Mode 5 : BESS output dispatch (Charging or discharging)

As the last mode type in normal cases, mode 5 is the stage for allocating the proper output value to BESS for charging or discharging batteries in AC MG and DC MG. Timing of switching to mode 5 from mode 2,3 and 4 as shown in Fig. 3.1 and the dispatched value of each BESS are decided by a high level operator considering the amounts of generation and loads in each MG on the whole. After a certain period of charging or discharging process of both or one of $\mathbf{BESS_{DC}}$ and $\mathbf{BESS_{AC}}$, mode 5 can return to mode 1 or mode 2 & 3 when both or one of $\mathbf{SOC_{BESS_{DC}}}$ and $\mathbf{SOC_{BESS_{AC}}}$ arrive at the pre-defined SOC point where BESS can restart the voltage formation of the linked grid instead of the dispatched power output operation. Additionally, mode 5 can go back to mode 4 when one of two BESS which has been forming the grid voltage reaches its SOC limit in the middle of charging or discharging the rest of BESS.

All the other operations of controllable units in hybrid AC/DC MG are equal to the previous mode operation before switching to mode 5 only except the fact that $P_{BESS_{DC}}$ or $P_{BESS_{AC}}$ becomes the specific non-zero power output which can mean charging (−) or discharging (+) of BESS. So, the roles of the controllable units in mode 5 will be described as one of Table 3.3 or 3.4 or 3.5 depending on the former control mode with the intended modification of BESS output values($P_{BESS_{DC}}$ and $P_{BESS_{AC}}$) . Eq. (3.1) and (3.2) are also true in mode 5.

3.2 Contingency operation

3.2.1 Mode 6 : Grid separation

Every case of the previous section operates its components in the form of hybrid AC/DC MG. However, some circumstances such as excessive amount of generation from RESs beyond the total grid capacity of energy storage which can cause overvoltage problem of the grid or maintenance issues related to new equipment installation or replacement of worn-out materials which have to accompany the blackout of AC MG or DC MG bring about the separation of hybrid AC/DC MG into two individual MG. When hybrid AC/DC MG has to be divided into electrically independent AC MG and DC MG without a type of power flow between MGs for any reason, it is called as the contingency case of hybrid AC/DC MG.

In these cases, ILC should become inactive (OFF) to disconnect two MGs. And, $\mathbf{BESS_{DC}}$ and $\mathbf{BESS_{AC}}$ would be in charge of controlling the rated grid voltage, V_{DC} and V_{AC}/f_{AC}, respectively. Diesel generators in AC MG are also going to be operated in droop mode providing the dispatched power output corresponding to its operating point. When there is a trip of RES component such as PV and WT or sudden increase of load in AC MG, diesel generators have to participate more in keeping supply and demand balance of AC MG compared to hybrid AC/DC MG case because there could not be any power delivery from DC MG to AC MG through ILC. DC MG will also have more trouble to maintain its grid voltage when

$\mathrm{BESS_{DC}}$ reaches its limitations. Thus, these results in the increase of fuel cost used for operating diesel generators and weakening the reliability of each MG in case of the generation and load variation.

On the other hand, as it is not avoidable to operate the whole system in a contingency case under some conditions, the normal operation of individual MG should be guaranteed. Therefore, the normality of individual operation of each MG will be shown and verified through the simulation in chapter 4. Additionally, mode 6 can be reached from any previous mode belonging to normal cases of the previous section from mode 1 to mode 5 because contingency cases can occur in every normal control mode.

3.2.2 Mode 7 : Ready for re-connection

Mode 7 is indicating the case that is ready to connect AC MG and DC MG to form hybrid AC/DC MG. In mode 6, each MG should be recovered from the contingency situation like excessive generation, grid faults and other maintenance works. In the connection process of two AC/DC MGs, the phase angle difference of each MG's system voltage does not have to be considered unlike the connection of two AC MGs because it is the combination of AC MG and DC MG. Only concerning point in the process from mode 7 to mode 1 is the voltage difference between grid voltage of DC MG and the DC terminal voltage of ILC because the gap of two voltage values can cause unexpected in-rush current of the system.

Chapter 4. Simulation Results

Chapter 4 shows the simulation results of hybrid AC/DC MG in Geocha-island based on the control modes classified in chapter 3 through Matlab/Simulink. The goal of this chapter verifies the seamless operation of the hybrid MG model suggested in this thesis by demonstrating the mode transitions for different operation cases. Each case will be described in detail with graphs obtained from simulation results in the next sections. In the simulation, all of elements of hybrid AC/DC MG in Geocha-island are modeled in the same way as explained in chapter 2 only except that the load values in AC MG are increased by about 10% in order to reflect possible load variations in the future and guarantee the effectiveness of the simulation results more reliably.

4.1 Normal cases

As explained in chapter 3, the form of hybrid AC/DC MG would be maintained in cases of normal operation. $BESS_{DC}$ charging, $BESS_{AC}$ charging and $BESS_{DC\&AC}$ charging are only four cases that can occur in the situation of normal operation according to the state flow shown in Fig. 3.1.

It is assumed that hybrid AC/DC MG is being operated in mode 1 in the beginning of every case. In other words, $BESS_{DC}$ and $BESS_{AC}$ control V_{DC} and V_{AC}/f_{AC} while ILC transfers a certain amount of dispatched power from one to the other as a start. And, then, the control mode of hybrid AC/DC MG starts to be changed into different mode according to the control strategy defined in chapter 3. The key indicators to make mode change decisions are SOC of BESSs in AC MG and DC MG. Initial SOC values of BESSs are set arbitrarily to trigger mode change as scheduled at the limitation conditions which are defined as 10% as a minimum level and 90% as a maximum level. Table 4.1 provides the initial SOC settings of $BESS_{DC}$ and $BESS_{AC}$ for four normal simulation cases.

Table 4.1 Initial SOC values for simulation cases

Case types	SOC of $BESS_{DC}$	SOC of $BESS_{AC}$
Case 1 ($BESS_{DC}$ discharging)	90.325 %	60 %
Case 2 ($BESS_{AC}$ charging)	60 %	13 %
Case 3 (Case 1 to Case 2)	90.325 %	13 %
Case 4 (Case 2 to Case 1)	90.325 %	13 %

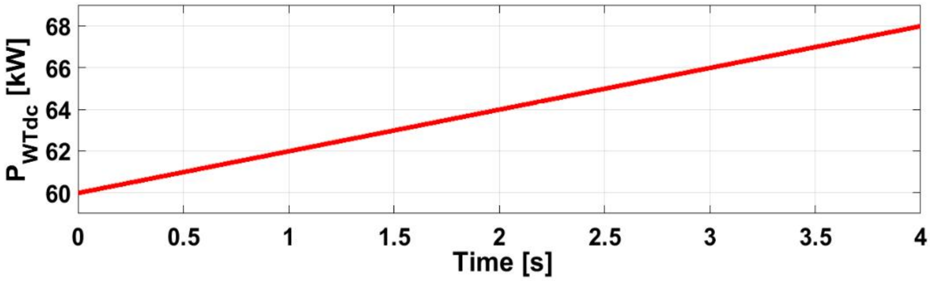
It is also assumed that the generation outputs from RES (WT and PV) appear in the similar manner for all cases as stated below and Fig. 4.1 (a) ~ (d) shows the graphs of active power output from RES units of DC MG and AC MG in case of mode 1 as an example.

$P_{WT_{DC}}$: Increase linearly from 60kW to 80kW for 10 seconds, then, decrease linearly to 60 kW for 10 seconds and repeating the same pattern

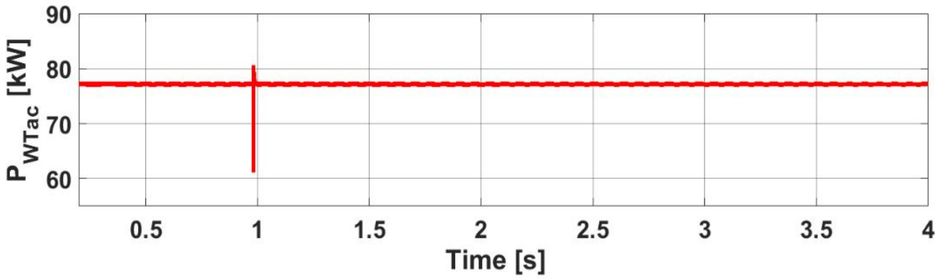
$P_{WT_{AC}}$: Generating about 80% (≒ 80kW) of its rated power

$P_{PV_{DC}}$: Generating about 75% (≒ 150kW) of its rated power

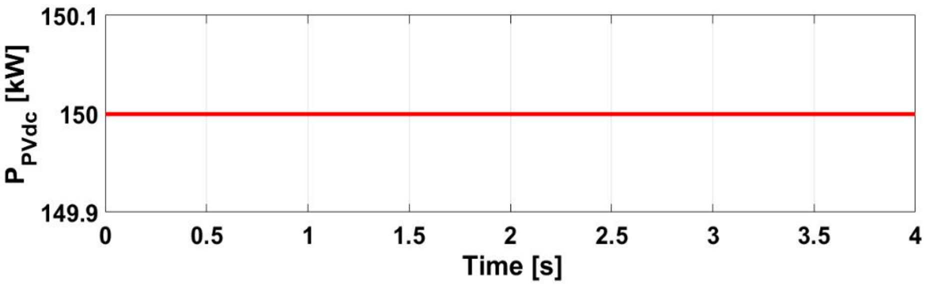
$P_{PV_{AC}}$: Generating about 80% (≒ 80kW) of its rated power



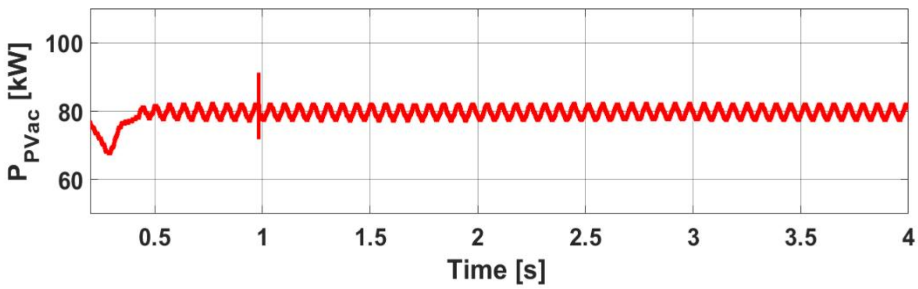
(a) Active power output from WT in DC MG



(b) Active power output from WT in AC MG



(c) Active power output from PV in DC MG



(d) Active power output from PV in AC MG

Fig. 4.1 Generation aspects from WT and PV in mode 1 operation

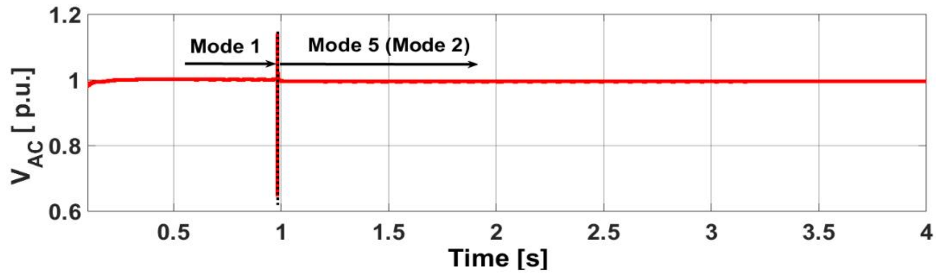
4.1.1 Case 1 : $BESS_{DC}$ discharging

In this case, hybrid AC/DC MG starts its operation in mode 1 at 0 s. After 0.95s, it is assumed that a system operator decides to discharge $BESS_{DC}$ because its SOC almost arrives to the high limitation (90% as a max). At this time, the system operator changes the control purpose of $BESS_{DC}$ from V_{DC} control to constant P output. And, ILC also switches its role from constant P transfer to maintaining V_{DC} at 0.98s. As the duration of zero output from $BESS_{DC}$ is assumed to be very short (almost zero) by the plan of the operator, the control mode can be seen as being changed into mode 5 from mode 1 directly. The whole operation schedule of the controllable sources according to the case scenario is summarized in table 4.2 and major simulation results of hybrid AC/DC MG operated based on the given schedule are shown in Fig. 4.2.

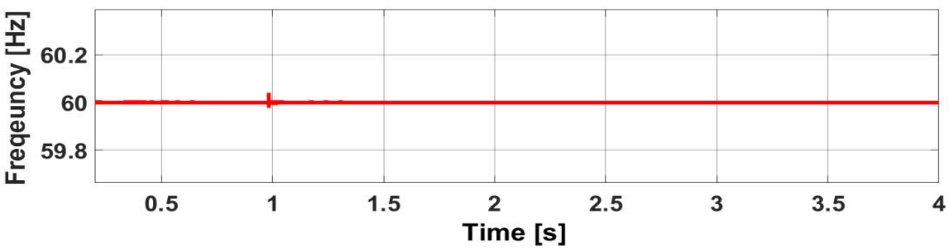
Table 4.2 Operation schedule of Case 1($BESS_{DC}$ discharging)

<table>
<tr><th rowspan="2">Mode</th><th rowspan="2">Time (s)</th><th colspan="4">Control function of controllable sources</th></tr>
<tr><th>$BESS_{DC}$</th><th>ILC</th><th>$BESS_{AC}$</th><th>D.G.</th></tr>
<tr><td>1</td><td>0 ~ 0.95</td><td>Form V_{DC}</td><td rowspan="2">Const. P Transfer (120kW)</td><td rowspan="3">Form V_{AC}/f_{AC}</td><td rowspan="3">Droop control</td></tr>
<tr><td rowspan="2">5(2)</td><td>0.95 ~ 0.98</td><td rowspan="2">Const. P (10kW)</td></tr>
<tr><td>0.98 ~ 4</td><td>Maintain V_{DC}</td></tr>
</table>

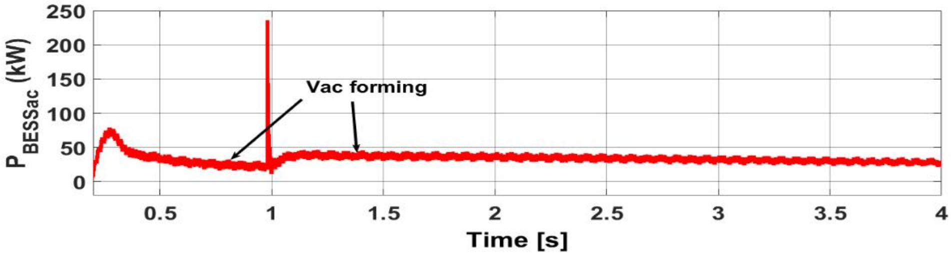
As seen in Fig 4.2 (a) and (f), system voltages of AC MG and DC MG (V_{AC} and V_{DC}) keeps stable only with small transition (within 0.1 p.u.) when control mode is changed. Frequency of AC MG, f_{AC}, is also kept in nearly constant value, 60 Hz seen in Fig 4.2 (b). V_{DC} is



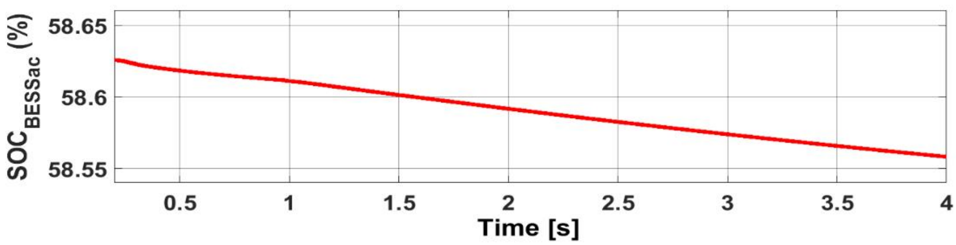
(a) System voltage of AC MG in p.u.



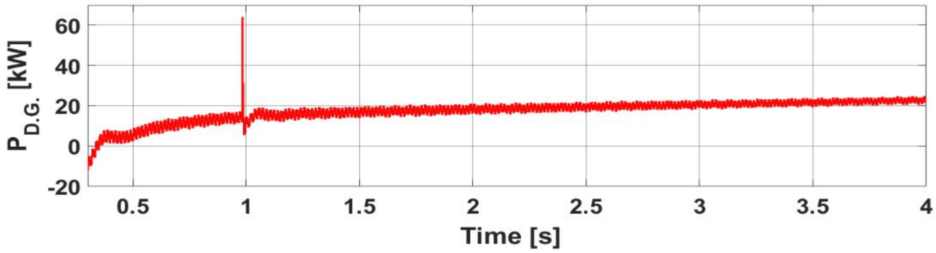
(b) Grid frequency of AC MG



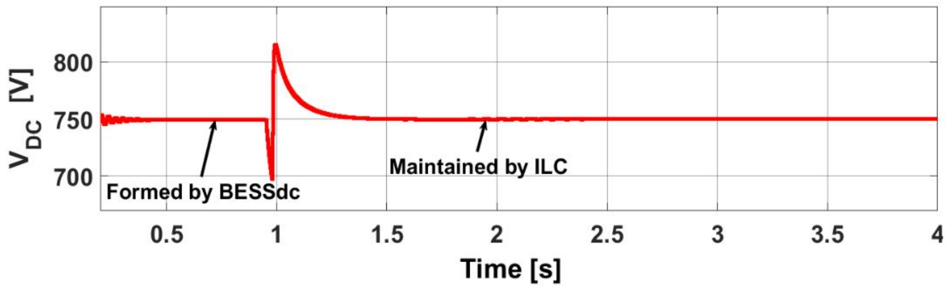
(c) Active power output of BESS in AC MG



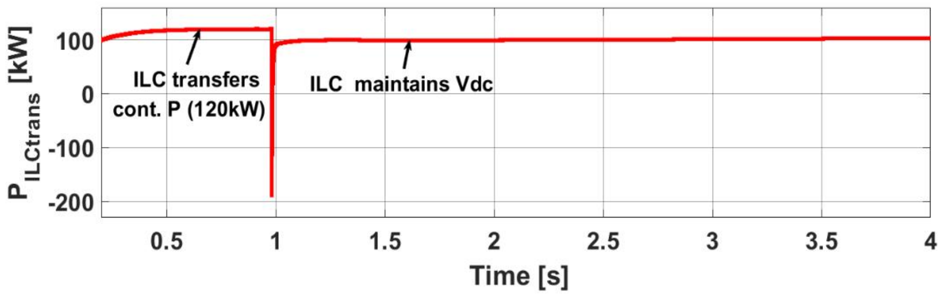
(d) SOC of BESS in AC MG



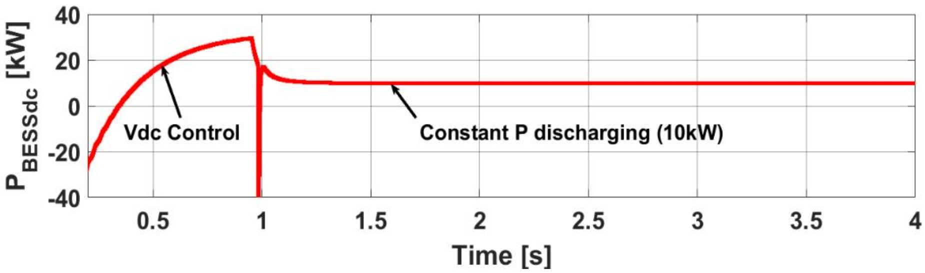
(e) Total active power output from diesel generators in AC MG



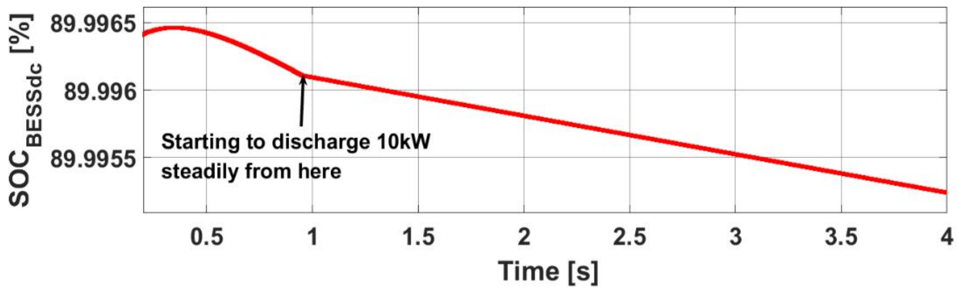
(f) System voltage of DC MG



(g) Transferred active power through ILC



(h) Active power output of BESS in DC MG



(i) SOC of BESS in DC MG

Fig. 4.2 Simulation results of hybrid AC/DC MG in case 1 : (a)~(e) belongs to AC MG and (f)~(i) to DC MG

controlled by $BESS_{DC}$ before 0.95s and after that, ILC maintains its rated DC grid voltage by reducing the amount of active power transferred from DC MG to AC MG as seen in Fig. 4.2 (g). $BESS_{AC}$ keep adjusting its output power to form V_{AC}/f_{AC} while $BESS_{DC}$ discharges constant power (10kW) after the mode change as shown in Fig. 4.2 (c) and (h). SOC of $BESS_{AC}$ keeps decreasing as seen in Fig 4.2 (d) because it provides its stored electric energy to the linked MGs to control V_{AC}/f_{AC} and SOC of $BESS_{DC}$ is also linearly decreasing since the mode change at 0.95s like Fig 4.2 (i). Fig 4.2 (e) shows the gradually increasing power output form diesel generators in AC MG.

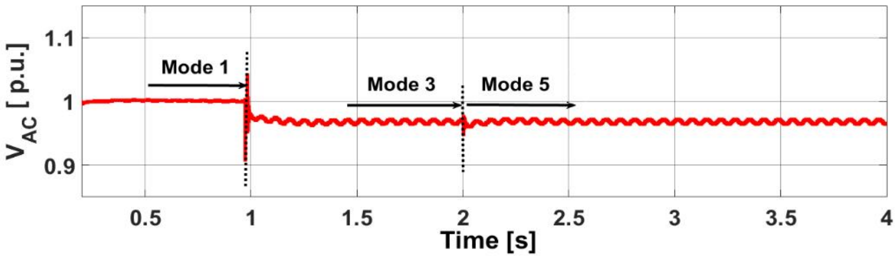
4.1.2 Case 2 : $BESS_{AC}$ charging

Case 2 also starts its operation at mode 1. SOC value of $BESS_{AC}$ sets at 13% initially in this case. As described in table 4.3, $BESS_{AC}$ stops supplying or absorbing any active power when SOC_{BESSac} get to the about low limit (10%) at 0.97s. ILC also changes its control from transferring constant power to maintaining f_{AC} at 0.98s, Finally,

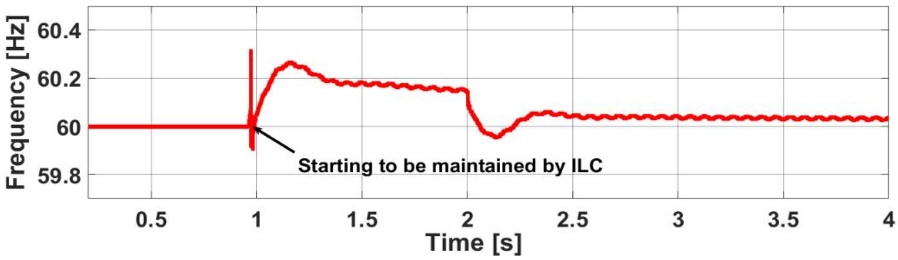
$BESS_{AC}$ starts to absorb active power(25kW) for charging at 2 s.

Table 4.3 Operation schedule of Case 2($BESS_{AC}$ charging)

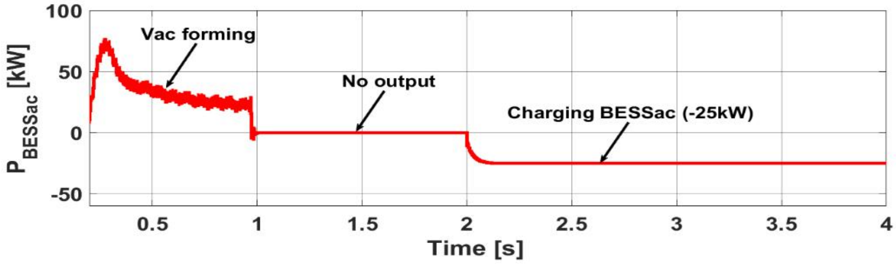
Mode	Time (s)	Control function of controllable sources			
		$BESS_{DC}$	ILC	$BESS_{AC}$	D.G.
1	0 ~ 0.97	Form V_{DC}	Const. P Transfer (120kW)	Form V_{AC}/f_{AC}	Droop control
3	0.97 ~ 0.98			Const. P (Zero)	
	0.98 ~ 2		Maintain f_{AC}		
5	2 ~ 4			Const. P (-25kW)	



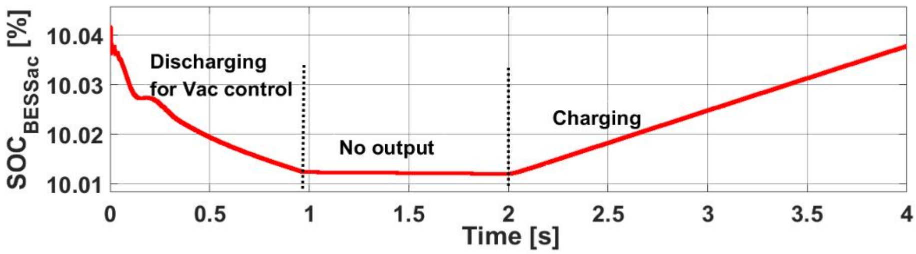
(a) System voltage of AC MG in p.u.



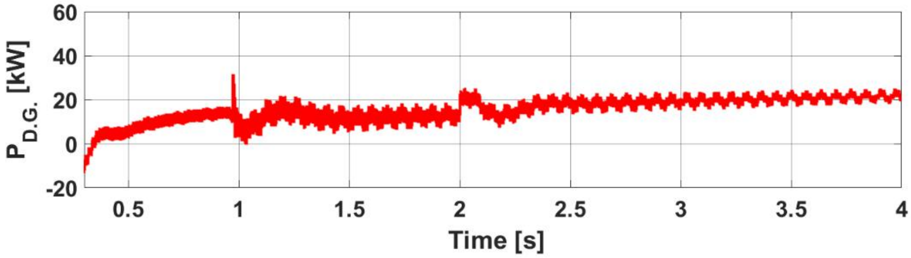
(b) Grid frequency of AC MG



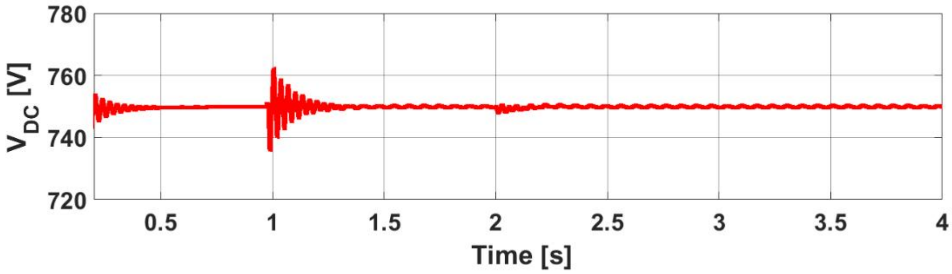
(c) Active power output of BESS in AC MG



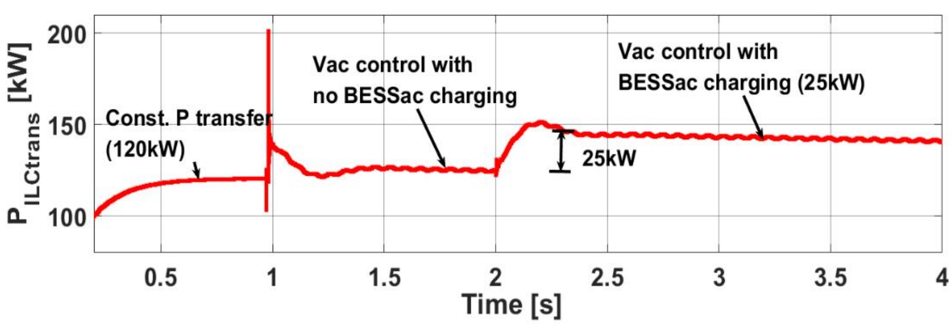
(d) SOC of BESS in AC MG



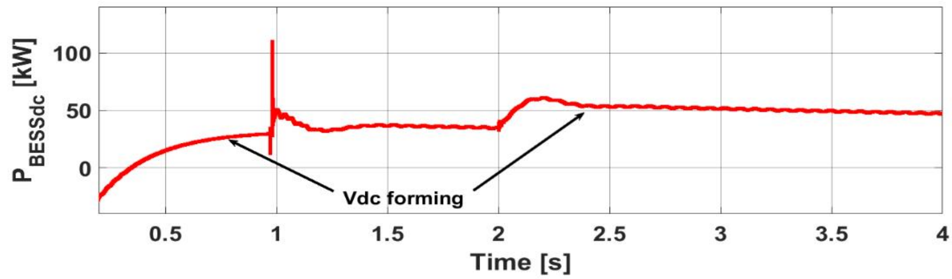
(e) Total active power output from diesel generators in AC MG



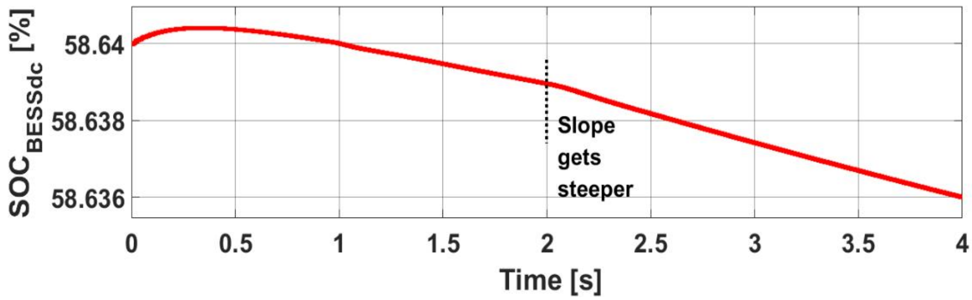
(f) System voltage of DC MG



(g) Transferred active power through ILC



(h) Active power output of BESS in DC MG



(i) SOC of BESS in DC MG

Fig. 4.3 Simulation results of hybrid AC/DC MG in case 2 : (a)~(e) belongs to AC MG and (f)~(i) to DC MG

Fig 4.3 (a)~(i) shows the overall characteristics of hybrid AC/DC MG in the case of $BESS_{AC}$ charging operation. V_{AC} and V_{DC} are satisfactorily controlled to the rated values when mode changes occur as seen in Fig 4.3 (a) and (f). There is more transient variation on V_{AC} compared to case 1 because V_{AC} is not exactly controlled anymore by voltage forming source. Frequency of AC MG, f_{AC} which is maintained by ILC since 0.98s, is also disturbed but remains within tolerable error range (+/− 0.3Hz) from the fundamental frequency like Fig 4.3(b). ILC starts to increase power transfer to maintain f_{AC} from 0.98s and increase more about 25kW which is similar to the amount of power supplied to $BESS_{AC}$ at 2s as seen in Fig 4.3 (g). In Fig 4.3 (c), active power output of $BESS_{AC}$

clearly shows the well–functioning control scheme of BESS in AC MG. Active power output of $BESS_{DC}$ in Fig 4.3 (h) looks very similar to that of ILC because most of output increase from ILC comes from $BESS_{DC}$. Fig 4.3 (d) and (i) shows the SOC variation of $BESS_{DC\&AC}$ and they are perfectly matched with the active power output change of BESSs shown in (c) and (h). In Fig 4.3 (e), the total active power output from diesel generators in AC MG seems to be increased very slowly because diesel generators take tens of seconds to get to the level of the rated output, which is set to 50kW for each of D.G. in the simulation, at its operating conditions.

4.1.3 Case 3 : Case1 ($BESS_{DC}$ discharging) to Case2 ($BESS_{AC}$ charging)

Case 3 and case 4 shows the continuous operation of BESSDC discharging (case1) and $BESS_{AC}$ charging(case2). Initial SOC values of $BESS_{DC}$ and $BESS_{AC}$ are set to be near the max or min limitation. (90.325% for $BESS_{DC}$ and 13% for $BESS_{AC}$). In case 3, it is assumed that $BESS_{DC}$ discharging process occurs first followed by $BESS_{AC}$ charging. Specific operation schedule of controllable sources to realize the performance of hybrid AC/DC MG intended in case 3 is given in Table 4.4.

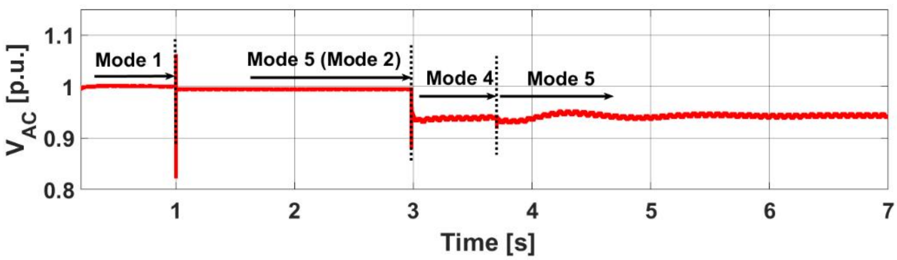
Table 4.4 Operation schedule of Case 3 (case 1 to case 2)

Mode	**Time (s)**	**Control function of controllable sources**			
		$BESS_{DC}$	**ILC**	**$BESS_{AC}$**	**D.G.**
1	0 ~ 1	Form V_{DC}	Const. P Transfer	Form V_{AC}/f_{AC}	Droop control
5(2)	1 ~ 2.98	Const. P (10kW)	Maintain V_{DC}		

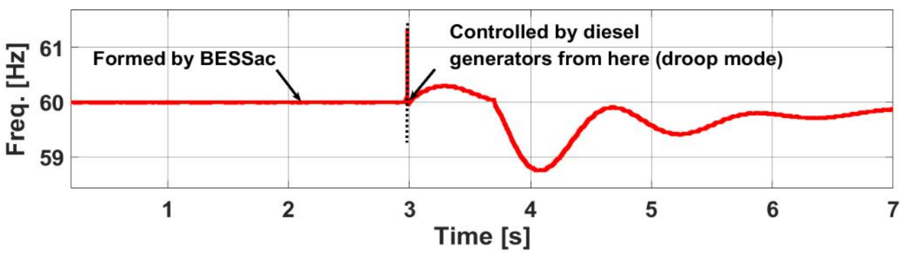
4	2.98 ~ 3.7			Const. P (Zero)	
5	3.7 ~ 7			Const. P (-25kW)	

As seen in Fig. 4.4 (a), the whole system changes its control mode based on the following order : mode 1 → mode (2) → mode 5 → mode 4 → mode 5. The first three mode transitions from mode 1 to (2) to 5 shows almost same characteristics of the case 1 shown before. Mode 2 also looks omitted here because non−zero output dispatch is given to $BESS_{DC}$ right on the moment of mode transition just like case 1.

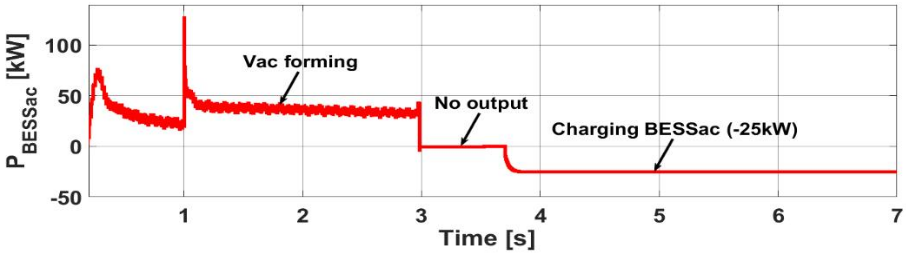
But, after 2.98s , when $BESS_{AC}$ is also assumed to reach its minimum SOC limit, $BESS_{AC}$ is no longer able to form V_{AC}/f_{AC}. Instead of $BESS_{AC}$ which just starts to make constant active power output, diesel generators operating in droop control mode should be responsible for the formation of V_{AC}/f_{AC} as seen in Fig 4.4 (a) and (b). Active power output and SOC of $BESS_{AC}$ in Fig 4.4 (c) and (d) almost



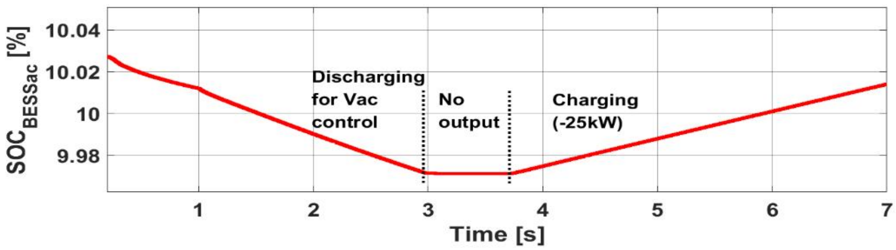
(a) System voltage of AC MG in p.u.



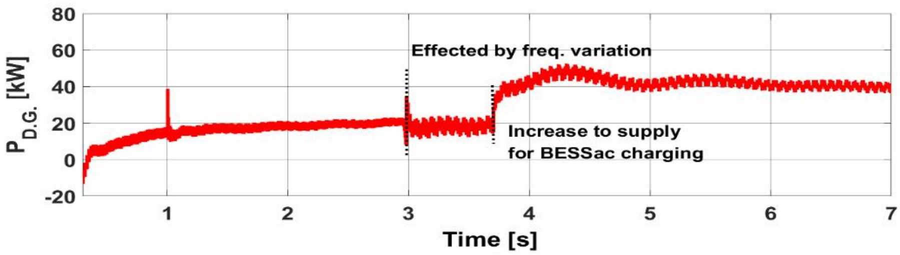
(b) Grid frequency of AC MG



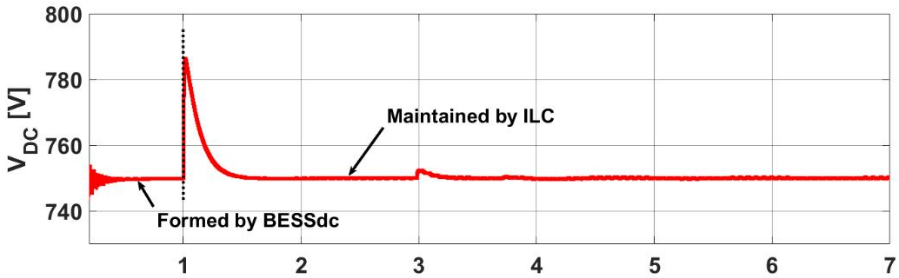
(c) Active power output of BESS in AC MG



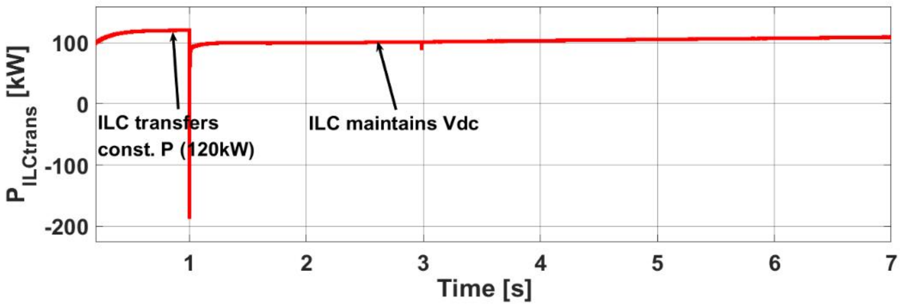
(d) SOC of BESS in AC MG



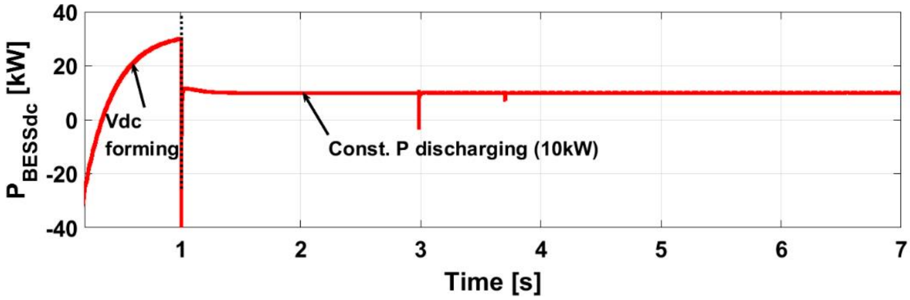
(e) Total active power output from diesel generators in AC MG



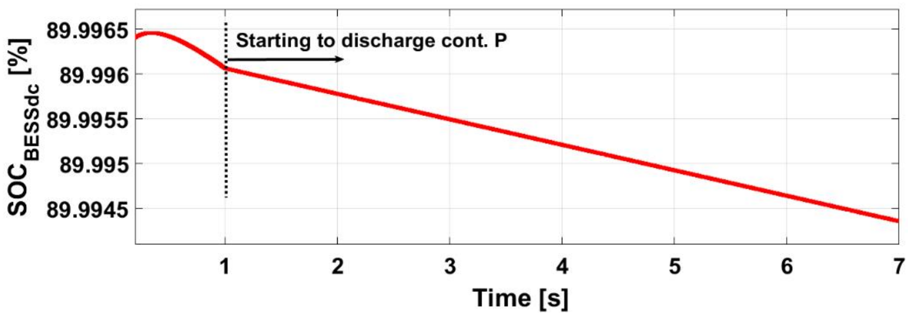
(f) System voltage of DC MG



(g) Transferred active power through ILC



(h) Active power output of BESS in DC MG



(i) SOC of BESS in DC MG

Fig. 4.4 Simulation results of hybrid AC/DC MG in case 3 : (a)~(e) belongs to AC MG and (f)~(i) to DC MG

looks same with Fig 4.3(c) and (d)of case 2. At 3.7s , diesel generators increase its active power output by about 25kW to supply power required to charge $BESS_{AC}$ like Fig 4.4 (e).

In DC MG, Fig 4.4 (f) shows the variation of V_{DC}. Except the transient fluctuation at the moment of mode change at 1s, V_{DC} is maintained with little variation. Active power output from ILC and

$BESS_{DC}$ and SOC of $BESS_{DC}$ seen in Fig 4.4 (g), (h) and (i) show the procedure of maintaining V_{DC} and discharging $BESS_{DC}$ after 1s. They also look very similar to Fig 4.2 (g), (h) and (i) from case 1 because they are fundamentally going through the same procedures in DC MG.

4.1.4 Case 4 : case2($BESS_{AC}$ charging) to case1($BESS_{DC}$ discharging)

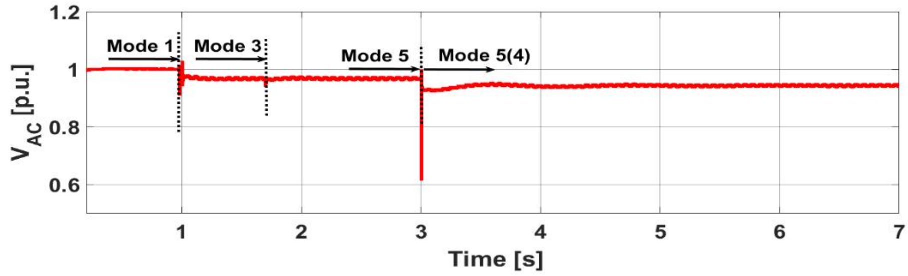
Case 4 has the same initial conditions of case 3. The only difference is the order of charging/discharging process. Unlike case 3, case 4 supposes that $BESS_{AC}$ starts its charging process at 0.98s including the period of zero-power output dispatch followed by $BESS_{DC}$ discharging process starting from 3 seconds. After 3s, $BESS_{DC}$ discharges constant active power to DC MG while ILC maintains V_{DC} and diesel generators forms V_{AC}/f_{AC} with droop characteristics. The whole procedure of operating controllable sources in case 4 is shown in table 4.4. The transition of control mode occurs based on the following order : mode 1 → mode 3 → mode 5 → mode (4) → mode 5.

Figures 4.5 (a) to (e) shows very similar performance from 0 s to 3 s with which seen in figure 4.3 (a) to (e) of case 2 because what is occurring during that period in AC MG is actually same with what in case 4 and case 2. But, after 3s, as ILC can no longer do the role of maintaining f_{AC}, AC grid's frequency formed by diesel generators and active power output from diesel generators show different aspects as seen in Fig 4.5 (b) and (e) compared to case 2. Most of these differences are coming from the characteristics of diesel generators' droop operation.

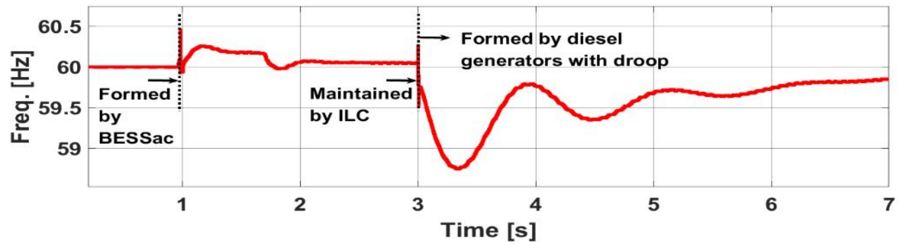
Table 4.5 Operation schedule of Case 4 (Case 2 to Case 1)

<table>
<tr><th rowspan="2">Mode</th><th rowspan="2">Time (s)</th><th colspan="4">Control function of controllable sources</th></tr>
<tr><th>$BESS_{DC}$</th><th>ILC</th><th>$BESS_{AC}$</th><th>D.G.</th></tr>
<tr><td>1</td><td>0 ~ 0.98</td><td rowspan="4">Form V_{DC}</td><td rowspan="2">Const. P Transfer (120kW)</td><td>Form V_{AC}/f_{AC}</td><td rowspan="5">Droop control</td></tr>
<tr><td rowspan="2">3</td><td>0.98 ~ 1</td><td rowspan="2">Const. P (Zero)</td></tr>
<tr><td>1 ~ 1.7</td><td rowspan="2">Maintain f_{AC}</td></tr>
<tr><td>5</td><td>1.7 ~ 3</td><td rowspan="2">Const. P (-25kW)</td></tr>
<tr><td>5(4)</td><td>3 ~ 7</td><td>Const. P (10kW)</td><td>Maintain V_{DC}</td></tr>
</table>

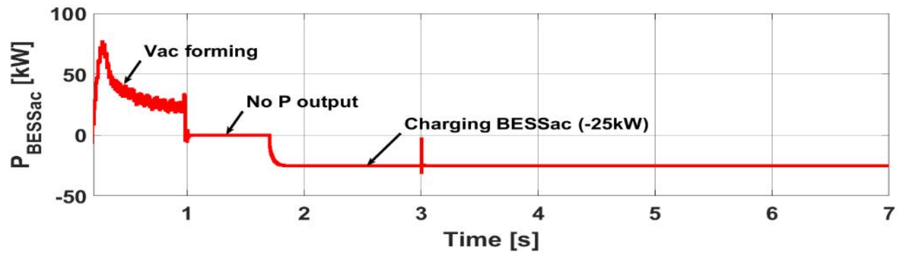
Meanwhile, simulation results of DC MG in case 4 appearing in Fig 4.5 (f) to (i) show the same performance from 0s to 3s with Fig 4.3 (f) to (i) of case 2 because of the same control procedures applied to both cases. However, after 3seconds, the role of controlling V_{DC} is given to ILC instead of $BESS_{DC}$ which starts to produce constant active power for discharging from that time. As a result, ILC maintains V_{DC} and active power output from $BESS_{DC}$ is fixed at 10kW while SOC of $BESS_{DC}$ keep constantly decreasing. Understandably, Fig 4.5 (f) to (i) after 3 seconds shows similar characteristics with Fig 4.2 (f) to (i) of case 1 after 1 seconds.



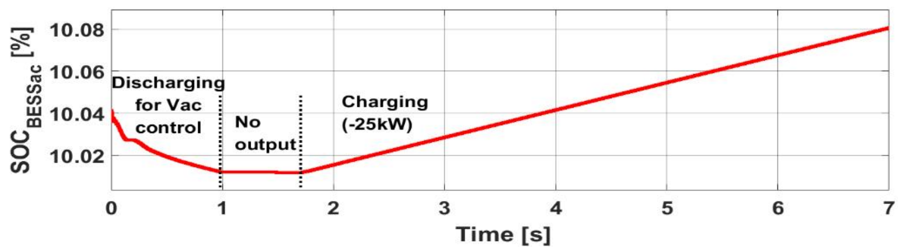
(a) System voltage of AC MG in p.u.



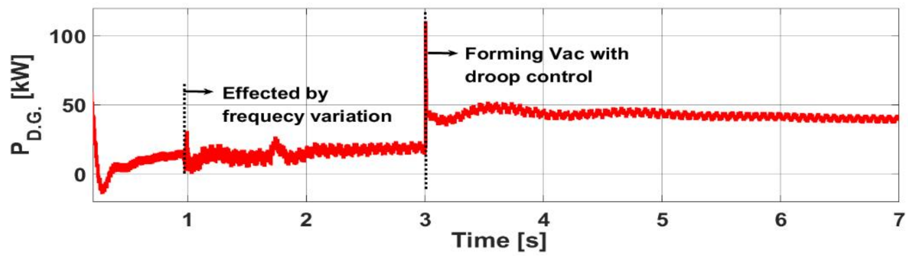
(b) Grid frequency of AC MG



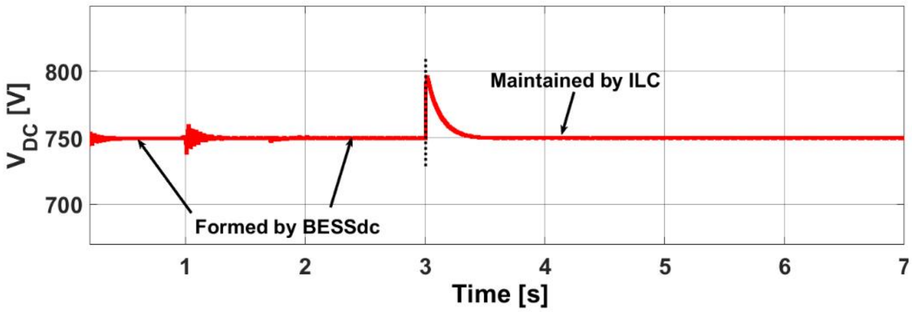
(c) Active power output of BESS in AC MG



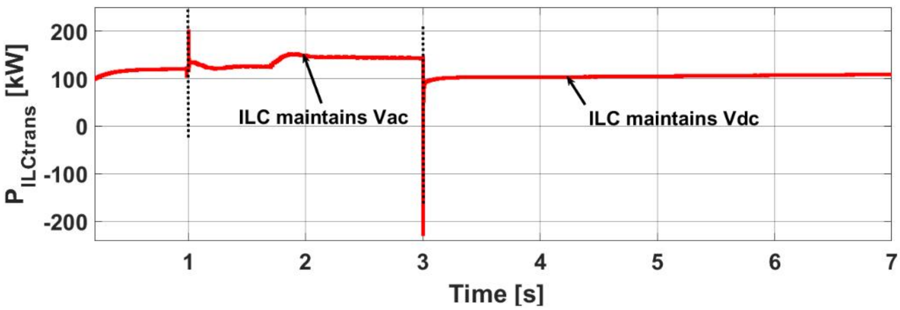
(d) SOC of BESS in AC MG



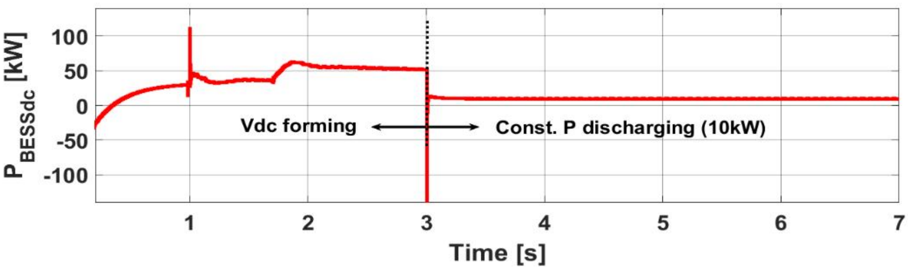
(e) Total active power output from diesel generators in AC MG



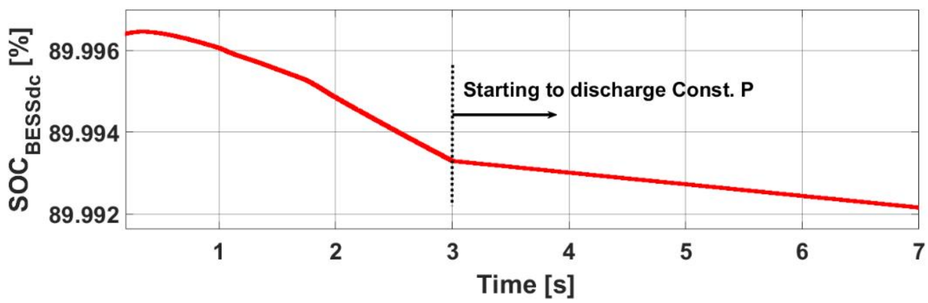
(f) System voltage of DC MG



(g) Transferred active power through ILC



(h) Active power output of BESS in DC MG



(i) SOC of BESS in DC MG

Fig. 4.5 Simulation results of hybrid AC/DC MG in case 4 : (a)~(e) belongs to AC MG and (f)~(i) to DC MG

4.2 Contingency cases

Hybrid AC/DC MG often needs to be divided into two separate MGs in case for maintenance work, grid fault occurrence and etc. These situations which require the separation of hybrid MG are called here as contingency cases.

4.2.1 Interlinking converter off

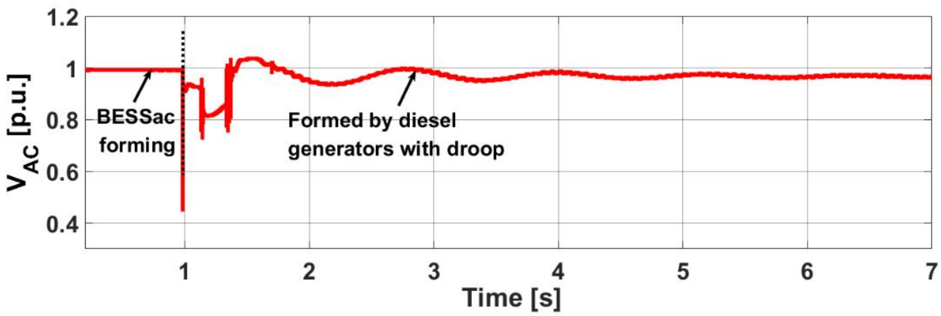
For whatever reasons, when ILC is not in operation meaning that there is no power transfer through ILC between AC MG and DC MG for any reason, it is the same case that involves the individual operation of two separated MGs.

If ILC cannot do any role to maintain V_{DC} or f_{AC}, the operation range of hybrid AC/DC MG would be very narrowed because each MG needs to have at least one controllable source which can form a grid voltage or frequency. For example, DC MG will lose its grid voltage, V_{DC}, control when $BESS_{DC}$ need to be charged/discharged. In case of AC MG, even though it has a set of diesel generators which can form grid voltage and frequency with droop operation, there would be significant frequency swing in the early stage of operation as diesel generators require tens of seconds to get to the point where they can generate enough amount of active power.

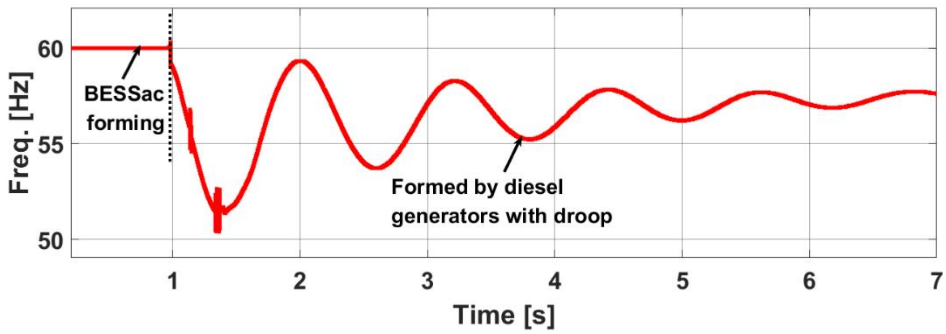
Fig 4.6 is the simulation results of case 4 without the interlinking converter operation. It is clearly shown that V_{DC} and f_{AC} are not able to be controlled properly within a tolerant error range as seen in Fig 4.6 (a) and (f). It is also expected that all the other cases from case 1 to case 4 will not show the performance as normal operation when the formation of hybrid AC/DC MG is no longer valid.

4.2.2 Re-connection

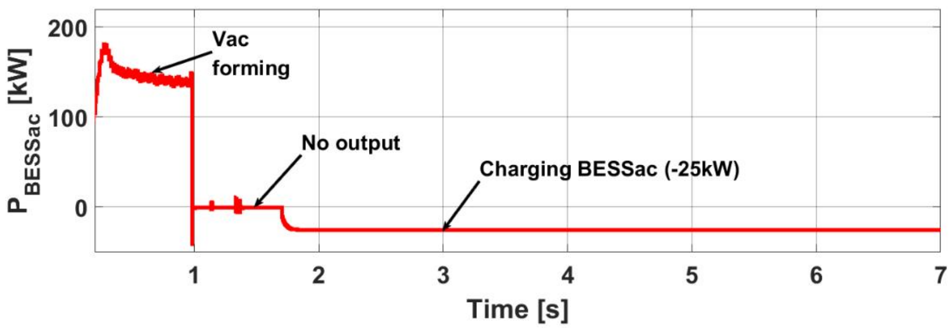
As explained in chapter 3, the reconnection process should be cautiously handled not to make in-rush current between MGs even though it does not have to consider issues related to phase angel difference, frequency deviation and etc. Details of connecting MGs after the recovery from contingency cases will be covered in other literatures.



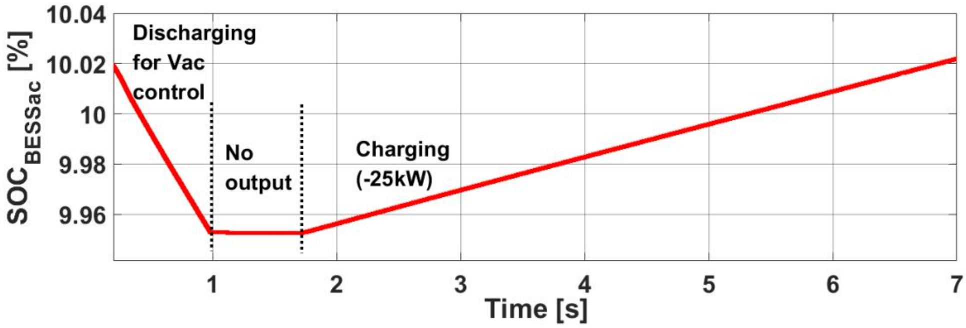
(a) System voltage of AC MG in p.u.



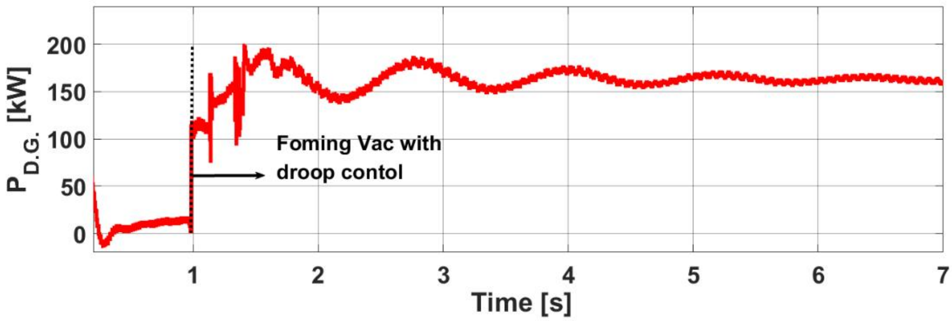
(b) Grid frequency of AC MG



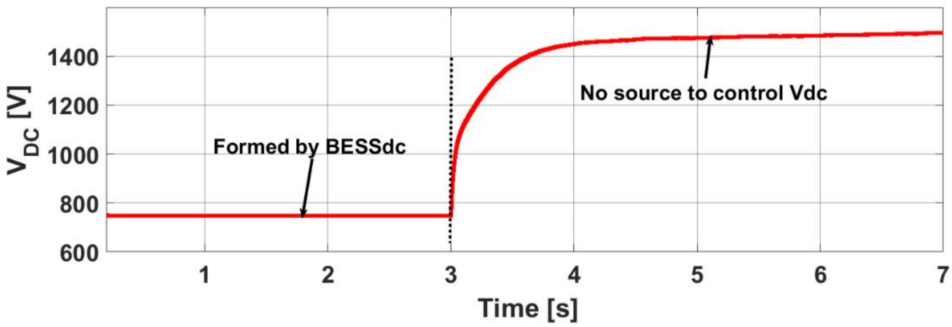
(c)　　Active power output of BESS in AC MG



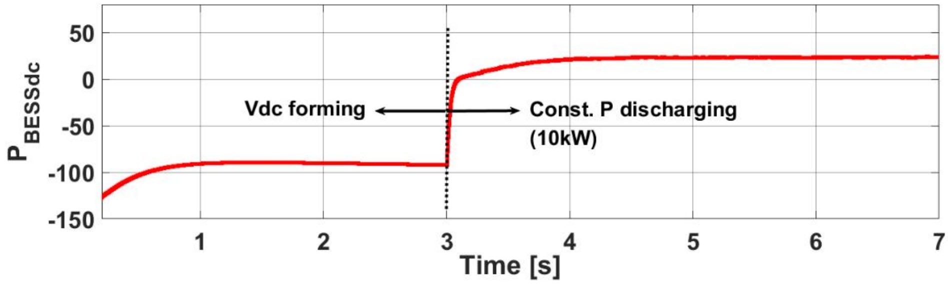
(d)　　SOC of BESS in AC MG



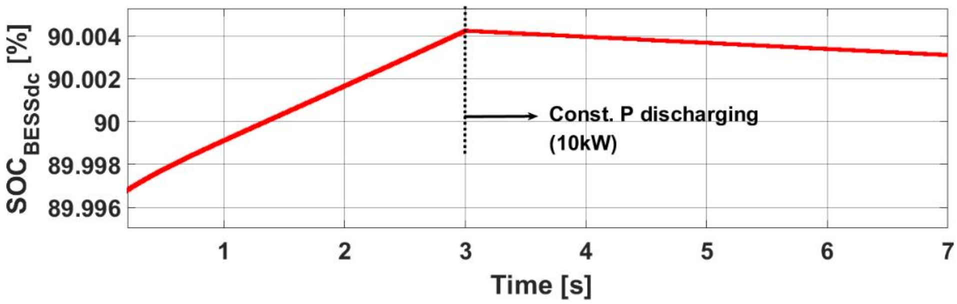
(e)　　Total active power output from diesel generators in AC MG



(f)　　System voltage of DC MG



(g)　　Active power output of BESS in DC MG



(h) SOC of BESS in DC MG

Fig. 4.6 Simulation results of hybrid AC/DC MG in case 4 when ILC is off : (a)~(e) belongs to AC MG and (f)~(h) to DC MG

Chapter 5. Conclusions and Further Studies

5.1 Conclusions

Hybrid AC/DC MG has been attracting lots of interest from researchers as a prominent form of MG that can maximize the potential benefits of the future power grid. Geocha-island , which is one island located in west-south part of Korea peninsula, can provide very good opportunity to be able to demonstrate the formation and operation of hybrid AC/DC MG with the smallest effort based on two existing AC MG and DC MG project that has already started to be operated or being constructed in the same island.

In this paper, the modeling of hybrid AC/DC MG is progressed by the integration of interlinking converter between AC MG and DC MG in Geocha-island. Based on the proposed modeling result of hybrid MG, the control strategy which can cover most of situations that are possible to happen in the middle of normal operation such as BESS charging/discharging and contingency occurrence is established. Finally, the suggested control strategy has been verified through the simulation proceeded on various case scenarios.

In conclusion, it is able to be successfully shown that hybrid AC/DC MG in Geocha-island can be implemented by the connection of the existing AC & DC MG using interlinking converter. And, when hybrid MG is operated based on proposed control strategy, the improved operation reliability can also be guaranteed by its simulation results when compared to the individual operation case of AC MG and DC MG.

5.2 Suggestions

In this dissertation, the connection of two MGs is carried out with the given design of previous projects. So, there is much room for the better design to improve hybrid MG performance and reliability because each design of MG does not fully reflect the configuration change brought by another MG project. Some of hardware and technical issues related to the present design of hybrid AC/DC MG will be briefly covered and the improvement measures will be suggested below for the purpose of upgrading the performance of hybrid AC/DC MG in Geocha−island.

Hardware designs

The capacity of interlinking converter designed in dc MG is 200kW which is similar to the capacity of one diesel generator in ac MG. It's not enough to cover the entire load in ac MG which can go up to over 300kW in the peak time in case of $BESS_{AC}$ charging and no generation of RES in AC MG. By that reason, it is suggested that the capacity rating of ILC be raised up to 300kW for the stable operation of hybrid MG and increase the normal operation range of the entire system.

Even if it is not shown in simulation results of chapter 4, V_{DC} can starts to destabilize and probably collapse when the transferred active power from DC MG to AC MG through interlinking gets over 0.8 p.u. of ILC rating(200kW). It is highly understandable if it is considered that the summation of total load in DC MG(about 130kW) and transferred power through ILC (160kW when 0.8p.u.) can be large enough compared to the summation of BESSDC output (Max 200kW) and the generation from WT and PV, which can affect the stability of V_{DC}. To solve this mater, the capacity increase of RESs in dc MG is highly required

There is also possibility of inefficiency caused by the same location of two WTs in dc MG and ac MG. The whole hybrid MG system can get vulnerable to the change of wind speed because the intermittent power characteristics of WTs would be severely amplified in this case. It is highly recommended that the location of WT in DC MG changed to the place apart from the existing WT in AC MG as far as territory condition allows

In DC MG, +/− 750 V lines are originally planned to be constructed as a bipolar type because it is more advantageous to widen the range of power supply and prepare for a contingency like a distribution line disconnection [18]. But, the bipolar type distribution design makes more sense only when it is constructed in overhead type. The original purpose of introducing a bipolar type distribution grid in DC MG wouldn't be achieved and the meaning of bipolar grid would be lost under the condition of underground line construction which is applied in this paper.

Droop control of interlinking converter

As a way of supporting the stability of hybrid AC/DC standalone MG, droop control method can be added to the function of interlinking converters. The principle and detail explanation of this method can be found in [11], [12] and [13]

5.3 Future works

There are several research fields that can improve the operation performance of hybrid AC/DC MG in Geocha−island. Here are some issues that can be addressed in the future research.

First of all, Hybrid AC/DC MG need to have high−level operator or system that can decide the timing of mode transition or set the dispatch value for BESS in AC MG and DC MG. To replace the role of system operator in the autonomous way, it is required to develop smart energy management system (EMS) specially optimized to operate hybrid MG. Secondly, the development of a certain type of control algorithm to be able to maintain SOC of BESS within the pre−defined range at any point of operation is also highly recommended. Reference [20] shows one method to be able to keep proper SOC of BESS while satisfying the purpose of MG control. Finally, in order to find more economic operation status of hybrid AC/DC MG, it is necessary to find an optimization algorithm that can let diesel generators run at an optimal operation point at which fuel cost to operate the entire hybrid MG could be minimized. As a result, developing the algorithm to set an optimal point of operation for diesel generators and other distributed generation sources is also another key research topic that is meaningful for the proper operation of hybrid AC/DC MG.

Bibliographies

[1] R. Lasseter, "Microgrids," in *Proc. IEEE Power Eng. Soc. Winter Meet.*, Jan. 2002, vol. 1, pp. 305–308

[2] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power Energy Mag.*, vol. 5, no. 4, pp. 78–94, Jul./Aug. 2007.

[3] B. Zhao, X. Zhang, J. Chen, C. Wang, and L. Guo, "Operation optimization of standalone microgrids considering lifetime characteristics of battery energy storage system," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 934–943, Oct. 2013.

[4] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," *IEEE Power Energy Mag.*, vol. 6, no. 3, pp. 54–65, May/Jun. 2008.

[5] T. Dragi ˇ cevi ´ c, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC microgrids—Part I: A review of control strategies and stabilization techniques," *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4876–4891, Jul. 2016.

[6] X. Liu, P. Wang, P. C. Loh, "A Hybrid AC/DC Microgrid and Its Coordination Control," *IEEE Trans. Smart Grid*, vol.2, no.2, pp.278– 286, June 2011.

[7] D. E. Olivares et al., "Trends in microgrid control," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, Jul. 2014.

[8] T. Dragicevic, J. Vasquez, J. Guerrero, and D. Skrlec, " Advanced LVDC electrical power architectures and microgrids: A step toward a new generation of power distribution networks.," *Electrification Magazine, IEEE*, vol. 2, no. 1, pp. 54–65, 2014.

[9] L. Xu and D. Chen, “Control and operation of a DC microgrid with variable generation and energy storage,” *IEEE Trans. Power Del.*, vol. 26, no. 4, pp. 2513–2522, Oct. 2011.

[10] T. Dragicevi ˇ c et al, “DC Microgrids – Part II: A Review of Power ´ Architectures, Applications, and Standardization Issues", *IEEE Trans. Power Electron.*, vol. 31, no. 5, pp. 3528–3549, May 2016.

[11] P. C. Loh, L. Ding, C. Yi Kang, and F. Blaabjerg, “Autonomous Operation of Hybrid Microgrid With AC and DC Subgrids,” *Power Electronics, IEEE Transactions on*, vol. 28, no. 5, pp. 2214–2223, 2013.

[12] N. Eghtedarpour and E. Farjah, “ Power control and management in a hybrid AC/DC microgrid,” *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1494–1505, May 2014.

[13] F. Nejabatkhah and Y. W. Li, "Overview of Power Management Strategies of Hybrid AC/DC Microgrid," *in IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 7072–7089, Dec. 2015.

[14] KEPCO Economy and Management Research Institute, “Domestic and overseas status of MGs research and policy trends” , *in KEMRI Power Economy Review*, vol. 49th, pp 7–10, Dec 21st, 2015.

[15] Y.-S. Kim, E.-S. Kim, and S.-I. Moon, “Frequency and voltage control strategy of standalone microgrids with high penetration of intermittent renewable generation systems,” *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 718–728, Jan. 2016.

[16] *Seoul National University – Recent news.* Available : https://www.snu.ac.kr/president/news?bm=v&bbsidx=12193

4&page=17
[17] Korea Electrical Engineering & Science Research Institute (KESRI), “Report on modeling of Microgrid in Geocha-island”, *Final project report*, Jul. 2016.
[18] H. Kakigano, Y. Miura, and T. Ise, “Low-voltage bipolar-type DC microgrid for super high quality distribution,” *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 3066-3075, 2010.
[19] L. Che, M. Shahidehpour, A. Alabdulwahab, and Y. Al-Turki, “Hierarchical coordination of a community microgrid with AC and DC microgrids,” *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 3042–3051, Nov. 2015.
[20] Y.-S. Kim, “A cooperative control method of active and reactive power for droop control-based standalone microgrids,” *Ph.d dissertation*, School of Electrical Engineering & Computer Science, Seoul National University, Feb. 2016.
[21] P. Kundur, *Power System Stability and Control*, New York : McGraw-Hill, 1994
[22] Yazdani, A.; Iravani, R. *Voltage-Sourced Converters in Power Systems*; John Wiley & Sons: Chichester, UK, 2010.
[23] M.A. Abdullah, “A review of maximum power point tracking algorithms for wind energy systems”, *Renewable and sustainable Energy Reviews*, 2012
[24] Blaabjerg, F.; Teodorescu, R.; Liserre, M.; Timbus, A.V., “Overview of control and grid synchronization for distributed power generation systems.” *IEEE Trans. Ind. Electron. 2006*, 53, 1398–1409.

Appendix A. Details of MG projects in Geocha-island

A.1 AC MG project

- Project Outline

과 제 명	도서지역 하이브리드형(풍력, 태양광) 마이크로그리드 시스템 기술개발 (R14DG01)
과제목표	하이브리드 마이크로그리드용 요소기술 개발 및 실증 (시스템 가동률 : >95%, 전압/주파수 유지율 : >99%, 전력공급단가 : 5% 감축)
주관기관	1세부 : ㈜해바람에너지(전남) / 2세부 : ㈜이엘티(광주)
참여기관	1세부 : 전력연, 전품연, 녹에연, 그린정보 / 2세부 : 전품연, 전남대
수행부서 / 책임자	전력연구원 에너지신산업연구소 선임 채우규
연구기간	2014.8 ~ 2017.07 (총 36개월)
과제성격	중장기 전략과제 / 정부과제 / 신수종창출형
총 연구비	86.7억 원 (현금 68.8억 원, 현물 17.9억 원), 전력연 : 24억 부담, 4억 사용(현금)
소요인력 (MM)	자체분 : 52.2 MM, 참여기관 : 469.8 MM

A.2 DC MG project

- Project Outline

과 제 명	저압 직류배전망 독립섬 실증 연구 (R15DA12)
과제목표	신재생에너지 연계 저압 직류배전망 설계 및 운영기술 개발 [전력전송 효율 향상 >10%, 전압유지율 >99%, SST 성능 > 13.2kV(95%)]
연구기간	2015.9 ~ 2018.08 (총 36개월)
과제성격	자체과제
총 연구비	366.6억 원 (현금 356.6억 원, 현물 10억 원)
소요인력 (MM)	1,110.3MM (자체분 : 248.4 MM, 참여기관 : 861.9 MM)

Appendix B. Site Images in Geocha-island(AC MG)

- Control center in West-Geocha

- Operation system in control center

- PV generation site in East-Geocha

- WT generation site in west-Geocha

- PCS of BESS in AC MG

- Li-battery of BESS in AC MG

- Emergency diesel generator of AC MG project in West-Geocha (not included in the modeling)

초　　록

실 계통에 기반한 소규모 하이브리드 AC/DC 독립형 마이크로그리드 모델링 및 제어전략 수립

하이브리드 AC/DC 독립형 마이크로그리드(MG) 는 소규모, 분산, 비집중화된 발전 방식 중심의 미래 차세대 전력망을 구현하는데 필수적인 MG의 주요형태로 발전할 것이 예상되는 한편, 국내 전남 서해안에 위치한 거차도에서는 2개의 다른 계통 형태의(AC/DC) MG 실증사업이 완료 또는 진행 중인 상태로, 이를 활용 향후 세계 최초의 하이브리드 AC/DC 독립형 MG 구축사업 추진을 위한 선행연구로써 본 연구를 진행하게 되었다.

거차도에 하이브리드 AC/DC MG 구현을 위한 첫 번째 과정으로서, 기존의 AC MG 및 DC MG 실증사업 내용을 바탕으로 모델링 작업을 진행하였다. 이 때, 두 개의 MG 물리적 접속점에 설치되어 적정한 양의 유효전력을 전달함으로써, DC MG의 계통전압 제어, AC MG의 계통주파수 제어, MG 간 일정 유효전력 전달의 역할을 구현할 수 있는 연계 컨버터의 제어모델을 새롭게 제안하였다.

다음으로, 앞에서 수행한 거차도 모델링 결과를 기반으로 하이브리드 AC/DC MG 제어전략을 수립하였다. 본 전략은 정상운영 상태에서의 5가지 제어모드, 비상운영 상태에서의 2가지 제어모드, 총 7가지 제어모드로 구성되어 계통 내 발생 가능한 모든 상황에서 전체 MG 계통의 안정적 운전을 보장 할 수 있도록 구성되었다. 각 모드는 개별 제어목적에

따라 MG 내 제어 가능한 요소 기기별 상이한 제어방법을 활용토록 설계되었다.

마지막으로, 제안된 제어전략의 유효성을 검증하기 위해 다양한 정상 및 비상운전 시나리오에 대해서 Matlab/Simulink를 활용한 시뮬레이션을 시행하였다. 그 결과, 거차도 하이브리드 AC/DC MG 가 주어진 계통운전 조건을 만족시키면서 안정적으로 운영될 수 있고, 개별 MG로 운전 될 경우보다 더 나은 성능을 발휘 할 수 있음을 검증하였다.

결론적으로, 새롭게 모델링한 거차도 하이브리드 AC/DC MG의 제어전략을 개발하고, 향후 활용을 위해 그 유효성을 시뮬레이션을 통해 검증한 것이 본 논문의 주요 기여점이다.

주요어 : 하이브리드 AC/DC 마이크로그리드, 독립형 마이크로그리드, 연계 컨버터, 배터리 에너지 저장시스템, 충전상태, 분산전원

학 번 : 2015-22783