

Stability and EMI Evaluation of Power Grid System Using Inverter-Based Resources for Expansion of Distributed Renewable Energy

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Stability and EMI Evaluation of Power Grid System Using Inverter-Based Resources for Expansion of Distributed Renewable Energy

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Abstract

Against a background of concerns about global climate change due to CO₂ emissions and fossil fuel resource depletion, distributed renewable energy power generation systems, such as solar power generation and wind power generation, have been developed in recent years.

In the power grid, the stability of the power system has been provided by the large inertial force of synchronous generators such as thermal power generation and hydroelectric power generation. Distributed power sources such as solar power, wind power, and battery energy storage system (BESS) are called IBR (Inverter-Based Resources) because they are connected to the power system via an inverter. Currently, most IBRs are connected to a commercial system via a GFL (Grid Following) inverter, but since the GFL inverter normally operates under constant output control, it cannot absorb the disturbance generated in the commercial system. Therefore, if the share of distributed renewable energy increases and the ratio of GFL inverters increases in the future, the inertial force of the power system may become insufficient and unstable. Recently, a self-sustaining and distributed energy system is strongly expected to be built. The energy system with a so-called black start function that can restore the power system without receiving power supply from the outside not only in remote areas and remote islands but also in the event of a widespread power outage due to a disaster.

A GFM (Grid Forming) inverter with a VSG (Virtual Synchronous Generator) function has been proposed to improve the stability of power systems that utilize IBR. Since the GFM inverter operates as a voltage source for the grid, it has a black start function even in the event of a grid power failure. The VSG function imitates the inertial characteristics of a synchronous generator and has external characteristics of active power-frequency control and reactive power-voltage control. Even if a large amount of IBR is introduced, the VSG function and GFM function can absorb the disturbance of the power system, so that the power system can be stabilized and can be operated independently.

Another issue related to the expansion of distributed renewable energy is the problem of electromagnetic interference (EMI). With the miniaturization and decentralization of IBR using renewable energy, the distance from broadcasting and communication equipment will be shorter than the large-capacity power supplies that have been installed in wide restricted areas, and there is concern about the occurrence of EMI. On the other hand, in order to comply with the EMI standard, the cost for evaluation and reduction against electromagnetic interference increases. In addition, excessive EMI reduction methods have the problem of increasing IBR energy loss.

In this thesis, we will discuss two major issues with the expansion of renewable energy distributed power sources. One is the system stability utilizing inverter-based distributed power sources. The other is the coexistence of distributed power sources and broadcasting communications.

The remainder of this thesis is organized as follows.

In Chapter 1, the importance of expansion of renewable energy sources is explained for reducing CO₂ emissions, and the major issues due to inverter-based sources expansion are pointed out. The purpose of this research is clarified.

In Chapter 2, the basics of GFL inverter, GFM inverter and VSG which belongs to IBR were described. the control methods of the VSG domestic and foreign studies are reviewed, and the differences are organized. A GFM inverter with the battery energy storage system (BESS) with VSG applied that called GFM-BESS has been proposed, and its operating principle will be explained.

In Chapter 3, the operating characteristics of GFM-BESS were analyzed and evaluated under parallel conditions with different operating modes of synchronous generators. The existing literature mainly introduces various virtual synchronization control methods and their implementation methods, but there is no literature that demonstrates synchronization force and inertial force by operating in parallel with a synchronous generator having an internal combustion engine. In order to put GFM-BESS to practical use, it is necessary to appropriately evaluate the effect of the introduction of GFM-BESS on the grid in a microgrid that operates in parallel with a synchronous generator having an internal combustion engine. This study proposes a method for evaluating the effect of GFM-BESS on the system of a configuration from a synchronous generator with an internal combustion engine. We built an off-the-grid environment that operates in parallel with a diesel synchronous generator with an internal combustion engine and GFM-BESS. When the load in the off-grid was changed, the load sharing characteristics based on the frequency droop characteristics (droop control) of the GFM-BESS and the synchronous generator and the stability of the off-grid system frequency were evaluated. In addition, when the control of the diesel synchronous generator was switched between droop control and isochronous control and operated in parallel with GFM-BESS, the effect of inertial control of GFM-BESS was confirmed.

In Chapter 4, As a method for quantitatively measuring and evaluating the inertial force of GFM-BESS, we proposed a method for evaluating an actual machine that operates in parallel with a synchronous generator. A microgrid of the same scale as the microgrid "Mutsuzawa Smart Wellness Town" in Mutsuzawa Town, Chiba Prefecture has been constructed, and the combined IBR ratio of GFM-BESS and GFL-BESS has reached 44.4%. The test conditions were determined with reference to the data of the power demand, solar radiation intensity, and PV module temperature of the Mutsuzawa microgrid that is actually in operation. The load fluctuated, the ratio of GFM inverter and GFL inverter was changed for 5 BESS, and the frequency stability, load sharing, and synchronization power were verified on the actual machine. It was demonstrated that the introduction of GFM-BESS suppresses the decrease in system frequency from 2.4Hz (50.0Hz to 47.6Hz) to 0.6Hz (50.0Hz to 49.4Hz) when the load fluctuation is 50kW by 70%.

In Chapter 5, GFM-PV was evaluated, which is a GFM inverter with imitated inertia characteristics applied to photovoltaic power generation. We constructed a microgrid in which GFM-PV and a synchronous generator operate in parallel, and conducted a load sudden change test. It was demonstrated that GFM inverter control suppresses the decrease in system frequency from 1Hz (50.0Hz to 49.0Hz) to 0.7Hz (50.0Hz to 49.3Hz) by about 30% when the load fluctuation is 20kW. For GFM-PV, it is possible to contribute to frequency stability by providing inertial force only by updating the control software without adding an energy buffer to supply inertial force.

In Chapter 6, the electromagnetic interference of GFM-BESS was measured and reduction methods were taken. Conducted electromagnetic interference reduction methods have improved electromagnetic interference to meet CISPR 11 class A, which is intended for use in industrial environments. In addition, we analyzed the EMI generation mechanism of a general inverter, evaluated the EMI reduction effect by equilibrating the circuit in comparison with the reduction effect by the conventional noise filter, and confirmed the reduction effect by up to 20 dB.

In Chapter 7, in GFM-BESS, the effect of the inductance of the line filter and EMI filter on the transient load sharing of GFM-BESS will be evaluated. Since the synchronization force in GFM-BESS changes depending on the inductance value of the internal filter, the mounting status of the line filter and the synchronization force are related. Therefore, the relationship between the synchronization force and the line filter will be examined. A method of predicting the overload sharing immediately after the load fluctuation is presented by the synchronization force. Two microgrids consisting of a synchronous generator and GFM-BESS were evaluated by simulation and demonstration experiments.

In Chapter 8, this research is summarized and the remaining issues and future efforts are described.

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Table of Contents

Abstract.....	ii
Acknowledgment.....	v
Table of Contents.....	vi
Chapter 1. Introduction	1
1.1. Background.....	1
1.2. Major issues	1
1.2.1. System Stability	1
1.2.2. EMI	3
1.3. Research Objectives.....	3
1.4. Conclusion	4
1.5. Reference	4
Chapter 2. Control Method of Inverter-Based Resources (IBR).....	6
2.1. Introduction.....	6
2.2. Grid Following Inverter (GFL).....	6
2.2.1. Grid Connected GFL.....	6
2.2.2. Stand-alone GFL	7
2.3. Grid Forming Inverter (GFM).....	7
2.3.1. Droop Control Inverter.....	8
2.3.2. Virtual Synchronous Generator (VSG)	8
2.3.3. GFM-BESS	9

2.4.	Conclusion	12
2.5.	Reference	12
Chapter 3. IBR in Parallel with Different Modes Synchronous Generator		15
3.1.	Introduction.....	15
3.2.	Simulation.....	15
3.2.1.	Configuration of Microgrid for Simulation.....	15
3.2.2.	IBR in Parallel with an Isochronous Mode Diesel SG.....	15
3.2.3.	IBR in Parallel with a Droop Mode Diesel SG	16
3.3.	Experiment.....	18
3.3.1.	Configuration of Microgrid for Experiment.....	18
3.3.2.	IBR in Parallel with Droop Mode Diesel SG.....	21
3.3.3.	IBR in Parallel with an Isochronous Mode Diesel SG.....	25
3.4.	Conclusion	30
Chapter 4. System Stability Evaluation in a Full Scale Microgrid		32
4.1.	Introduction.....	32
4.2.	Description of the Imitated Microgrid	33
4.2.1.	Microgrid Characteristics.....	33
4.2.2.	Configuration of the Imitated Microgrid.....	34
4.2.3.	Frequency Measurement	36
4.3.	GFM-BESS and Diesel Synchronous Generator in Stand-Alone Mode.....	36
4.3.1.	GFM-BESS in Stand-Alone Mode.....	37
4.3.2.	SG in Stand-Alone Mode.....	37
4.4.	IBR in Parallel with a Droop Mode Diesel Synchronous Generator	41
4.4.1.	Results from field operations	42

4.4.2.	Effect of Transformer Impedance	47
4.4.3.	System Stability Evaluation Versus GFM-BESS Penetration Ratio	47
4.4.4.	Power Sharing Evaluation Versus GFM-BESS Penetration Ratio	49
4.5.	Conclusion	53
4.6.	Reference	53

Chapter 5. System Stability Evaluation on GFM with Virtual Synchronous Generator

Control Applied to Photovoltaic Power Systems 55

5.1.	Introduction.....	55
5.2.	Control Method of GFM-PV.....	56
5.3.	Microgrid Configuration.....	59
5.4.	Results from Field Demonstration	60
5.4.1.	GFL-BESS in Parallel with a Diesel SG.....	60
5.4.2.	GFM-PV in Parallel with a Diesel SG when Irradiation Power less than Command Power.....	61
5.4.3.	GFM-PV in Parallel with a Diesel SG when Irradiation Power larger than Command Power.....	61
5.4.4.	Power Sharing and Inertia Evaluation.....	62
5.5.	Conclusion	65
5.6.	Reference	65

Chapter 6. EMI Measurement and Reduction of IBR 67

6.1.	Introduction.....	67
6.2.	EMI Measurement and Reduction for GFM-BESS	67
6.3.	Analysis of Noise Issues in General IBR.....	69
6.4.	Noise Generation Mechanism.....	71

6.5.	EMI Reduction with EMI Filter.....	71
6.6.	EMI Reduction with Balanced Technique	73
6.7.	Experiment.....	76
6.8.	Conclusion	78

Chapter 7. Evaluation of the Effect of Synchronous Reactance on Synchronization

Power 79

7.1.	Introduction.....	79
7.2.	Synchronization Power	79
7.3.	Evaluation of Transient Load Sharing Effected by Synchronization Power	80
7.3.1.	Configuration of the simulated microgrid.....	80
7.3.2.	Evaluation of Transient Load Sharing in One IBR and One SG System	82
7.4.	Evaluation of the Effect of Inductance on Synchronization Power	84
7.5.	Evaluation of Transient Load Sharing by Synchronization Power in a Five IBR and One SG Microgrid	85
7.6.	Conclusion	88

Chapter 8. Conclusions and Future Works..... 89

8.1.	Learned from the demonstration experiment	89
8.2.	Conclusions.....	89
8.3.	Future works	90

Chapter 1. Introduction

1.1. Background

Against a background of concerns about global climate change due to CO₂ emissions and fossil fuel resource depletion, Japan declared "2050 carbon neutral" in October 2020, and promoted the use of renewable energy such as solar power generation and wind power generation as the primary power source for the realization of a carbon-free society. The regional decarbonization roadmap was formulated at the National and Local Decarbonization Realization Conference on June 9, 2021. Among them, we worked to reduce greenhouse gases in fields that are closely related to the region and daily life, and achieved virtually zero CO₂ emissions associated with electricity consumption in the consumer sector (household sector and business and other sectors). The goal is to create at least 100 locations by 2030. "Construction of regional microgrids, etc. by utilizing existing system lines and self-employed lines" is also listed as decarbonized leading area.

When a wide-area power outage occurred in Chiba Prefecture due to the Boso Peninsula typhoon in 2019, the microgrid "Mutsuzawa Smart Wellness Town" in Mutsuzawa Town, Chiba Prefecture, used a c synchronous cogeneration generator using locally produced natural gas provided energy continuously. After a black start, the power supply to roadside stations and houses was resumed. From the viewpoint of strengthening resilience, it is important to operate independently on the off-grid, which is always connected to the main system and separated from the main system in the event of a wide-area power outage such as a disaster.

1.2. Major issues

1.2.1. System Stability

It is known that the output of solar energy generation and wind power generation changes irregularly according to changes in solar radiation and wind conditions. The mass implementation of distributed renewable energy power generation systems will lead to various adverse effects on the power system. This will reduce the inertial ability and synchronization force of the entire system. It is difficult for a low proportion of SGs to maintain the system frequency, and the stability of the system will be reduced.

Fig. 1.1 shows the mechanism for connecting various power sources to the power system. Conventional nuclear power, thermal power, hydroelectric power generation, etc. are directly connected to the grid by a synchronous generator (alternating current (AC) direct interconnection). However, since most variable renewable energy power sources such as solar power generation and wind power generation are direct current (DC) power generation and asynchronous power generation, alternating current is applied to the power system via power conversion (direct current / AC conversion,

Chapter 1

etc.) by an inverter. It is inverter interconnection.

In the case of grid interconnection via such an inverter, there are the following problems with respect to the power system.

Photovoltaic power generation is a DC power source and has no mechanically rotating element, so it cannot exert an inertial effect on the system. Wind power generation consisting of asynchronous generators such as variable speed generators is a rotary power source, but since it is grid-connected via a power converter, the inertial effect is not transmitted to the grid as well.

Since the synchronous generator does not have the unique synchronization power, it is difficult to maintain the stability of the entire system. The inertial effect of the generator is a "buffer effect" that absorbs/releases the unbalanced portion by the mechanical energy of the rotating inertial body when a transient supply-demand imbalance occurs in the system. In conventional synchronous generators, the turbine and generator rotor has a moment of inertia, which has contributed to the maintenance of transient stability of the system frequency as a result. On the other hand, if a large amount of renewable energy power sources having no inertial effect are introduced into the system and the ratio of the conventional synchronous machine power sources is relatively small, it becomes difficult to stably maintain the system frequency of the entire system. For example, according to the UK National Grid, the system inertia constant in the off-peak demand section in 2034/35 is about 2 seconds, which is about 1/4 of the system inertia constant in the peak demand section in 2014/15, which is 9 seconds. It is considered that it may be difficult to maintain the frequency of the power system.

Therefore, a virtual synchronous generator (VSG) that controls an inverter-connected distributed power source to have the same characteristics as a synchronous generator has been proposed [1]-[12]. By applying virtual synchronous generator control, the inverter-connected distributed power source will have virtual inertia, can absorb the disturbance of the system, and keep the system stable even if it is introduced in large quantities. Also, as with the synchronous generator, the operation can be continued even if the line is disconnected from the grid.

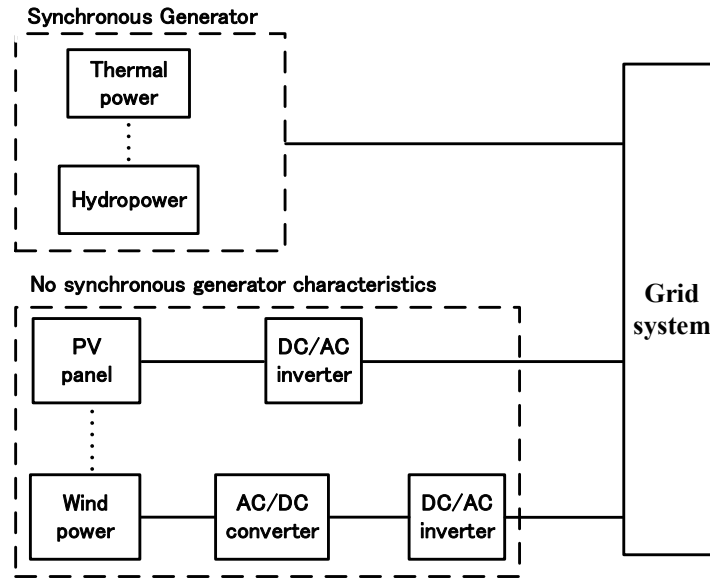


Fig. 1.1 Grid connect to the power supply system

1.2.2. EMI

Compared to the large-capacity power supplies installed in a large restricted area in the past, with the miniaturization and decentralization of renewable energy power supplies, the distance from broadcasting and communication is getting closer, so there is a growing concern that electromagnetic interference will occur. On the other hand, in order to realize the EMC standards, the development costs for evaluation and countermeasures for electromagnetic interference are high. In addition, excessive EMC measures increase the energy loss of renewable energy power sources, and there is also the problem of reducing the CO₂ reduction potential.

1.3. Research Objectives

1. GFM (Grid forming inverter) with inertia has been proposed as a contribution to system stability. Establishing a quantitative evaluation method for the contribution of pseudo-inertial GFM to system stability is important. (Proposed a method evaluate the inertial force by operating a diesel synchronous generator and a pseudo-inertia GFM in parallel in a microgrid environment)
2. Imply inertia control to Inverter-Based resources with battery systems (IBR-BESS) and IBR with renewable energy (such as IBR-PV).
3. Measure the EMI of the existing IBR and study the reduction method to satisfy the standard value such as CIRPR.
4. Evaluate the effect of the inductance of line filters on the synchronous power of IBR-BESS and EMI suppression.

1.4. Conclusion

With the growing shift toward renewable energy, attention focused on the disadvantages of current control inverter-based distributed generators, such as lack of grid-forming ability and inertia. Compared to the large-capacity power supplies installed in a large restricted area in the past, with the miniaturization and decentralization of renewable energy power supplies, the distance from broadcasting and communication is getting closer, so there is a growing concern that electromagnetic interference will occur. This project is expected to demonstrate a new lifestyle, with natural sustainable resources for improved resiliency and EMI for the expansion of distributed renewable energy.

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Chapter 1

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Chapter 2. Control Method of Inverter-Based Resources (IBR)

2.1. Introduction

In recent years, the introduction of renewable energy power sources and storage batteries has been promoted from the viewpoint of environmental problems. Most of the distributed power sources such as photovoltaic power generation and fuel cells are generated by direct current, so it is necessary to convert them to alternating current by an inverter in order to connect to the alternating current system. Since storage batteries such as lithium-ion batteries, lead-acid batteries, and nickel-metal hydride batteries are also output as direct current, an inverter is required to connect to the AC system. Distributed power sources that are generated by alternating current, such as gas engine cogeneration systems and wind power generation, are different from the system frequency. Therefore, it is converted to direct current using a rectifier, converted to commercial frequency by an inverter, and connected to the system. This chapter describes the control method of such an inverter-connected distributed power source and clarifies the problems of the conventional method that is generally used.

2.2. Grid Following Inverter (GFL)

2.2.1. Grid Connected GFL

Mega-solar, household solar power generation systems, wind power generation systems, etc. connected to the power system generally do not have a storage battery, so it is necessary to transmit the same power as the generated power to the power system side through the inverter circuit. Therefore, a current-controlled inverter that can easily control the output power is often used [1]. It is stabilized by taking a voltage / current signal from the output of the inverter circuit and controlling the current value of the output power of the distributed power source so that the voltage becomes a constant value.

By using the PLL of the control block shown in Fig. 2.1, the angular velocity ω of the grid voltage can be obtained, and the active power and the active power of the output can be derived from the voltage value and the current value. By comparing this value with the reference value of the active power and the active power of the distributed power source, the differential power of the active power and the active power is obtained. By passing this differential power through PI control, the phase and magnitude of the reference sine wave can be derived. By comparing the derived reference sine wave with the carrier wave of the switching operation, the gate signal of the inverter circuit can be generated and the power conversion amount can be controlled. This control method has the advantage of being able to control the output power of the inverter at high speed and is used in many distributed power

sources connected to the power system.

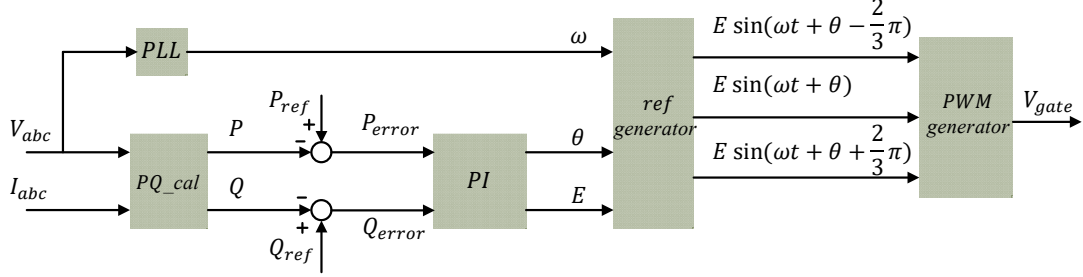


Fig. 2.1 Control block of GFL

2.2.2. Stand-alone GFL

When operating independently, operate with constant voltage / constant frequency control (Constant Voltage Constant Frequency). When operating in parallel with CVCF control, use the master/slave method. In this method, CVCF control is performed using any GFL with the largest capacity as the master device, and the other GFLs operate as slave devices, and the output of the master device is used as the control reference. Therefore, even if the slave device fails, the power system can continue to operate without any problem, but if the master machine is cut off, the control standard disappears and the power system cannot operate. All load fluctuations are shared by the master device, and the slave device tracks and controls the output of the distributed power source, thereby stabilizing the power system. With this system control method, it is difficult to switch from independent operation to grid-connected operation without interruption because the system cannot be put into grid-connected operation without switching the control [1].

2.3. Grid Forming Inverter (GFM)

Although GFLs have the advantage of a faster response compared with conventional synchronous generators (SGs), two drawbacks have been noted for GFLs. First, they do not have an inertial ability and cannot form a grid, and this has limited the penetration of GFLs in power systems up to now. As the penetration of GFLs increases, this will reduce the inertial ability and synchronization force of the entire system. It is difficult for a low proportion of SGs to maintain the system frequency, and the stability of the system will be reduced. Second, GFLs cannot work in a stand-alone mode. Because the control method for GFLs needs a PLL to synchronize the inverter to the grid, GFLs are not able to black start.

To maintain a healthy grid, a variety of grid-forming methods have been developed. Inverters with grid-forming controllers are called grid-forming inverters (GFMs). GFMs allow GFLs, other GFMs, and SGs to coexist in the same system [2]. GFMs can be categorized as droop control inverters [3]-

[6], virtual synchronous inverters [7]-[30], and virtual oscillator inverters [31].

2.3.1. Droop Control Inverter

In order for the load power to be shared autonomously in the steady state of multiple units operating in parallel, the concept of droop is necessary. This section introduces an example [17-19] in which the independent operation and parallel operation of the inverter are examined only by droop control.

Droop control inverters can imitate the steady-state characteristics of SGs, as originally proposed in [3]. These inverters introduce a linear trade-off between active-power frequency and reactive-power voltage [4]-[6]. When applied to microgrid systems, droop control inverters usually contribute to the primary control, in which the steady-state power sharing of parallel inverters depends on the capacity of the inverters and the droop slope rate.

2.3.2. Virtual Synchronous Generator (VSG)

Droop control inverters can improve the power sharing ability and stability of a system. However, systems with droop control inverters still do not have inertial support, and transient changes are not satisfactorily controlled. To enhance the inertial ability of power systems, virtual synchronous machines (VSMs) [7-10], synchronverters [11]-[14], and virtual synchronous generators (VSGs) [15]-[22] have been proposed. Specifically, these methods imitate mainly the body model of an SG, active-power and frequency regulation, and the characteristics of reactive-power voltage regulation. Therefore, these methods allow inverters to be operated as traditional SGs in terms of the operating mechanism and external characteristics. Current-controlled VSMs was first proposed in [7], which simulated mainly the swing equation of the SG by external characteristics and did not simulate the voltage regulation characteristics of an SG. Furthermore, technology in [8]-[10] can better reflect the whole operating characteristics of SGs.

However, current-controlled VSMs are equivalent to current source, and they cannot easily provide voltage and frequency support for the system. To make up for the shortcomings of current-controlled VSMs, voltage-controlled virtual synchronous inverter technology has been proposed [11]-[28]. Some proposed synchronverters incorporate the dynamic model of the AC side of the inverter, and at the same time consider the electromechanical and electromagnetic transient characteristics of the SG [11]-[13]. Such synchronverters realize the physical and mathematical model equivalent of the SG very well. They can also realize the self-synchronization operation of the inverters without a PLL [14]. However, the second-order model used in synchronverters is complex, and a huge number of parameter settings are needed. A VSG [15]-[22] used as a first-order model that is based mainly on the mechanical transient characteristics of the SG has been reported. It improves the stability of the system frequency by imitating the inertia of the rotor and the frequency control characteristics of the SG. In terms of voltage control, the reactive power and voltage relationship are considered to stabilize mainly

Chapter 2

the output voltage. The power controller and voltage frequency controller give the VSG the dual functions of power control and frequency modulation. Although the principle of the VSG is the same, the basic control method is not unique. Various control methods related to VSGs have been reported, including frequency and voltage control [15]-[20], system protection [21]-[24], fault ride-through and system recovery [25]-[26], and modeling and simulation [27]-[28].

Table 2.1 Related domestic and overseas technology development examples

Technology developer		Overview
Japan	Osaka University	Development of system stabilization control technology including inverter-connected distributed power supply using virtual synchronous generator
Japan	Kawasaki Heavy Industries	Development of grid-connected inverter using algebraic virtual generator model
Japan	Chubu Electric Power	Verification of the stabilization effect of the power system when introducing a large amount of PV using the virtual synchronous generator function
Japan	Waseda University	Developed an independent and decentralized operation control method for multiple power storage systems in an off-the-grid using a virtual synchronous generator inverter
Germany	Clausthal University of Technology	Development of an interconnection inverter (Virtual Synchronous Machine: VISMA) that simulates the static and dynamic characteristics of a synchronous generator.
Netherlands	Energy Research Center	Development of an inverter with VSG function to prevent the instability of system frequency due to the decrease in inertial effect of synchronous generators due to the mass introduction of renewable energy power sources in the EU (VSYNC project)
English	University of Liverpool	Development of interconnection inverter "Synchronverter" with VSG function for distributed power sources and renewable energy power sources

2.3.3. GFM-BESS

Based on the control method of reference [21], a voltage-controlled virtual synchronous inverter with a storage battery is developed. Here, the abbreviation is GFM-BESS (Grid Forming Inverter with Battery Energy Storage Systems).

The GFM-BESS consists of a 15-kWh lithium-ion battery (Toshiba SCiB™), a DC/DC converter, and a three-phase 202-V/20-kVA inverter. These were installed in a $1,200 \times 530 \times 1,715$ mm frame. The main circuit of the GFM-BESS is shown in Fig. 2.2, where u_{abc} , e_{abc} , and i_{abc} are the GFM-BESS three-phase output voltage, induced electromotive force, and three-phase output current, respectively; R_s and L_s are the equivalent stator resistors and equivalent synchronous inductors, respectively; and P_e and Q_e are the real power and reactive power output by the GFM-BESS, respectively.

The control system consists mainly of the main body model and a control algorithm. The main body model simulates the mechanical motion characteristics of the synchronous generator from the operating mechanism, and the control algorithm simulates the external characteristics of the SG, such as the active power-frequency adjustment characteristics and the reactive power-voltage adjustment characteristics.

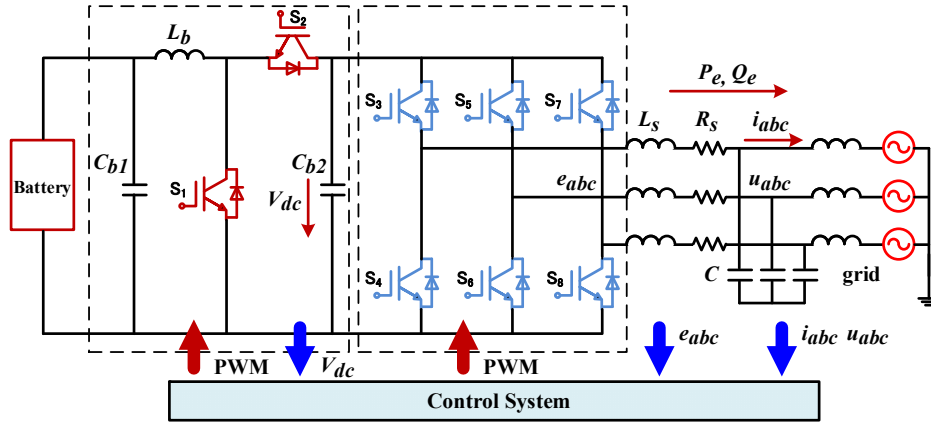


Fig. 2.2 Basic topology of GFM-BESS

Fig. 2.3 shows a schematic block diagram of the GFM-BESS control algorithm [21]. The inertial force and braking characteristics of the rotor are simulated based on the equation of motion of the SG rotor in (1). The active power and frequency control operation by the droop governor can be represented by (2), where J is the inertia moment, ω_{mea} is the system angular frequency, ω_{ref} is the command value of system angular frequency, T_m is the mechanical torque, T_e is the electrical torque, T_d is the braking torque, P_{ref} is the command value of active power, P_{mea} is the output active power, k_{droop} is the droop rate of the governor, and ΔP is the load sudden change.

$$T_m - T_e - T_d = \frac{P_{ref} + P_{droop} - P_{mea}}{\omega} = J \frac{d\omega_{mea}}{dt} \quad (1)$$

$$\Delta P = (\omega_{ref} - \omega_{mea}) \frac{1}{k_{droop}} \quad (2)$$

The unit inertia coefficient M can be calculated from (3) and (4), where M_0 is the inertia coefficient and P_{base} is the base power for per unit (pu) calculation.

$$M_0 = J\omega_{\text{ref}}^2 \quad (3)$$

$$M = \frac{M_0}{P_{\text{base}}} \quad (4)$$

The GFM-BESS receives the values of the frequency command, active power command, voltage command, and invalid power command from the host control system, such as an energy management system (EMS). The inertia imitation unit consists of a first-order delay $1/(1 + 8 \text{ s})$ and phase compensation $(1 + 0.16 \text{ s})/(1 + 0.04 \text{ s})$ for open-loop phase margin, assuming a unit inertia coefficient of 8 s as a general synchronous generator. The output phase signal δ is then calculated through integration of the command angular frequency and deviation angular frequency. When an GFM-BESS unit is started, the phase of the system-side voltage is detected and that phase is set as the initial value at startup. This eliminates the difference between the voltage phase generated by the inverter at startup and the phase on the system side, enabling synchronous startup without transient phenomena. The three-phase voltage signals V_a , V_b , and V_c are created from the phase signal δ and the voltage amplitude signal E given by the voltage control unit. The three-phase voltage signal is transferred to the pulse width modulation (PWM) block, and the on/off pulse of each arm of the inverter is determined.

As with the SG, droop control is added and is performed so as to contribute to maintaining the frequency of the system. In voltage control, the voltage at the point where the inverter is connected with the system side is controlled to be constant. Reactive power control is implemented in the same way as in the SG. This GFM-BESS operates in parallel with the SG. During operation, neither the PLL that detects the phase of the voltage on the system side nor the current control is used for the inverter. Each GFM-BESS unit generates a three-phase voltage and operates in synchronization with other power sources, such as the SG. Because the GFM-BESS is designed to imitate an SG, it continues to operate until its own device protection is activated. Therefore, the fault ride through (FRT) function is not implemented. In addition, GFM-BESS has the same characteristics as a generator and is treated with the same considerations, so the independent operation detection function is not implemented.

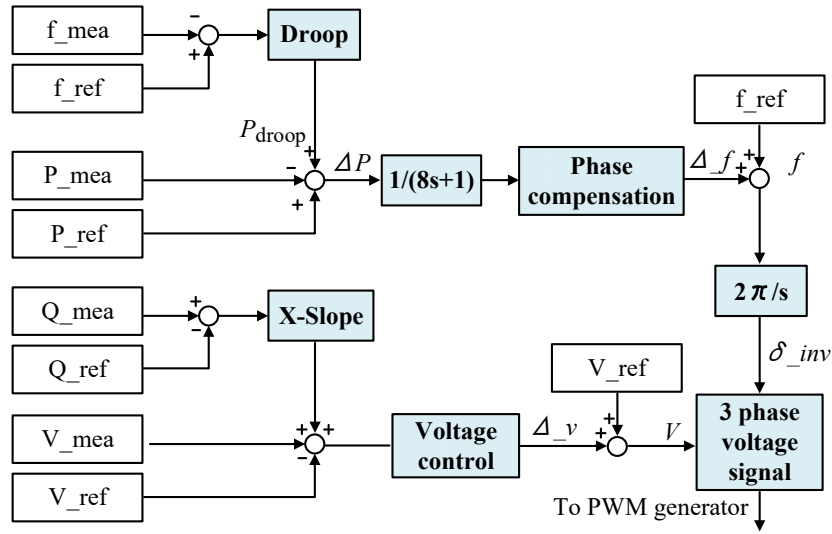


Fig. 2.3 Block diagram of GFM-BESS control algorithm

2.4. Conclusion

The basics of GFL inverter, GFM inverter, and VSG which belong to IBR were described. the control methods of the VSG domestic and foreign studies are reviewed, and the differences are organized. A GFM inverter with the battery energy storage system (BESS) with VSG applied that is called GFM-BESS has been proposed, and its operating principle is explained.

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Chapter 3. IBR in Parallel with Different Modes Synchronous Generator

3.1. Introduction

The operating characteristics of GFM-BESS were analyzed and evaluated under parallel conditions with different operating modes of synchronous generators. The existing literature mainly introduces various virtual synchronization control methods and their implementation methods, but there is no literature that demonstrates synchronization force and inertial force by operating in parallel with a synchronous generator having an internal combustion engine. In order to put GFM-BESS to practical use, it is necessary to appropriately evaluate the effect of the introduction of GFM-BESS on the grid in a microgrid that operates in parallel with a synchronous generator having an internal combustion engine. This study proposes a method for evaluating the effect of GFM-BESS on the system of a configuration from a synchronous generator with an internal combustion engine. We built an off-the-grid environment that operates in parallel with a diesel synchronous generator with an internal combustion engine and GFM-BESS. When the load in the off-grid was changed, the load sharing characteristics based on the frequency droop characteristics (droop control) of the GFM-BESS and the synchronous generator and the stability of the off-grid system frequency were evaluated. In addition, when the control of the diesel synchronous generator was switched between droop control and isochronous control and operated in parallel with GFM-BESS, the effect of inertial control of GFM-BESS was confirmed.

3.2. Simulation

3.2.1. Configuration of Microgrid for Simulation

The simulated microgrid system is shown in Fig. 3.1. The GFL-BESS and the GFM-BESS are operated in parallel with the isochronous control synchronous generator and the droop control synchronous generator, respectively. The rated capacity of the synchronous generator was 50 kVA, and the rated capacity of the inverter was 20 kVA. The initial load is 20kW, the inverter breaker-on at 2s, and the load 10kW breaker-on at 5s. The inertial force and droop characteristics of the GFM-BESS compared to the GFL-BESS are evaluated.

3.2.2. IBR in Parallel with an Isochronous Mode Diesel SG

Isochronous control is a control that adjusts the frequency to the reference value regardless of the load. Fig. 3.2 shows the load sharing during parallel operation between a GFL-BESS with a command

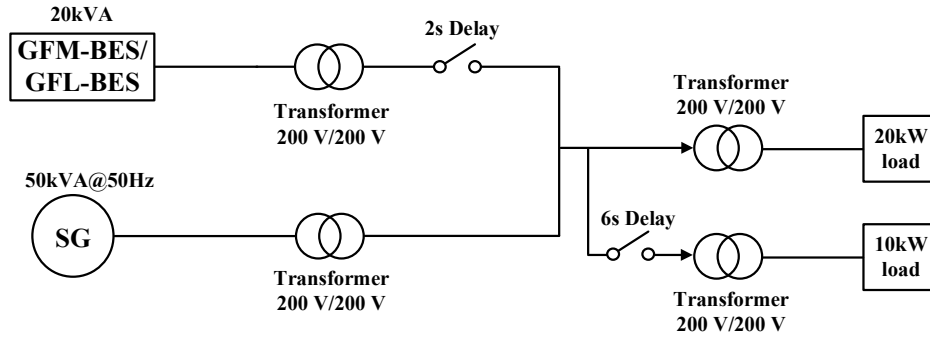


Fig. 3.1 Microgrid for Simulation

active power output value of 10 kW and an isochronous-controlled SG. The GFL-BESS output follows the command output value of 10 kW for a load fluctuation at 6 s. From this result, it can be confirmed that the GFL-BESS has no frequency adjustment force. Fig. 3.3 shows the load sharing during parallel operation of a GFM-BESS with a command output value of 10 kW and an isochronous-controlled SG. The GFM-BESS adjusts the frequency fluctuation caused by the load fluctuation by the inertial force. Due to the characteristics of the isochronous controlled generator, the generator shares all the load fluctuations in the steady state, and the frequency returns to 50Hz. Fig. 3.4 shows a comparison of frequency fluctuations between a GFL-BESS and a GFM-BESS. In the case of sudden load change, it was confirmed that the system with the GFM-BESS reduces the frequency change rate and the maximum frequency deviation value by improving the inertial force.

3.2.3. IBR in Parallel with a Droop Mode Diesel SG

Droop control is a control that adjusts the output active power in response to the frequency fluctuations. Fig. 3.5 shows the load sharing during parallel operation of the GFL-BESS and the droop control SG. The active power command value of the SG was set to 14.28 kW and the active power command value of the inverter was set to 5.72 kW so that the steady state frequency at 5 s would be 50 Hz. Since the active power released by the GFL-BESS for a load fluctuation at 6s is constant at 5.72 kW, it can be seen that there is no inertial force. Fig. 3.6 shows the load sharing during parallel operation of the GFM-BESS and the droop-controlled SG. After loading the load at 6 s, the GFM-BESS adjusts the frequency fluctuation caused by the load fluctuation by the inertial force. And since the SG is also droop controlled, the primary adjustment is performed by droop control. Due to the characteristics of droop control, there is a frequency deviation in the steady state. The active power sharing can be calculated from Eq. (1). In equation (1), P_n is the rated capacity, f_n is the reference frequency, and R is the rotor speed adjustment rate. Since the speed adjustment rate of GFM-BESS is 4%, which is equivalent to that of SG, it can be confirmed that the load fluctuation is shared in proportion to the capacity of SG and GFM-BESS.

$$\Delta P_G = \frac{\Delta f / f_n}{R} P_n \quad (1)$$

Fig. 3.7 shows a comparison of frequency fluctuations between a GFL-BESS and a GFM-BESS. Regarding the inertial force, the same conclusion as when using the isochronous controlled generator can be obtained. It was also confirmed that the frequency can be further adjusted by the primary adjustment of the droop control.

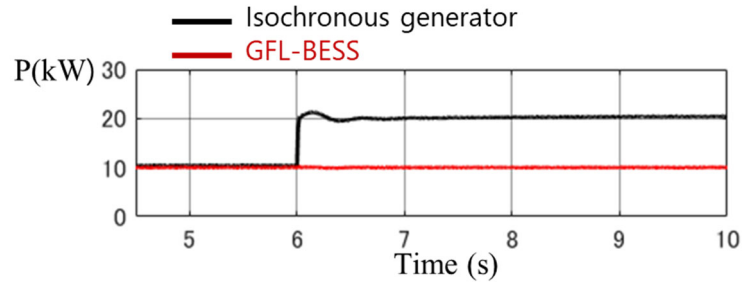


Fig. 3.2 Load sharing between current control inverter (command value 10kW) and isochronous control generator

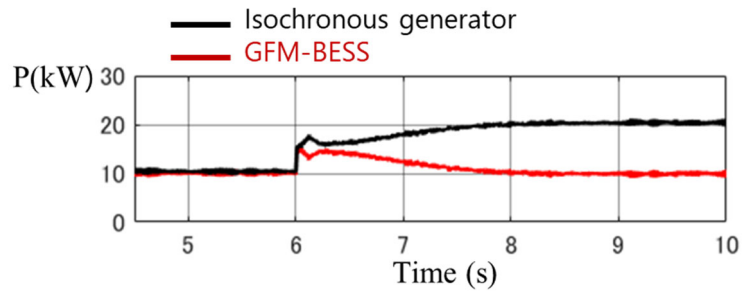


Fig. 3.3 Load sharing between voltage control synchronous inverter (command value 10kW) and isochronous control generator

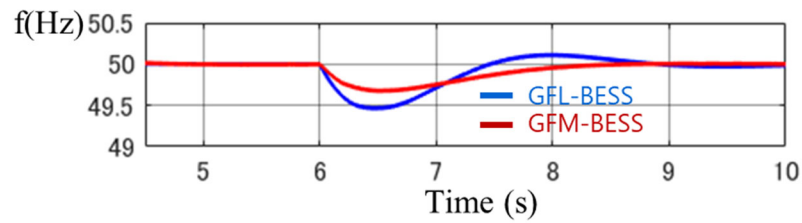


Fig. 3.4 Frequency fluctuation comparison

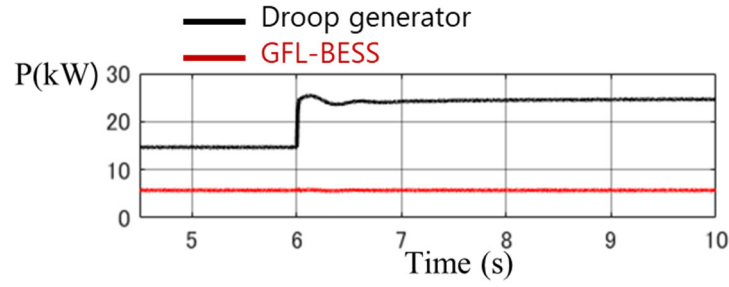


Fig. 3.5 Load sharing between current control inverter (command value 5.72kW) and droop control generator (command value 14.28kW)

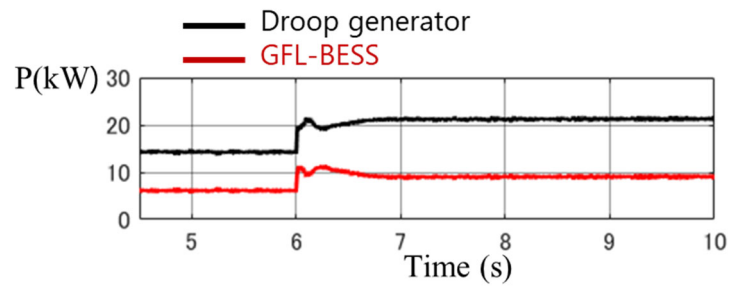


Fig. 3.6 Load sharing between voltage control synchronous inverter (command value 5.72kW) and droop control generator (command value 14.28kW)

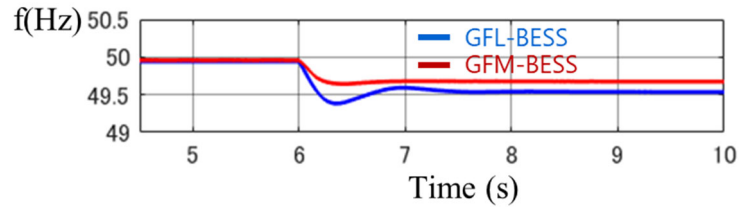


Fig. 3.7 Frequency fluctuation comparison

3.3. Experiment

3.3.1. Configuration of Microgrid for Experiment

In order to simulate the frequency fluctuation when the power outage occurred, a method of evaluating the inertial force with a sudden load change was used. Fig. 3.8 shows a microgrid for an experiment that consists of a 50 kVA synchronous generator, which is the main power generator of the microgrid, two 20 kVA GFM-BESS, a 50 kW three-phase load device, which corresponds to a power consumer, a transformer, which corresponds to a power transmission and distribution transformer.

Chapter 3

Table 3.1 shows the parameters of the diesel SG used in the experiment. Table 3.2 shows the design parameters of GFM-BESS. The inertial coefficient and damping coefficients are 8 s and 1 s, respectively, as in Ref. [21] in chapter 2. The test environment is shown in Fig. 3.9. The SG shown in Fig. 3.10 can be switched between the droop control mode and the isochronous control mode by the electronic governor.

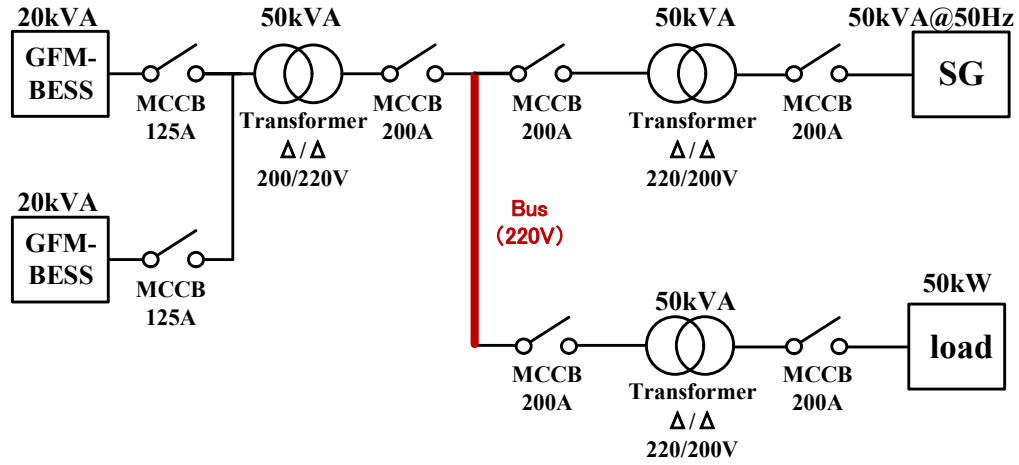


Fig. 3.8 Microgrid system for experiment

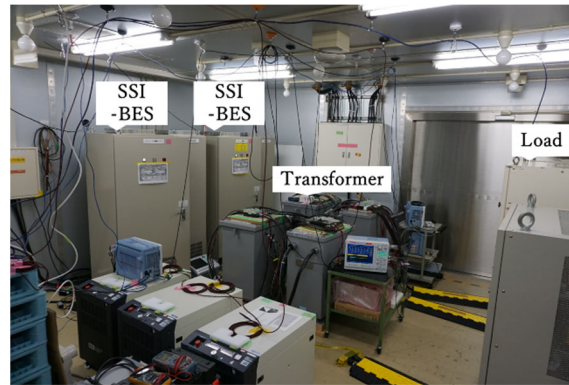


Fig. 3.9 50kVA platform indoor

Chapter 3



Fig. 3.10 50kVA diesel synchronous generator
outdoor

Table 3.1 Parameters of Diesel Synchronous Generator.

Parameter	Value	Parameter	Value
V_{base_SG}	200 V	S_{base_SG}	50 kVA
f_{base_SG}	50 Hz	Droop gain ($SG_{calculated}$)	-5%

Table 3.2 Designed Parameters of GFM-BESS.

Parameter	Value	Parameter	Value
V_{base_GFM}	200 V	M_{GFM}	8.0 s
S_{base_GFM}	20 kVA	D_{GFM}	1.0
f_{base_GFM}	50 Hz	Droop gain (GFM-BESS)	-5%

Table 3.3 Conditions of Experiment.

Case#	Generator	GFM-BESS	Capacity	Load (kW)
Case 1	Droop control 50 kVA x 1	20 kVA x 2 (off)	50 kVA	0>20>0 (0.4 pu)
Case 2	Droop control 50 kVA x 1	20 kVA x 2 (off)	50 kVA	0>40>0 (0.8 pu)
Case 3	Droop control 50 kVA x 1	20 kVA x 2 (on) Pref=0kW Pref=0kW	90 kVA	0>40>0 (0.44 pu)

3.3.2. IBR in Parallel with Droop Mode Diesel SG

3.3.2.1. Load response analysis

Droop control is a control that adjusts the output active power in response to frequency fluctuations. Table 3.3 shows the test conditions when a 50 kVA droop control synchronous generators and two 20 kVA GFM-BESS units are operated in parallel. Case 1 and Case 2 verify the load response of SG when 20 kW and 40 kW load changes are applied on a grid in which a droop-controlled synchronous generator is operated independently without a GFM-BESS breaker-on. Fig. 3.11 shows the load sharing and frequency fluctuations. The three-phase load device is changed to 0 kW, 20 kW, and 0 kW when the generator of Case 1 is operated stand-alone. When a sudden load change happens at $t = 2$ s, the active power output of the SG is about 20 kW. As the load sharing increases, the system frequency gradually drops due to the inertial force of the SG. After that, the rotor accelerates due to the frequency drooping characteristics of the generator, and the system frequency returns to 49.3 Hz. When the load fluctuates to 0 kW at $t = 5.8$ s, the generator output returns to 0 kW. At the moment when the load fluctuates, the system frequency rises, but due to the drooping characteristics of the generator, the rotor slows down and the system frequency returns to 50 Hz.

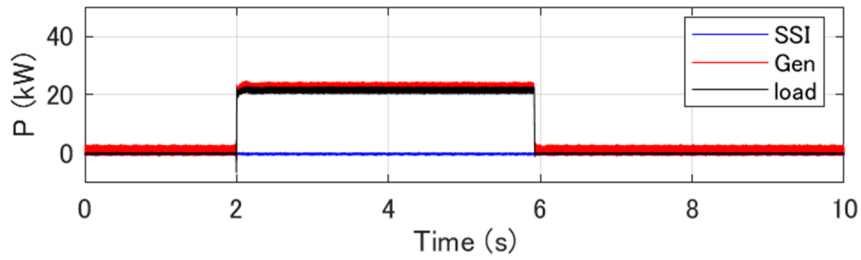
Fig. 3.12 shows the load sharing and frequency fluctuations when the load of the three-phase load device is changed to 0 kW, 40 kW, and 0 kW when the SG of Case 2 is operated stand-alone. When a sudden load change happens at $t = 2$ s, the load sharing of the generator is 40 kW, which is equivalent to 0.8 pu of the power generation system capacity, and the frequency drops significantly to 43 Hz. Then, due to the frequency drooping characteristics of the generator, the rotor accelerates and the system frequency returns to 48 Hz. From equation (3), the droop rate of the generator is calculated to be about 5%. When the load is set to 0 kW at $t = 8.5$ s, the load sharing of the generator returns to 0 kW. The system frequency rises at the moment when the load fluctuates, but the frequency does not rise significantly even if the same load fluctuates due to the speed limitation of the rotor by the acceleration protection function of the generator. After that, the rotor decelerates and the system frequency returns to 50 Hz.

The load sharing and the fluctuation of the system frequency in Case 3 are shown in Fig. 3.13 (a) and (b), the load of the three-phase load device was changed to 0 kW, 40 kW, and 0 kW when the 50 kVA SG of Case 3 and two 20 kVA GFM-BESS units were operated in parallel. The command value of GFM-BESS is 0 kW. Since the system frequency is 50 Hz up to $t = 2$ s, the actual output of GFM-BESS is 0 kW as instructed. When a 40 kW sudden load change happens at $t = 2$ s, the SG and two GFM-BESS units share the load. Fig. 3.14 (a) shows an zoom-in view of the load sharing characteristics when the load increases. At the moment of load fluctuation, GFM-BESS and the SG share the load fluctuation at the same time by the mutual synchronization force. After that, the SG gradually increases the output, and GFM-BESS gradually decreases the output, adjusting the output

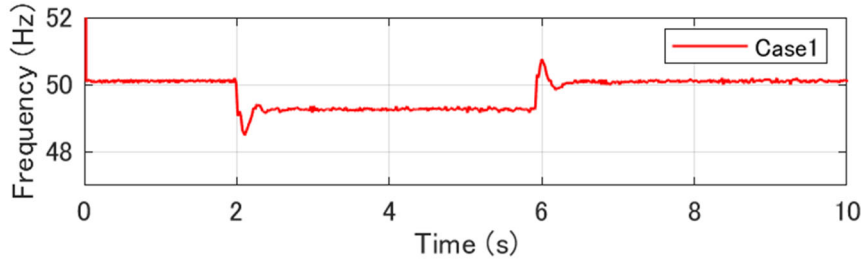
to the steady state. Here, since the droop ratios of the synchronous generator and GFM-BESS are both 5%, the load sharing in the steady state is proportionally shared with the capacity of the power generation device by the equation (3). In the steady state, the load sharing calculated from the droop rate is 8.9 kW for GFM-BESS and 22 kW for the generator, which is in agreement with the test results in Fig. 3.13 (a). It can be confirmed that GFM-BESS autonomously shares the load power.

Fig. 3.14 (b) shows a zoom-in view of the load sharing waveform when the load is reduced. After reducing the load to 0 kW, the generator momentarily reduces the output to 0 kW, but since the GFM-BESS is equipped with a battery storage system, the GFM-BESS is in charge mode and the extra energy is stored in the battery storage system of GFM-BESS. The rotor of the generator does not over speed and operates stably against a sudden decrease in load. GFM-BESS is considered to contribute to the improvement of system flexibility and safety.

In Fig. 3.13 (b), when the load change happens at $t = 2$ s, the maximum frequency decrease is 49.2 Hz because there is an SG and GFM-BESS, and the frequency decrease is smaller compared to Fig. 3.12 (b). It can be confirmed that the inertial force is larger in the system in which GFM-BESS is operated in parallel than in the case of the SG stand-alone in Fig. 3.12 (b).

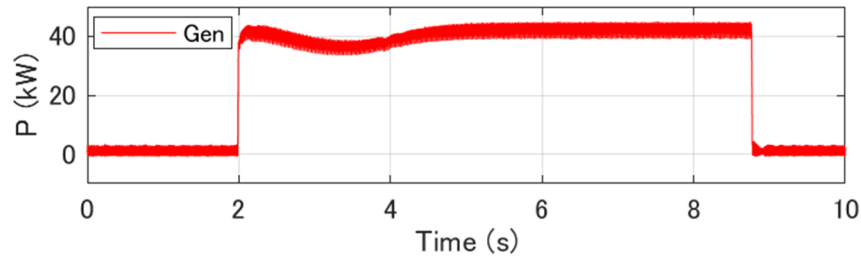


(a) Active power output of synchronous generator and load



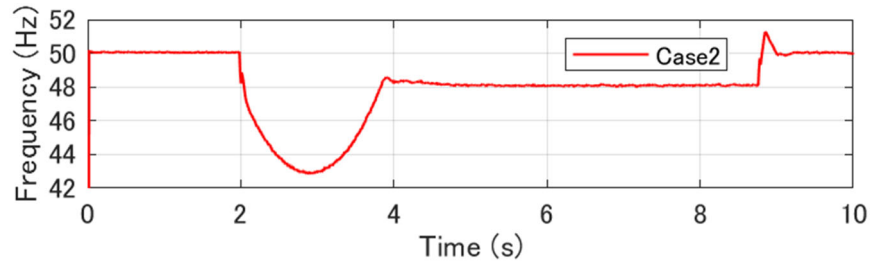
(b) Generator frequency

Fig. 3.11 Experimental result of Case1 (load:0kW $\Rightarrow$ 20kW $\Rightarrow$ 0kW)



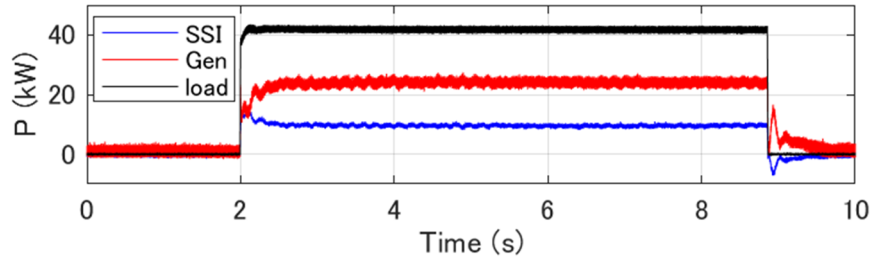
Chapter 3

(a) Active power output of synchronous generator

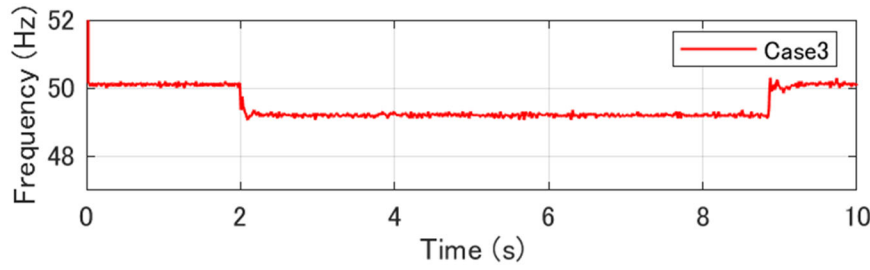


(b) Generator frequency

Fig. 3.12 Experimental result of Case2 (load:0kW $\Rightarrow$ 40kW $\Rightarrow$ 0kW)

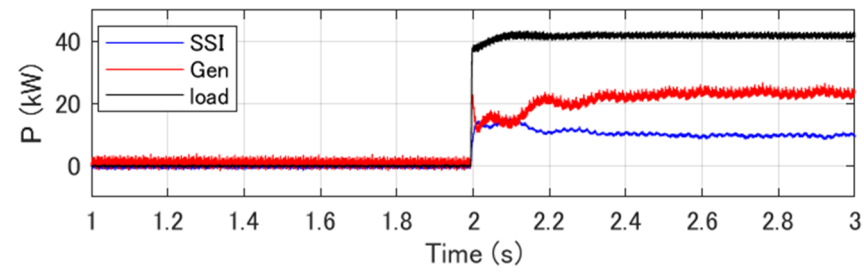


(a) Active power output of synchronous generator, GFM-BESS and load

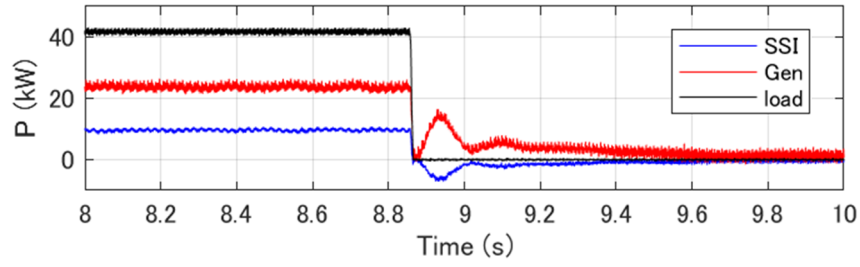


(b) Generator frequency

Fig. 3.13 Experimental result of Case3 (load:0kW $\Rightarrow$ 40kW $\Rightarrow$ 0kW)



(a) Load change from 0kW to 40kW



(b) Load change from 40kW to 0kW

Fig. 3.14 Active power output of Case3 (load:0kW $\Rightarrow$ 40kW $\Rightarrow$ 0kW)

3.3.2.2. Comparison of system inertia

Fig. 3.15 and Fig. 3.16 show the frequency fluctuations and frequency change rate fluctuations of the system during sudden load change in Case 1, Case 2, and Case 3, respectively. Similarly, when the load fluctuates by 40 kW, Case 3 has two GFM-BESS units compared to Case 2, so the inertia of the system increases, and the system is maintained stable. We will compare the inertia change of the system from the load increase test of Case 1 and Case 3. Since the load fluctuations of Case 1 and Case 3 are 0.4 pu and 0.44 pu with respect to the power generation capacity of the experiment system, respectively, they are considered to be compared under the same conditions. The evaluation indexes of inertia are (1) the maximum drop from the steady frequency of 50 Hz and (2) the absolute value of the rate of change of frequency (RoCoF) in 0.2 s after the load change. Table 3.4 Evaluation of inertial forces summarizes the parameters to be compared. Since Case 3 has GFM-BESS, the frequency change rate after the load fluctuation is reduced, and the maximum deviation value can be reduced by 0.7 Hz. It can be confirmed that GFM-BESS improves the inertia of the system.

Table 3.4 Evaluation of inertial force

Evaluation index	Case 1	Case2	Case 3
Maximum frequency drop [Hz]	48.5	43	49.2
RoCoF [Hz/s]	8	18	5

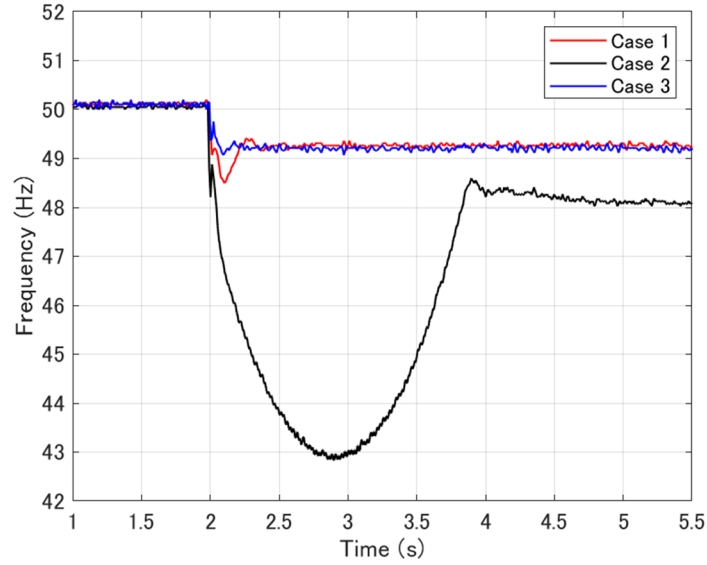


Fig. 3.15 Comparison of generator frequency droop

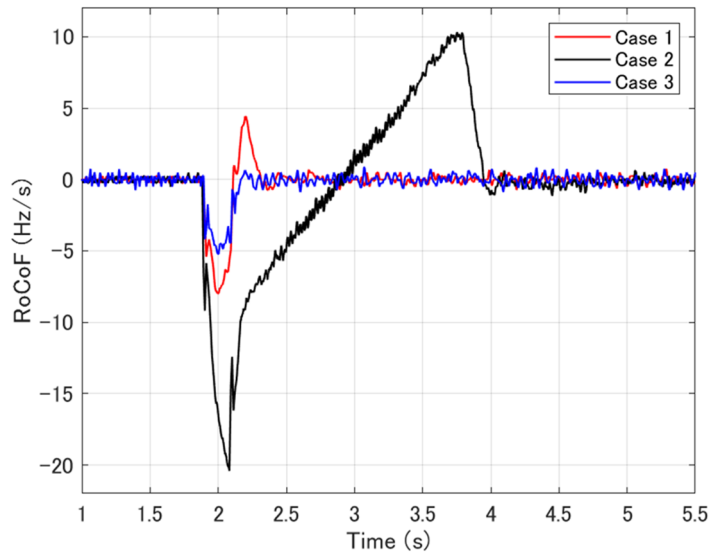


Fig. 3.16 Comparison of RoCoF

3.3.3. IBR in Parallel with an Isochronous Mode Diesel SG

3.3.3.1. Load response analysis

Isochronous control is a control that adjusts the frequency to the reference value regardless of the load change. Table 3.5 shows the test contents that a 50 kVA isochronous controlled SG and two 20 kVA GFM-BESS units are operated in parallel. Case 4 and Case 5 verify the responsiveness at load

changing of 20 kW and 40 kW in a system in which the isochronous controlled SG is operated independently without operating GFM-BESS. Fig. 3.17 shows the load sharing and frequency fluctuations when the load of the three-phase load device is changed to 0 kW, 20 kW, and 0 kW when the SG of Case 4 is operated stand-alone. When load changes $t = 2$ s, the output of SG is 20 kW. As the load increases, the system frequency gradually drops due to the inertia of the SG, the rotor accelerates by the generator governor, and the system frequency returns to 50 Hz due to the isochronous control characteristics. When the load sharing is changed to 0 kW at $t = 5.6$ s, the output of the SG returns to 0 kW. At the moment when the load fluctuates, the system frequency rises, but the rotor decelerates by the speed governor of the SG, and the system frequency returns to 50 Hz.

Fig. 3.18 shows the load sharing and frequency fluctuations when the load of the three-phase load device is changed to 0 kW, 40 kW, and 0 kW when the SG of Case 5 is operated stand-alone. When a load is applied to $t = 2$ s, the generator output is 40 kW. When the load increases, the system frequency gradually drops due to the inertial force of the generator, but the load fluctuation is 0.8 pu with respect to the power generation capacity of the SG, so the inertia of the SG is insufficient and the frequency is decreased to 46 Hz. It can be also confirmed that it decreased fast. Then, by the governor of the SG, the rotor accelerates and the system frequency returns to 50 Hz. When the load fluctuates to 0 kW at $t = 8.2$ s, the generator output returns to 0 kW. At the moment when the load fluctuates, the system frequency rises, but at this time, the acceleration protection function of the generator operates and the speed of the rotor is limited, so the frequency does not rise significantly even if the same load fluctuates. After that, the rotor decelerates and the system frequency returns to 50 Hz.

Fig. 3.19 (a) shows the load sharing when the load of the three-phase load device is changed to 0 kW, 40 kW, and 0 kW when the 50 kVA synchronous generator of Case 6 and two 20 kVA GFM-BESS units are operated in parallel. The command value of GFM-BESS is 0 kW. Since the system frequency is 50 Hz until $t = 2$ s, the actual output of GFM-BESS is 0 kW as instructed. When a load change of 40 kW is applied at $t = 2$ s, the SG and two GFM-BESS units share the load together. Fig. 3.20 (a) shows a zoom-in view of the load increase and the load sharing waveform. At the moment of load fluctuation, GFM-BESS and the SG share the load fluctuation at the same time by the mutual synchronization force, and then adjust the output to the steady state. The active power command value of GFM-BESS is 0 kW, and the system frequency returns to the standard 50 Hz by the isochronous control of the SG, so the load sharing of GFM-BESS is 0 kW in the steady state, and SG shares all the load of 40 kW. When operating in parallel with the isochronous controlled SG, it can be confirmed that GFM-BESS autonomously shares the excessive load fluctuation in transient and the output of the steady state following the command value. Fig. 3.20 (b) shows a zoom-in view of the load sharing waveform when the load is reduced. After reducing the load to 0 kW, the SG instantaneously outputs 0 kW, but since the GFM-BESS is equipped with a battery storage system, the GFM-BESS goes into

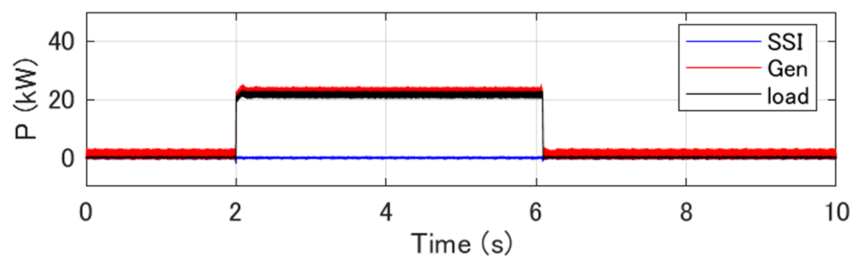
Chapter 3

charge mode and the extra energy is absorbed by the battery storage system of GFM-BESS. Even if the load suddenly drops, the rotor of the SG can be operated stably without over speed. GFM-BESS is considered to improve the flexibility and safety of the system.

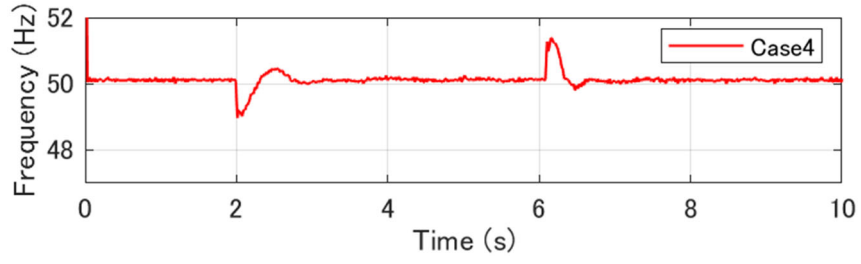
In Fig. 3.19 (b), the frequency fluctuation of Case 6 are shown. The load of the three-phase load device is changed to 0 kW, 40 kW, and 0 kW. The 50 kVA synchronous generator of Case 6 and two 20 kVA GFM-BESS units are operated in parallel. When a load change is applied at $t = 2$ s, the frequency gradually decreases to 49.3 Hz due to the inertia of the power generation device. The frequency rises due to the synchronization force of the power generation device, and the system frequency returns to 50 Hz by isochronous control. Compared with the case of the SG operating stand-alone in Fig. 3.18 (b), the SG also shares the 40 kW load, but it can be verified that the system in which GFM-BESS is operated in parallel has lower frequency fluctuation and larger inertia.

Table 3.5 Conditions of Experiment.

Case#	Generator	BES-SSI	Capacity	Load (kW)
Case 4	Isochronous control 50 kVA x 1	20 kVA x 2 (off)	50 kVA	0->20->0 (0.4 pu)
Case 5	Isochronous control 50 kVA x 1	20 kVA x 2 (off)	50 kVA	0->40->0 (0.8 pu)
Case 6	Isochronous control 50 kVA x 1	20 kVA x 2 (on) Pref=0 kW Pref=0 kW	90 kVA	0->40->0 (0.44 pu)

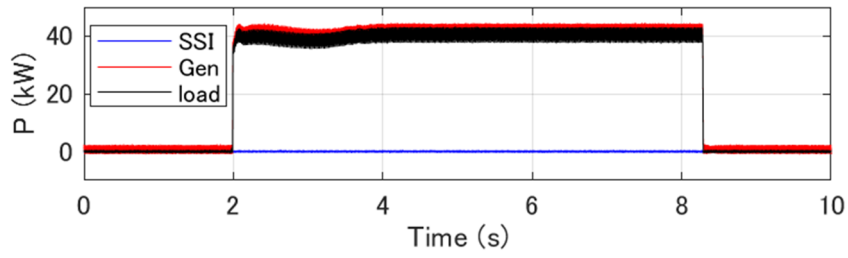


(a) Active power output of synchronous generator and load

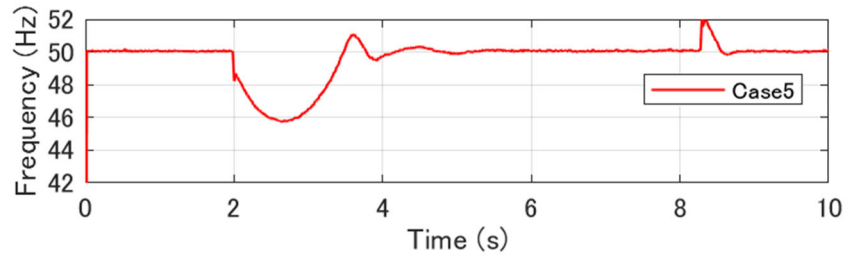


(b) Generator frequency

Fig. 3.17 Experimental result of Case4 (load:0kW $\Rightarrow$ 20kW $\Rightarrow$ 0kW)

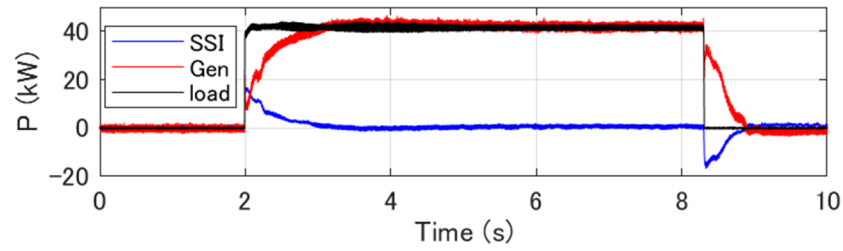


(a) Active power output of synchronous generator and load

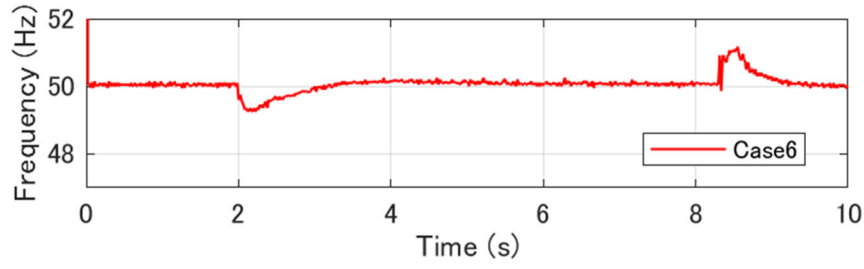


(b) Generator frequency

Fig. 3.18 Experimental result of Case5 (load:0kW $\Rightarrow$ 40kW $\Rightarrow$ 0kW)

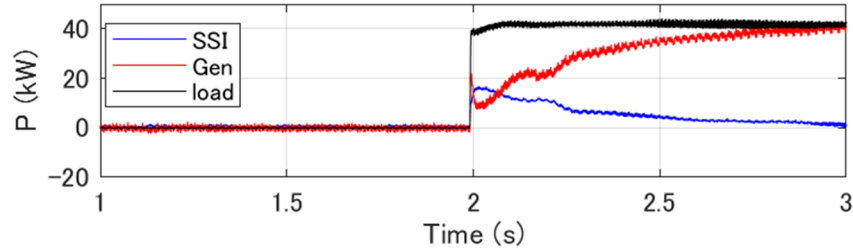


(a) Active power output of synchronous generator, GFM-BESS and load

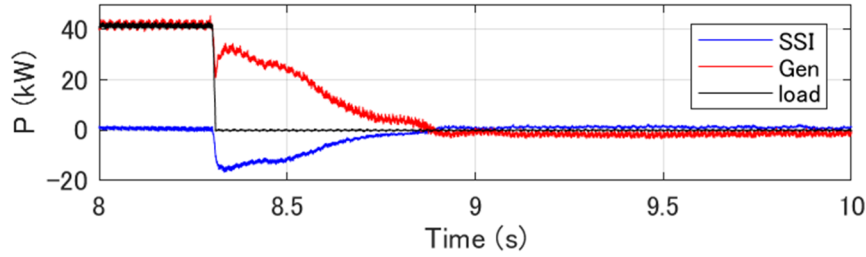


(b) Generator frequency

Fig. 3.19 Experimental result of Case6 (load:0kW $\Rightarrow$ 40kW $\Rightarrow$ 0kW)



(a) Load change from 0kW to 40kW



(b) Load change from 40kW to 0kW

Fig. 3.20 Active power output of Case6 (load:0kW $\Rightarrow$ 40kW $\Rightarrow$ 0kW)

3.3.3.2. Comparison of system inertial force fluctuations

Fig. 3.21 and Fig. 3.22 show the frequency fluctuations and RoCoF fluctuations of the system during load changes in Case 4, Case 5, and Case 6, respectively. When a 40 kW load change happens, Case 6 has two GFM-BESS units compared to Case 5, the inertia increases so that the system is maintained stable. We will compare the inertia change of the system from the load change test of Case 4 and Case 6. As mentioned above, the load fluctuations of Case 4 and Case 6 are 0.4 pu and 0.44 pu with respect to the power generation capacity, respectively, but they are regarded as the same comparison conditions. Table 3.6 summarizes the parameters for comparison. Since Case 6 has GFM-BESS, the frequency change rate after the load change is reduced, and the maximum frequency deviation value can be reduced by 0.3 Hz. It can be confirmed that GFM-BESS improves the inertia of the system.

Table 3.6 Evaluation of inertial force

Evaluation index	Case 4	Case5	Case 6
Maximum frequency drop [Hz]	49	45.5	49.3
RoCoF [Hz/s]	5.8	11	4

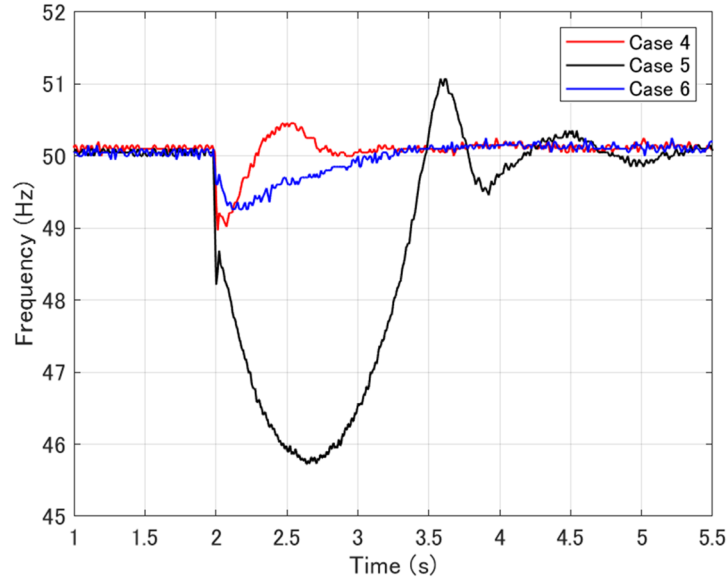


Fig. 3.21 Comparison of generator frequency droop

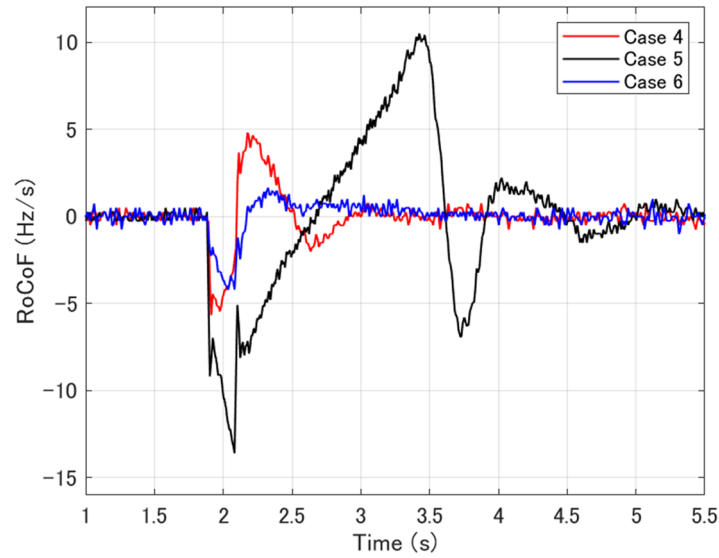


Fig. 3.22 Comparison of RoCoF

3.4. Conclusion

The inertia, load sharing, and frequency drooping characteristics of GFM-BESS in parallel with different mode SG in a simulated microgrid were verified by simulation and experiment. When the load changes suddenly, the GFM-BESS supplied the inertia power immediately without delay and

Chapter 3

shared the load changes at the same time with the paralleled SG. When operating in parallel with an isochronous controlled generator, GFM-BESS still outputs active power in a steady state if there is a frequency deviation. If there is no system frequency deviation, GFM-BESS outputs active power only in the transient state. When compared under the same conditions, it was confirmed that the system with GFM-BESS had larger inertia. In the case of parallel operation with the droop control generator, since the frequency drooping characteristic is included, there is a steady frequency deviation of the system, and GFM-BESS outputs active power in both transient and steady states. When the speed adjustment rate of the generator and the inverter is the same, the load fluctuation is shared in proportion to the capacity of generation devices. Comparing under the same conditions, it was confirmed that the system with GFM-BESS had larger inertia.

Chapter 4. System Stability Evaluation in a Full Scale

Microgrid

4.1. Introduction

Various research challenges for VSGs have been discussed in the literature cited above. However, only a few experimental demonstrations have been reported. The IEEE Standard Project 2988 for VSGs was launched on March 25, 2021, and it is considered to be a new technology that is nearly ready for practical use. Therefore, experimental demonstrations on a real-scale grid are important for establishing technical standards for VSGs. A small-scale microgrid field demonstration with five VSGs was implemented in [1]. The autonomous operation of a home grid to achieve tight voltage and frequency regulation was demonstrated without relying on a communication network. However, the home grid did not contain an actual SG, the parallel operation characteristics of VSGs and SGs were not clarified, and control of transient phenomena was not discussed. Ref. [2] discussed the parallel operation characteristics of VSGs and SGs, and [3] discussed the transient characteristics of VSGs in parallel with SGs. However, the SGs in [2] and [3] were motor generators, which are usually used for experiments in the laboratory. The characteristics of VSGs with a real SG are not clear. Ref. [4] characterized a real stand-alone gas-engine generator using a VSG and energy storage system but in a small-scale system.

Motivated by the above issues, the following novelties are presented to contribute to the body of knowledge.

- 1) We proposed a large-scale microgrid structure for operational evaluation. The microgrid consists of VSGs and a real diesel SG, which was constructed based on a real local microgrid. Almost the same power generation capacity and load change as a real local microgrid are used for experiments and evaluation. Moreover, the proposed microgrid increased the penetration ratio of inverters to 44.4%, which can offer a new style of distributed power generation system.
- 2) Because the rotor inertia constant of a diesel SG is not clearly established, we inferred the approximate inertia constant of the diesel SG from the experimental results in SG stand-alone mode. The SG model was constructed and the inferred inertia constant is then compared with the fitted inertia constant in the simulation for verification. This is expected to be helpful for simulations by other researchers on this topic.
- 3) A sudden-load-change demonstration experiment was implemented, and the characteristics of grid forming, synchronization, frequency regulation, and power sharing were demonstrated through field tests.

4) We proposed an evaluation scheme. The inverter with battery energy system (inverter-BESS) could operate in grid forming inverter with BESS (GFM-BESS) mode or grid following inverter with BES (GFL-BESS) mode. Under the parallel operation of the five 20-kVA inverter-BESS and the 125-kVA SG, six different combinations of GFM-BESS and GFL-BESS operation were evaluated comparatively. Different cases demonstrated that the system inertia was improved by increasing the penetration ratio of GFM-BESS.

5) Autonomous operation of the simulated grid to achieve frequency and power regulation was demonstrated without relying on a communication network.

6) We verify the inertial frequency step response by evaluating the frequency nadir and rate of change of frequency (RoCoF) of the experimental results, which demonstrate the actual inertial characteristic in the microgrid contained a diesel SG.

7) The actual transient and steady-state power sharing characteristics in the microgrid under different penetration ratios of GFM-BESS are analyzed and demonstrated.

8) There were some findings learned from the actual tests that were not predicted by the simulations. Because the inertia constant of the 125-kVA SG is very small, a large load change may cause the inverters to shut down for protection in low GFM-BESS penetration ratio cases. The step response delay of the diesel SG is not constant because of its actual mechanical characteristics, and the delay varies between different load changes. The high quality BESS can recharge very quickly to provide inertial energy

4.2. Description of the Imitated Microgrid

4.2.1. Microgrid Characteristics

The inverters had two control modes, GFL-BESS mode and GFM-BESS mode. All the GFM-BESS units are equipped with a self-synchronized droop controller with many advanced functions, including black-start and grid-forming capabilities, self-synchronization without a PLL, voltage and frequency regulation, and power-sharing control. The purpose of the developed GFM-BESS was to achieve stable operation in off-grid locations, microgrids, or islands with over 70% penetration rate of renewable energy sources in the future, and contribute to CO₂ emission reduction. In particular, in conventional research and development, installing a large battery storage system in one place is efficient for large-scale systems such as power transmission and distribution systems where power demand and power supply configurations do not change easily. However, in islands and microgrids, it is considered difficult to apply a large-scale system from the point of view of ensuring the flexibility of system construction. In contrast, the approach of installing a battery storage system in a small and distributed manner is suitable for flexibly changing the system configuration according to changes in the supply and demand.

Therefore, GFM-BESS is thought to be suitable for application in relatively small-scale grids, such as new regional electric power systems and off-grid locations. The battery packs store energy when the load demand is less than the generation capacity, and release energy when the load demand is greater than the capacity.

The microgrid used for the demonstration experiment was built based on a real microgrid in Mutsuzawa, Japan. The semi-microgrid in Mutsuzawa consists of two SG 80-kVA units, a 20-kW GFL-PV system, and a load (20 home units). Based on the real load fluctuation data in Mutsuzawa shown in Fig. 4.1, a nearly 50-kW-scale load changes occur over a short time. The simulated microgrid was built with the microgrid architecture and simulated using a diesel SG and GFM-BESS units at approximately 1:1 power capacity scale with Mutsuzawa, and was operated under the same load changes. In the simulated grid, inverter-BES units are used instead of part of the SG capacity, and the inverter-BES units achieved a power generation penetration of 44.4%. The configuration of the simulated microgrid is shown in Fig. 4.2. In this study, an experimental demonstration based on the real power capacity scale model was implemented.

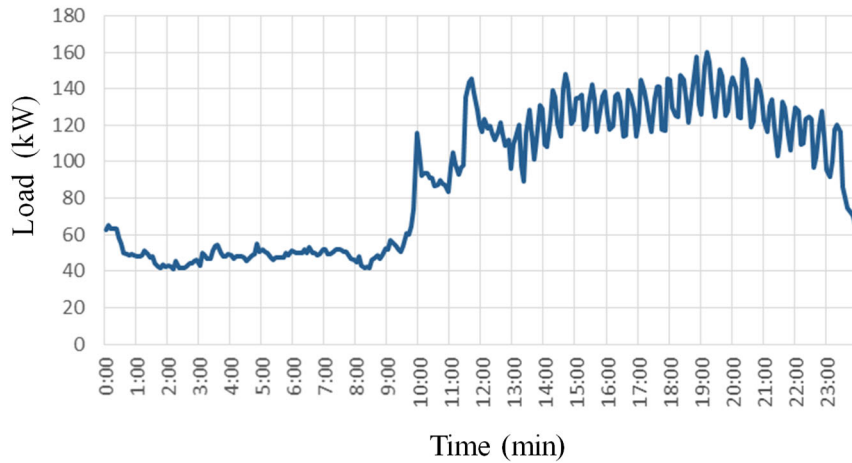


Fig. 4.1 Real load change data of Mutsuzawa, Japan, over 23 min

4.2.2. Configuration of the Imitated Microgrid

Fig. 4.2 shows the microgrid system comprising a 125-kVA SG, which is the main power generator of the microgrid, and five 20-kVA inverter-BES units. The voltages of the inverters are set to 202 V for the voltage drop of the transmission lines. Because proof of concept (PoC) safety management is difficult if the power grid is set to 6.6 kV, the power grid was set to 400 V. Considering the flow ability of the transformer, a Y connection node was used for the bus side. The neutral point of the Y connection side floated. Three 50-kW three-phase devices were connected in parallel as the load. To confirm the effect of the transformer, one of the five inverter-BES units was connected under a 50-kVA transformer.

Fig. 4.3 shows the 125-kVA diesel generator, for which the terminal voltage was set to 440 V and the operation frequency was 50 Hz. Fig. 4.4 shows the demonstration environment, which was housed in a shielded room. Field operation of the microgrid was performed to demonstrate the operation of the system: (1) Evaluation of the inertia constant of the diesel SG by simulation and experiment; (2) Multiple GFM-BESS units in parallel with diesel SG and GFL-BESS to respond automatically to load fluctuations within a few seconds without relying on a communication network; (3) Many advanced functions, namely, grid forming, synchronization, frequency regulation, and power sharing; (4) Confirmation of the inertial effect on frequency fluctuations according to sudden load changes under the cases of different ratio of GFM-BESS penetration; (5) Confirmation of the effect of the impedance of the transformer; (6) Confirmation of power sharing in transient and steady states.

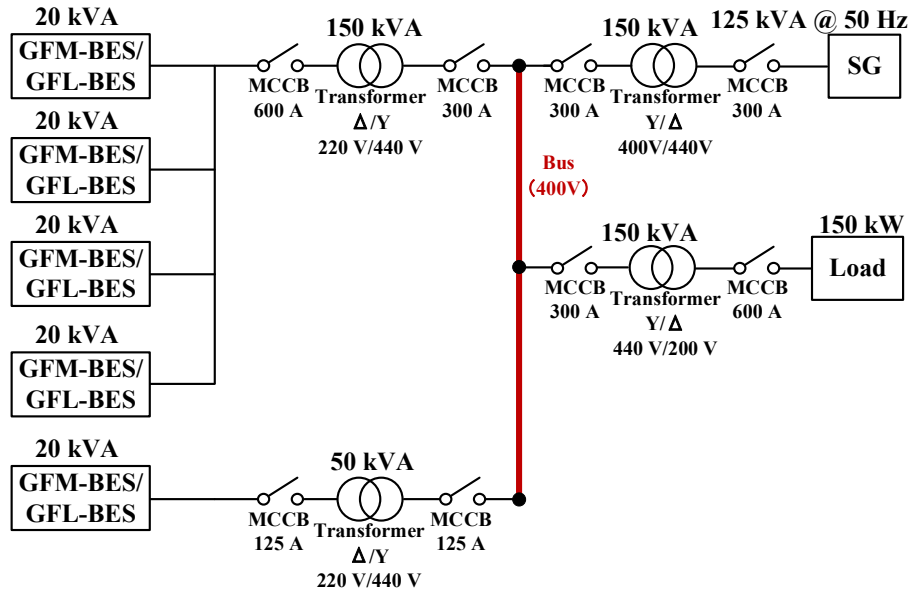


Fig. 4.2 Configuration of the simulated microgrid (MCCB = molded-case circuit breaker)



Fig. 4.3 125-kVA diesel synchronous generator

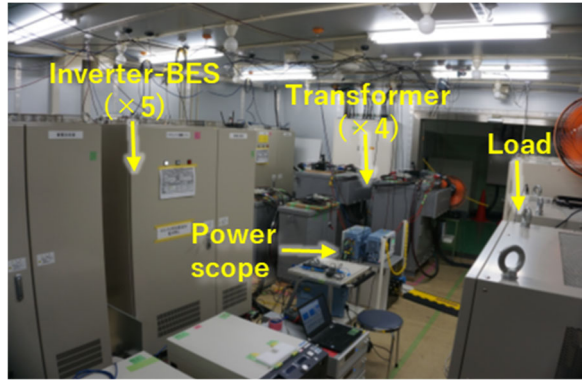


Fig. 4.4 Demonstration environment in a shield room

4.2.3. Frequency Measurement

The grid frequency was calculated by counting the number of zero crossings of the grid voltage. A moving average method was then implemented for the frequency average calculation to reduce error. It is important to select an appropriate sampling frequency for the measurement instruments and select an appropriate interval time for the moving average method. In this study, a power scope with a sampling frequency of 50 k/s is selected for grid voltage measurement. Because the commanded grid frequency is 50 Hz, the interval range for the moving average calculation was set to 100 points. This means that the frequency is refreshed every 0.002 s after the moving average calculation. Because the grid frequency changes every 0.02 s, the frequency calculation is thought to be accurate.

4.3. GFM-BESS and Diesel Synchronous Generator in Stand-Alone Mode

Because demonstration experiments in the field of power systems are expensive and difficult to implement for many researchers, simulation is an important research method, and parameters that closely approximate real equipment are very important for accurate modeling and simulations. For example, according to the standard system model of the Institute of Electrical Engineers of Japan, the rotor inertia constant of a large-capacity thermal power generator is between 7 s and 10 s. It is convenient to use this value for a large-scale grid simulation. However, the rotor inertia constant of the small-capacity power generators used for small-scale grids, such as microgrids, has not been clearly established. This section describes how the rotor inertia constant of the 125-kVA diesel SGs used in small-scale microgrids was surveyed by calculating from the experimental results. The calculated results were compared with simulation results.

4.3.1. GFM-BESS in Stand-Alone Mode

First, simulation of the GFM-BESS stand-alone mode was implemented to compare the result with the experimental result. Parameters for the GFM-BESS are shown in Table 4.1. The active power command value for the GFM-BESS was 20 kW, and the load change was 20 kW. As shown in Fig. 4.5, the slopes of the frequency decrease in the simulation result and experimental result are almost the same. This confirms that the GFM-BESS operated as designed.

Table 4.1 Parameters of GFM-BESS and Diesel SG

Parameter	Value	Parameter	Value
$V_{\text{base_GFM}}$	200 V	M_{GFM}	8.0 s
$S_{\text{base_GFM}}$	20 kVA	D_{GFM}	1.0
$f_{\text{base_GFM}}$	50 Hz	Droop gain (GFM-BESS)	-4%
L_s	0.05 pu.	Xslope gain	-4%
Phase compensation	(1+0.16s)/ (1+0.04s)	Voltage control	20/s
$V_{\text{base_SG}}$	400 V	$S_{\text{base_SG}}$	125 kVA
$f_{\text{base_SG}}$	50 Hz	Droop gain (SG)	-4%

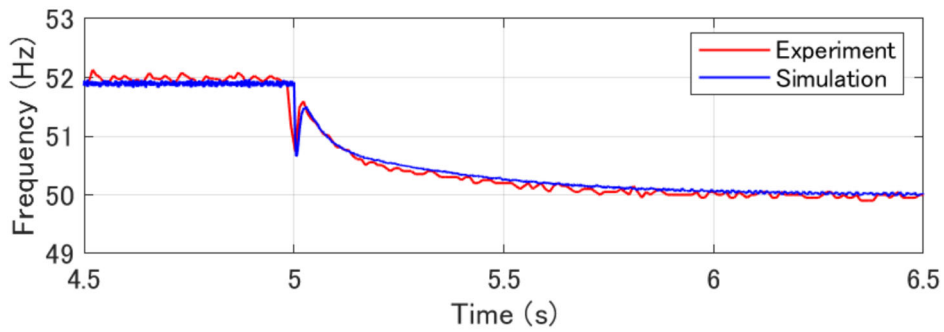


Fig. 4.5 Frequency regulation of GFM-BESS operating on stand-alone mode

4.3.2. SG in Stand-Alone Mode

The parameters of the SG as taken from the nameplate are shown in Table 4.1. Because the rotor inertia constant of diesel SGs has not been clearly established, the approximate inertia constant of the diesel SG is inferred from the experimental results. The inferred inertia constant is then compared with the fitted inertia constant in the simulation.

The inertia constant can be calculated based on the swing equation of the SG rotor as shown in (5)

where M is the unit inertia constant, ω_{mea} is the system angular frequency, T_m is the mechanical torque, T_e is the electrical torque, T_d is the braking torque, P_m is the mechanical power of SG, P_{mea} is the electrical output of the active power, and P_d is the braking power.

$$T_m - T_e - T_d = \frac{P_m - P_{\text{mea}} - P_d}{\omega_{\text{mea}}} = M \frac{d\omega_{\text{mea}}}{dt} \quad (5)$$

Equation (6) is defined for the case of a sudden load change ΔP occurring. The braking power P_d is ignored for simplicity of calculation.

$$\Delta P = P_m - P_{\text{mea}} = M \omega_{\text{mea}} \frac{d\omega_{\text{mea}}}{dt} \quad (6)$$

Three cases of sudden load change experiments, for changes of 20 kW, 30 kW, and 50 kW are implemented for determining the inertia constant. The frequency regulation of the SG operating in stand-alone mode is shown in Fig. 4.6 for the three cases. Based on (6), the change in frequency over 0.1 s was used for the calculation. The instantaneous frequency and frequency deviation and the calculated inertia constant of the three cases are summarized in Table 4.2. Note that all of the parameters in the calculation use the pu value. The inertia constant of the diesel SG is approximately 1.5 s.

The SG model shown in Fig. 4.7 is studied in the simulation. The model was also built based on the swing equation of the SG rotor. The delay of the power regulation is emulated by T_{sg} . The SG parameters in the simulation are summarized in Table 4.3. Like the experiment, three cases of sudden load changes of 20 kW, 30 kW, and 50 kW were implemented to evaluate the inertia constant. A fitted inertia constant of 1.12 s was obtained by tuning the parameter of M in Fig. 4.7. Because the rotor inertia constant of diesel SGs has not been clearly established, the parameters of the SG model in MATLAB were used for reference. As shown in Table 4.4, 0.34 s was assumed for the default inertia constant of the 125-kVA diesel SG. When the load change is 50 kW, the simulation and experimental results of the SG in stand-alone mode are compared. Comparisons of SG with the default inertia constant 0.34 s, and the fitted inertia constant 1.12 s, and the experiment results are shown in Fig. 4.8. With the default value, the frequency slope of the simulation is smaller than that of the experimental results. With a fitted inertia constant of 1.12 s, the frequency slope of the simulation matches the experiment very well.

The difference in the inertia constant of the SG between the value calculated from the experimental results and the value obtained by fitting to the simulation is probably due to differences between the calculation and the real mechanical characteristics of the actual diesel SG. This paper discusses only the effect of the rotor inertia constant, and studying the effect of other parameters is planned as future work. The inertial constant of the 125-kVA diesel SG is considered to be around 1.12 s.

The frequency regulation of an SG operating in stand-alone mode in the simulation is shown in Fig.

Chapter 4

4.9 for the three cases. Compared with the experimental results in Fig. 4.8, it can be seen that the time to reach the minimum frequency is the same in the simulation but different in the experiment. The time to reach the minimum is affected mainly by T_{SG} , which is the power regulation delay. Although it is a constant value in the simulation and the delay in a real diesel SG is controlled by an electric governor, the load change response speed is also affected by the value of the load change. This is one lesson learned from the demonstration experiment.

Table 4.2 Inertia calculation of SG from experiment results

Metric	Case 1	Case 2	Case 3
Load change (kW)	20	30	50
instantaneous frequency in experiment (Hz)	50.76	50.36	49.64
Frequency deviation in experiment (Hz)	0.52	0.72	1.26
Calculated from experiment			
M (s)	1.51	1.65	1.59

Table 4.3 Parameters of SG in simulation

Parameter	Value	Parameter	Value
V_{base_SG}	400 V	X_d'	0.3 pu
S_{base_SG}	125 kVA	X_d''	0.23 pu.
f_{base_SG}	50 Hz	X_q	1.65 pu.
M_{sg_fitted}	1.12 s	X_q'	0.25 pu
$M_{sg_default}$	0.34 s	X_q''	0.15 pu.
X_d	1.81 pu	T_{SG}	0.3 s

Table 4.4 SG parameters in MATLAB model

Case	Frequency	Capacity	Pole Pairs	M
1		85 kVA	4	0.2072 s
2	50 Hz	250 kVA	4	0.3506 s
3		670 kVA	4	0.3694 s
4	60 Hz	100 kVA	4	0.2536 s
5		300 kVA	4	0.3972 s

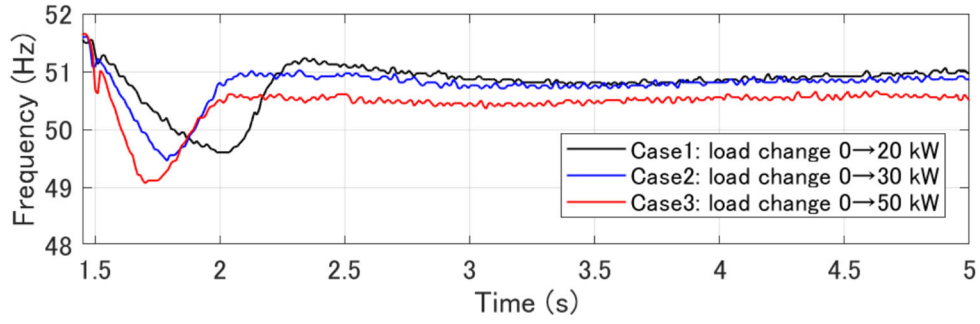


Fig. 4.6 Frequency regulation of SG operating on stand-alone mode in three cases load change experiment

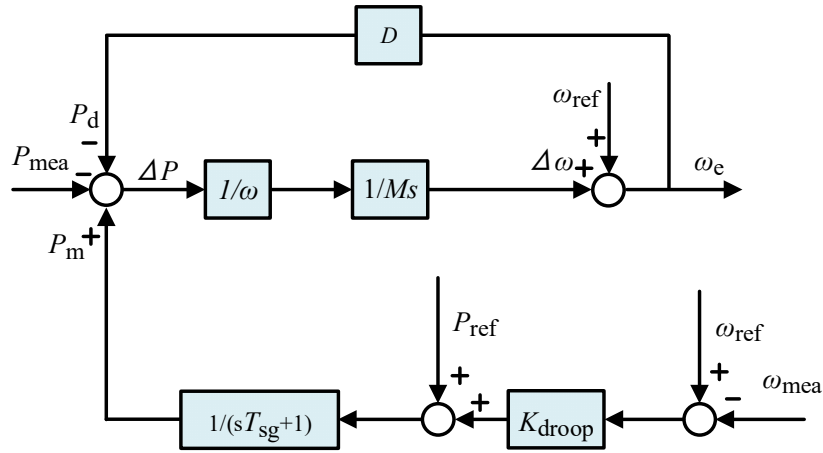


Fig. 4.7 Block diagram of SG control algorithm used in simulation

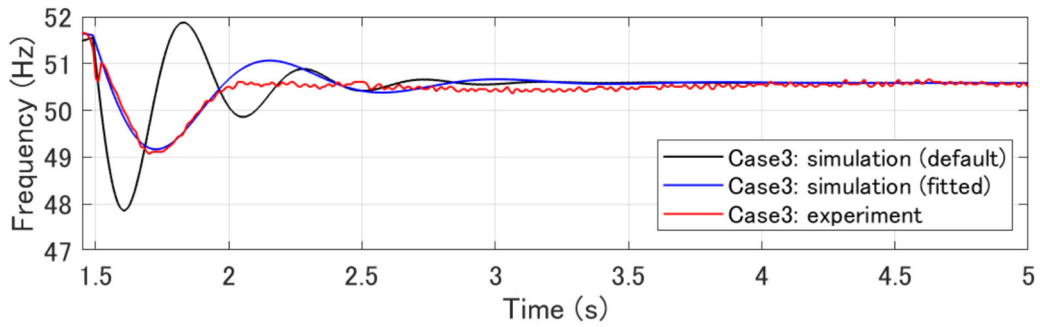


Fig. 4.8 Frequency regulation of SG operating on stand-alone mode in three cases load change experiment

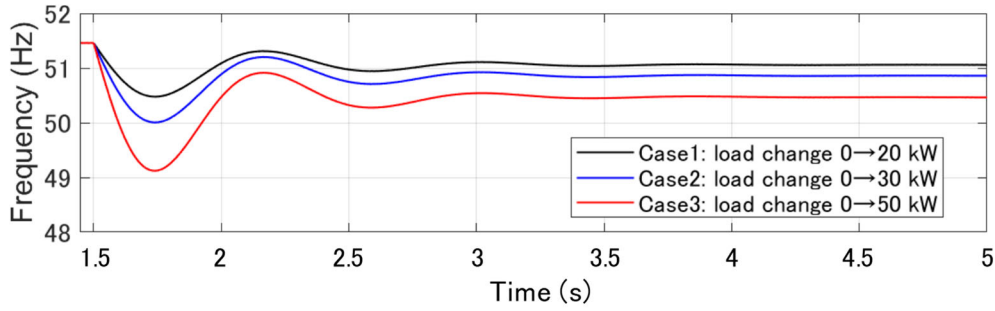


Fig. 4.9 Frequency regulation of SG operating on stand-alone mode in three cases load change simulation

4.4. IBR in Parallel with a Droop Mode Diesel Synchronous Generator

The developed GFM-BESS units can be switched to GFL-BESS mode, which is a normal current control inverter mode, by setting the control software. Under the parallel operation of five 20-kVA inverter-BES units and the 125-kVA SG, the penetration ratio of GFM-BESS and GFL-BESS was changed in six cases. The response to load changes of the SG, GFM-BESS, and GFL-BESS were compared for system inertia evaluation in a sudden load change experiment.

Table 4.5 Experimental conditions

Case #	Numbers of Inverters		GFM-BESS penetration (power capacity of GFM-BESSs / power capacity of total system) (%)	Load change (kW)
	GFM-BESS	GFL-BESS		
Case 1	0	5	0	72 to 120
Case 2	1	4	8.8	72 to 120
Case 3	2	3	17.7	72 to 120
Case 4	3	2	26.6	72 to 120
Case 5	4	1	35.5	72 to 120
Case 6	5	0	44.4	72 to 120

4.4.1. Results from field operations

The parameters of the GFM-BESS units and diesel SG are shown in Table 4.1. The experimental conditions are shown in Table 4.5. The initial load was 72 kW. All of the active power reference values of the inverters were set to 6.4 kW, with the remaining 40 kW shared by the SG. The rotor speed of the SG was adjusted by operating the operation panel of the SG until a grid frequency of 50 Hz was achieved. At this moment, the active power command value of the SG was 40 kW theoretically. This is considered the initial state. Because the inertial constant of the GFM-BESS is 8 s, 10 s of data were taken by power scope for each experiment.

In case 1, five GFL-BESS units and one SG were operated in parallel. The load changed from 72 kW to 120 kW at $t=1.5$ s, and the power sharing and frequency change are shown in Fig. 4.10. Because the GFL-BESS units do not have inertia, it was found that even if the load fluctuated at $t=1.5$ s, the GFL-BESS output followed the reference value of 6.4 kW without sharing the load. The load sharing of the SG is 90 kW, which is equivalent to 0.4 pu of power generation capacity. As the load increases, the grid frequency gradually drops due to the inertia of the SG, and finally has a significant transient drop to 47.6 Hz. It can be concluded that the inertia of the diesel SG is very small. After this, the synchronous force of the SG accelerates the rotor, and the grid frequency returns to 49.47 Hz due to the frequency drooping characteristics in steady state.

The power sharing and frequency change in case 2 are shown in Fig. 4.11. The active power reference value of the GFM-BESS is 6.4 kW. Because the grid frequency is 50 Hz until $t=1.5$ s, the actual output of the GFM-BESS units is also 6.4 kW, as commanded. The output of the GFL-BESS units still follows the reference value of 6.4 kW without sharing the load change. After the load change at $t=1.5$ s, the load is shared by one GFM-BESS unit and the SG together. At the moment of load fluctuation, the GFM-BESS and SG share the load fluctuation at the same time by the mutual synchronization force. After this, the output of the GFM-BESS gradually increases, and the output of the SG gradually decreases. However, due to the low inertia of the diesel SG, the frequency deviation is very large during transients. Due to the droop control and inertia of the GFM-BESS, the output of the GFM-BESS keeps increasing to regulate the frequency deviation. Finally, it reaches the overload protection limit and shuts down the inverter. Although the load change of 48 kW, which is equivalent to 0.213 pu of the power generation capacity, is not large, it should be noted that the inertia of the diesel SG is too low and may cause GFM-BESS shutdown when GFM-BESS units operate with a diesel SG.

The power sharing and frequency change in case 3, where two GFM-BESS units are active, are shown in Fig. 4.12. When the frequency was 50 Hz before $t=1.5$ s, the droop control of the GFM-BESS did not operate and the GFM-BESS output before $t=1.5$ s is the same as the commanded value of 6.4 kW. The GFL-BESS operated in the same way as discussed above. When the load suddenly

changed at $t=1.5$ s, the GFM-BESS and SG start to share the load change due to the mutual synchronous force. The GFM-BESS output then increases gradually, and the SG output decreases gradually until both reach a steady state. Load sharing of SG and inverters in the steady state can be calculated based on (7) and (8), where ΔP is the total load change, P_{ni} is the rated power of each power generation device, ΔP_i is the power sharing of each power generation device, $K_{\text{droop}i}$ is the droop rate of each device, f_n is the based frequency, and Δf is the frequency deviation in the steady state.

$$\Delta f [\text{pu}] = -K_{\text{droop}1} \frac{\Delta P_1}{P_{n1}} = \cdots - K_{\text{droop}n} \frac{\Delta P_n}{P_{nn}} \quad (7)$$

$$\Delta P = \Delta P_1 + \Delta P_2 + \cdots \Delta P_n \quad (8)$$

Eliminate Δf from (7) and (8), so that

$$\Delta P_i = \left(\frac{\frac{P_{ni}}{K_{\text{droop}i}}}{\sum_{j=1}^n \frac{P_{nj}}{K_{\text{droop}j}}} \right) \Delta P \quad (9)$$

Because the droop gain of the GFM-BESS and SG units is the same as shown in Table 4.1, the load sharing in the steady state is proportionally shared with the rated power of each power generation device. In the steady state, the load sharing calculated from (9) is 12.2 kW for the GFM-BESS and 76.3 kW for the generator, which matches the test results in Fig. 4.12. It was confirmed that the GFM-BESS units could share the load power autonomously. When the load suddenly changed at $t=1.5$ s, the frequency gradually decreased to 48.68 Hz due to the inertia of the power generation device, the frequency increased due to the synchronization force of the power generation device, and the system frequency returned to 49.53 Hz due to the frequency drooping characteristic. By increasing the penetration ratio of GFM-BESS in the system, the inertia of the system could be increased and the frequency deviation during transients could be suppressed.

Three GFM-BESS units were implemented in case 4. The power sharing and frequency regulation are shown in Fig. 4.13. In the case where the load changed to 48 kW, the maximum transient power sharing of each GFM-BESS unit was 17.7 kW, and the maximum frequency deviation was 0.93 Hz. Increasing the penetration ratio of GFM-BESS significantly improved the stability of the system. The power sharing and frequency change in cases 5 and 6 are shown in Fig. 4.14 and Fig. 4.15, respectively. The number of GFM-BESS units in the system increased from four to five. The frequency nadir reduction effect by GFM-BESS due to inertia imitated control was further confirmed.

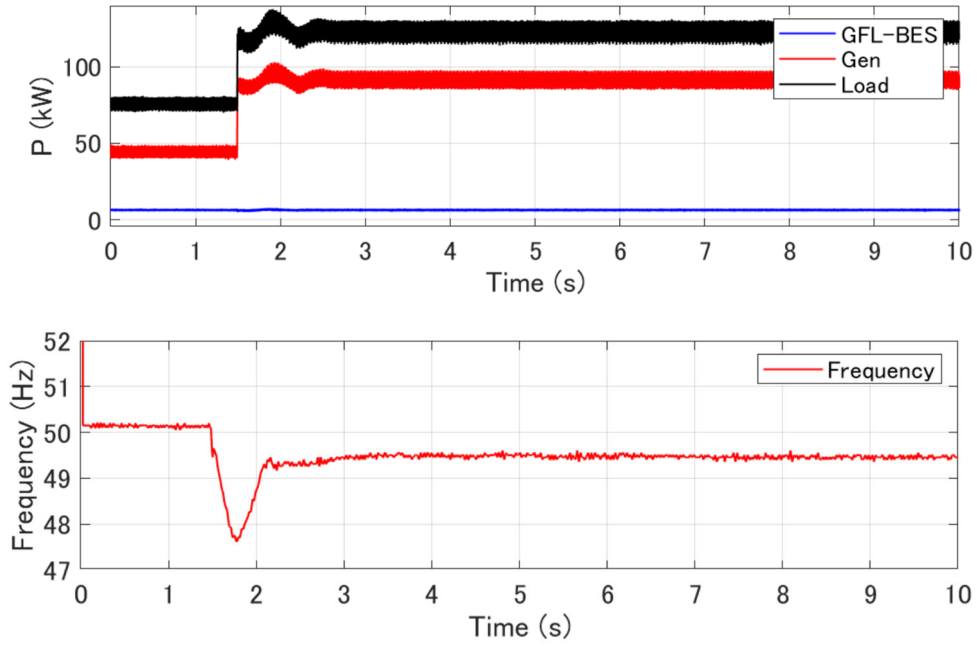


Fig. 4.10 Case 1: Power sharing and grid frequency change for five GFL-BESS units, zero GFM-BESS units, and one SG

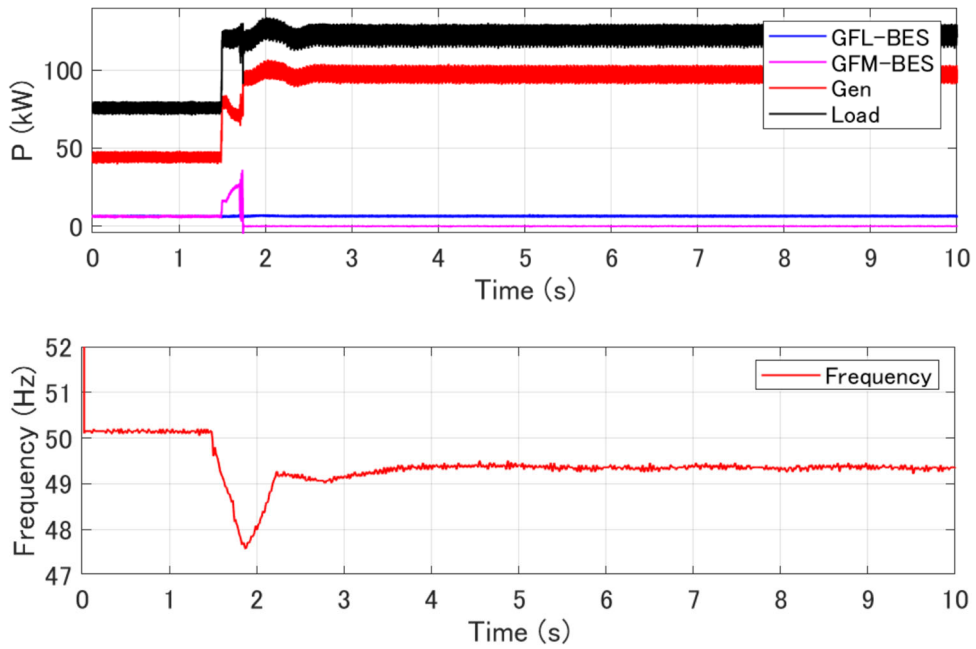


Fig. 4.11 Case 2: Power sharing and grid frequency change for four GFL-BESS units, one GFM-BESS unit, and one SG

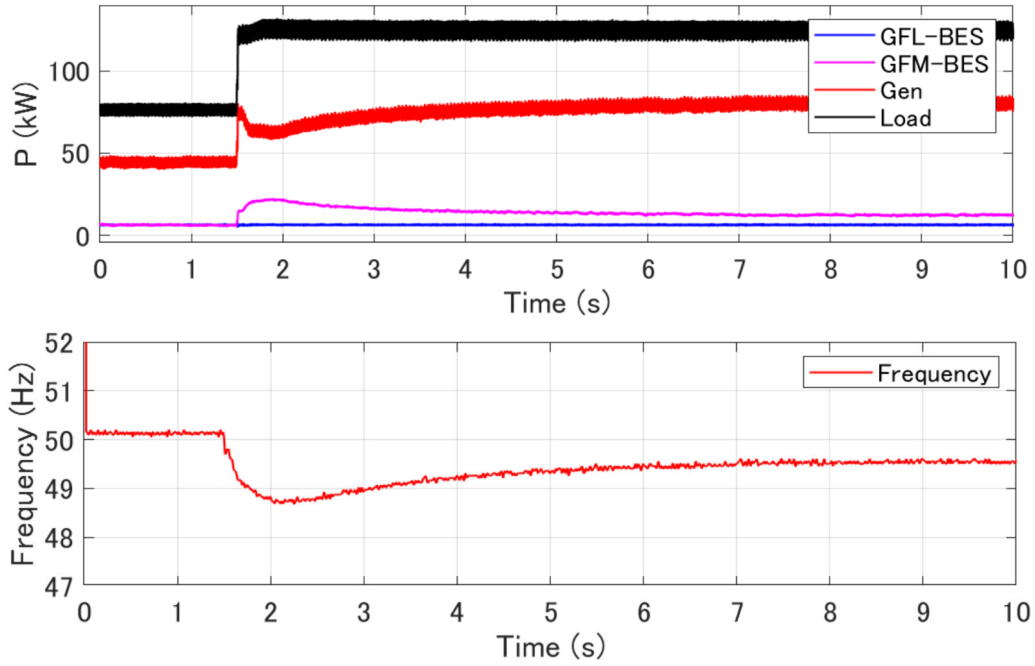


Fig. 4.12 Case 3: Power sharing and grid frequency change for three GFL-BESS units, two GFM-BESS units, and one SG

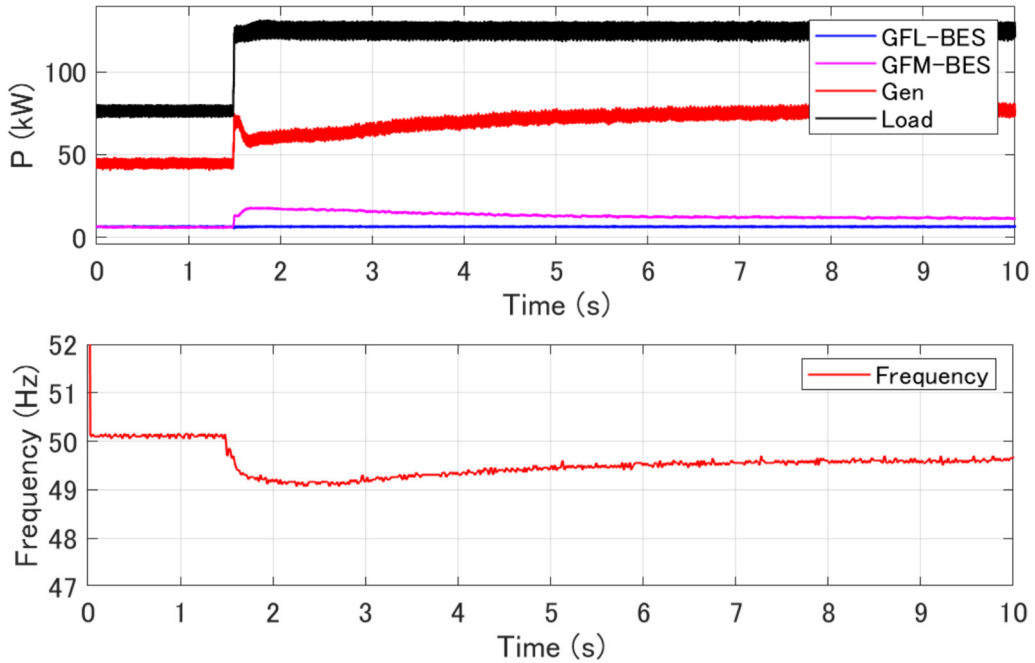


Fig. 4.13 Case 4: Power sharing and grid frequency change for two GFL-BESS units, three GFM-BESS units, and one SG

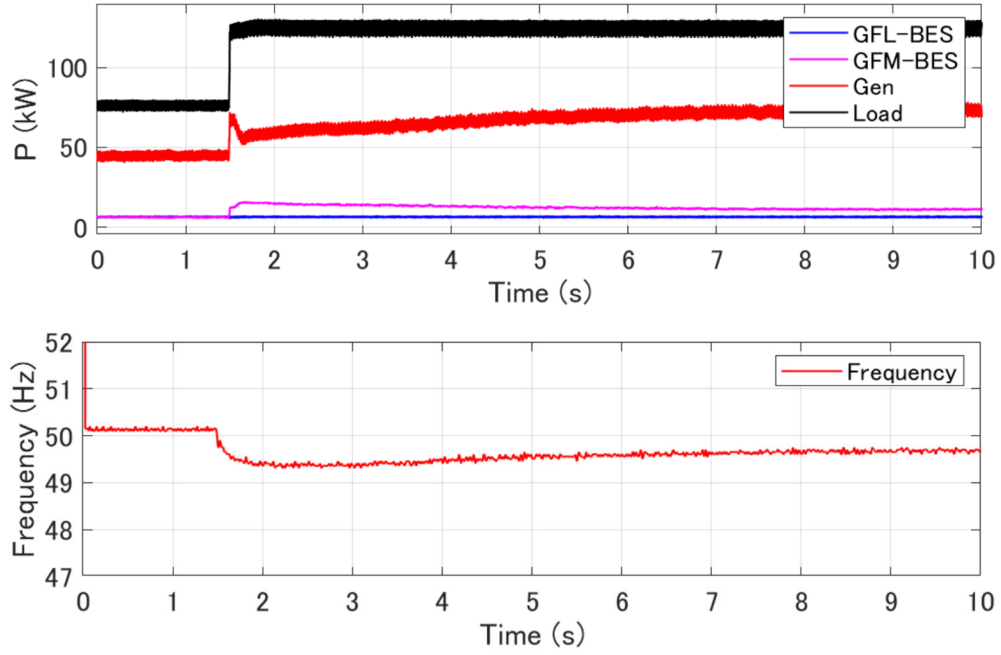


Fig. 4.14 Case 5: Power sharing and grid frequency change for one GFL-BESS unit, four GFM-BESS units, and one SG

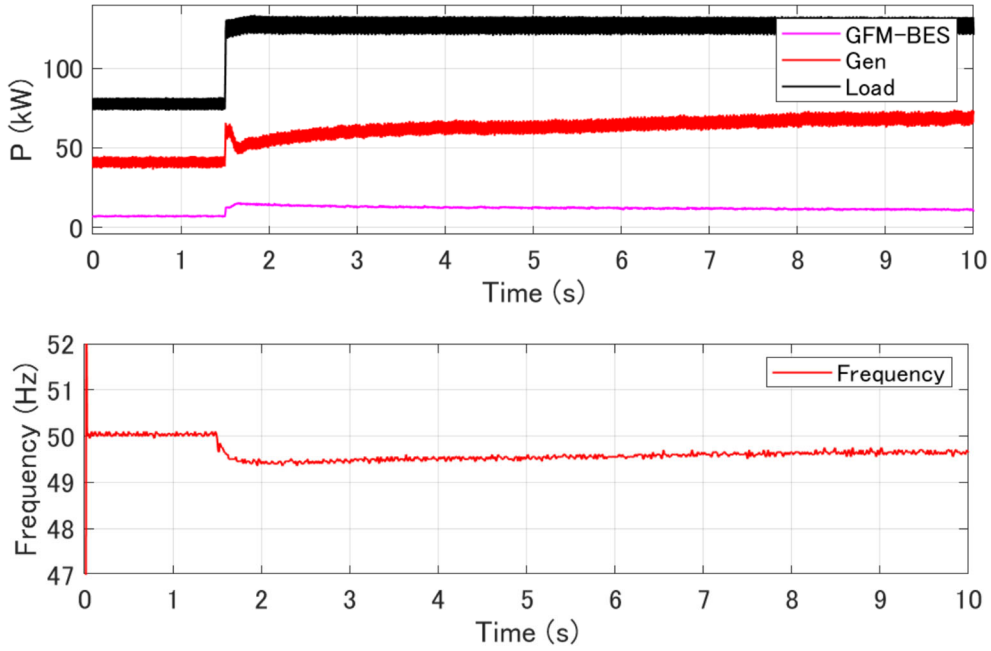


Fig. 4.15 Case 6: Power sharing and grid frequency change for zero GFL-BESS units, five GFM-BESS units, and one SG

4.4.2. Effect of Transformer Impedance

The active power output of each GFM-BESS unit when all five units were operated in parallel is shown in Fig. 4.16. All five GFM-BESS units have the same characteristics. Four GFM-BESS units are connected with a transformer with a rated power of 150 kVA, rated voltage of 440 V, and impedance of 3.71 %, and one GFM-BESS unit is connected with a transformer with a rated power of 50 kVA, rated voltage of 440 V, and impedance of 3.28 %. As shown in Fig. 4.16, the transient and steady-state characteristics of each GFM-BESS unit are almost the same, confirming that the influence of different transformer impedance is small.

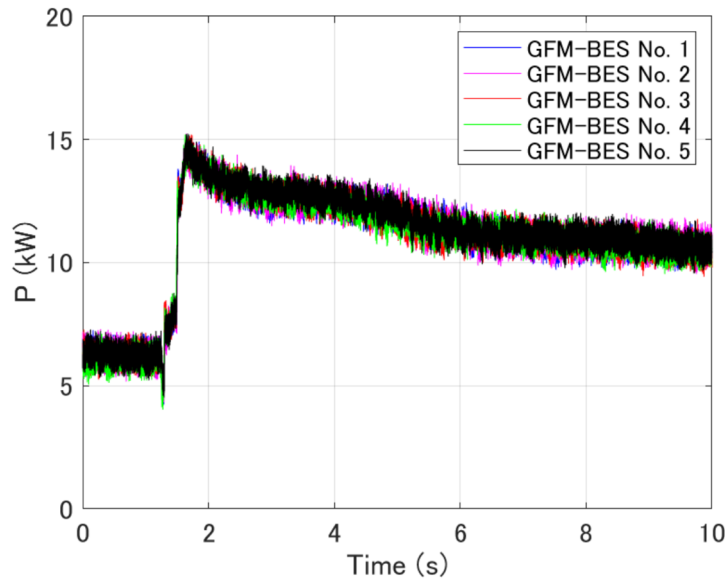


Fig. 4.16 Load sharing comparison of each GFM-BESS in case 6.

4.4.3. System Stability Evaluation Versus GFM-BESS Penetration Ratio

Evaluation of the inertial effect for different GFM-BESS penetrations ratio is discussed in this section. Frequency regulation with different GFM-BESS penetrations is shown in Fig. 4.17. In the case of one GFM-BESS unit, the load fluctuation exceeds the surplus capacity of the GFM-BESS, and as shown in Fig. 4.11, the GFM-BESS is inactivated by the protection function. Thus, case 2 was excluded from the comparison. It was confirmed that when the load changed, the GFM-BESS contributed to frequency adjustment. One index for evaluating the inertia is the minimum frequency nadir. As the penetration ratio of the GFM-BESS increases, the frequency nadir increases significantly. Compared with zero and five GFM-BESS units, the minimum frequency nadir with respect to load fluctuation could be reduced by 1.75 Hz. The frequency nadir in different cases is summarized in Table 4.6.

The other evaluation index of inertia is the rate of change of frequency (RoCoF). The RoCoF evaluation index is defined as the frequency reduction rate at the time of system upset as shown in

(10).

$$\text{RoCoF} = \frac{\Delta f}{\Delta t} \quad (10)$$

The grid code RoCoF limit in England and Ireland is 1 Hz/s (Δt is 0.5 s); in Germany is 2 Hz/s (Δt is 0.5 s); in Spain, Italy and Denmark is 2 Hz/s (Δt is 1 s). However, the grid code RoCoF limit in Japan has not been decided. According to grid interconnection regulations, power generation devices need to be able to tolerate (continue to operate) under a frequency fluctuation of 2 Hz/s (the fault ride-through regulation). In this study, $\Delta t = 0.1$ s is used for the RoCoF calculation by giving consideration to the minimum detection time in this paper. It is assumed that distributed power generation devices follow this regulation. The RoCoF in different cases is summarized in Table 4.6.

In case 1 and case 3, the RoCoF is over 2 Hz/s. In particular, two GFM-BESS units are active in case 3, and when the RoCoF exceeds 2 Hz/s, the distributed power generation devices are consecutively dropped, further reducing the frequency that may lead to a blackout. In case 4, the GFM-BESS penetration is 26%, and operation is considered to be stable even when a large load change occurs either on-grid or off-grid. It was confirmed that increasing the GFM-BESS penetration can improve the inertia of the power system. The trend of the frequency change rate and frequency nadir due to the different GFM-BESS penetrations ratio are compared in Fig. 4.18. It can be found that the RoCoF will lower than 2 Hz/s if the penetration ratio of the GFM-BESS is over 20%. The frequency change rate of the generation system is reduced significantly, and the frequency nadir is increased significantly by increasing the GFM-BESS penetration, which also verified that system inertia increases with increasing the GFM-BESS penetration ratio.

Table 4.6 Inertia evaluation

Metric	Case 1	Case 3	Case 4	Case 5	Case 6
GFM-BESS penetration (%)	0	17.7	26.6	35.5	44.4
Frequency nadir (Hz)	47.62	48.68	49.07	49.36	49.37
Maximum Frequency deviation (Hz)	2.38	1.32	0.93	0.64	0.63
RoCoF (Hz/s)	7.93	2.44	1.52	1.23	1.13
Steady state frequency (Hz)	49.47	49.53	49.61	49.65	49.67

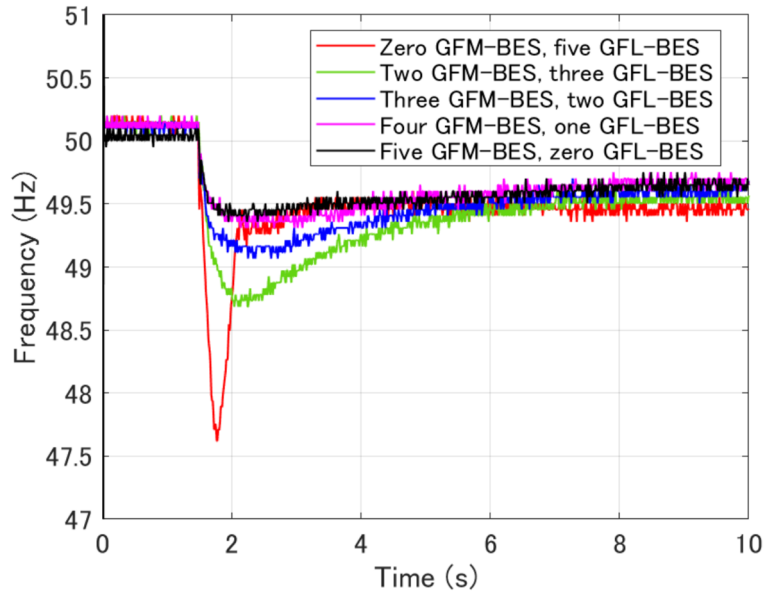


Fig. 4.17 Frequency regulation with different penetrations of GFM-BESS.

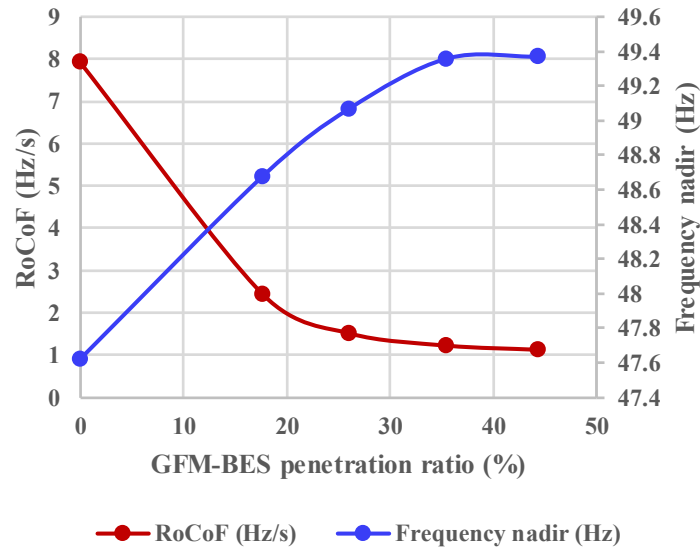


Fig. 4.18 RoCoF index and Frequency nadir with different penetrations ratio of GFM-BESS.

4.4.4. Power Sharing Evaluation Versus GFM-BESS Penetration Ratio

Load sharing of one GFM-BESS unit and an SG with different GFM-BESS penetrations is shown in Fig. 4.19 and Fig. 4.20, respectively. The power sharing in transient and steady states under different GFM-BESS penetrations ratio are summarized in Table 4.7. Steady state load sharing calculated based

Chapter 4

on (9) compared with the experimental results are also summarized in Table 4.7. Compared with two GFM-BESS units in case 3 and five GFM-BESS units in case 6, according to the increased system inertia, the maximum transient power sharing of GFM-BESS and SG could be reduced by 5.6 kW and 14.8 kW, respectively. According to the GFM-BESS droop control, the load sharing of GFM-BESS and SG in the steady state could be reduced by 1.9 kW and 14.7 kW, respectively. The trend of the transient load sharing of SG and GFM-BESS with different penetrations of GFM-BESS are shown in Fig. 4.21. The transient load sharing reduced linearly by increasing the GFM-BESS penetration. It can be found that the maximum transient power sharing of GFM-BESS is lower than 20 kW if the penetration ratio of the GFM-BESS is over 20 %. The GFM-BESS will operate in safety because the rated power of GFM-BESS is 20 kW. The trend of the steady-state load sharing of GFM-BESS and SG with different penetrations of GFM-BESS in simulation and experiment are shown in Fig. 4.22. The steady-state load sharing also reduced linearly by increasing the GFM-BESS penetration. The error between the simulation results and the experimental results is less than 10%.

The results confirm that it is possible for multiple GFM-BESS units in parallel with diesel SG and GFL-BESS to respond automatically to load fluctuations within a few seconds. By increasing the GFM-BESS penetration, the system inertia and transient tolerance also improved. The steady-state power sharing effect by the droop control of the GFM-BESS was also confirmed.

Table 4.7 Power sharing evaluation

Metric	Case 1	Case 3	Case 4	Case 5	Case 6
GFM-BESS penetration (%)	0	17.7	26.6	35.5	44.4
Maxmium transient power sharing of SG at t=1.53s (kW)	89.5	76.4	71.9	68	61.6
Maxmium transient power sharing of GFM-BESS at t=1.63s (kW)	Not applicable	20.6	17.7	15.8	15.0
Steady state power sharing of SG in calculation (kW)	88	76.3	72.4	69.2	66.6
Steady state power sharing of SG in experiment (kW)	90	83.8	79.8	74.1	69.1
Steady state power sharing of GFM-BESS in calculation (kW)	Not applicable	12.2	11.6	11.1	10.6
Steady state power sharing of GFM-BESS in experiment (kW)	Not applicable	12.9	12.1	11.8	11.0

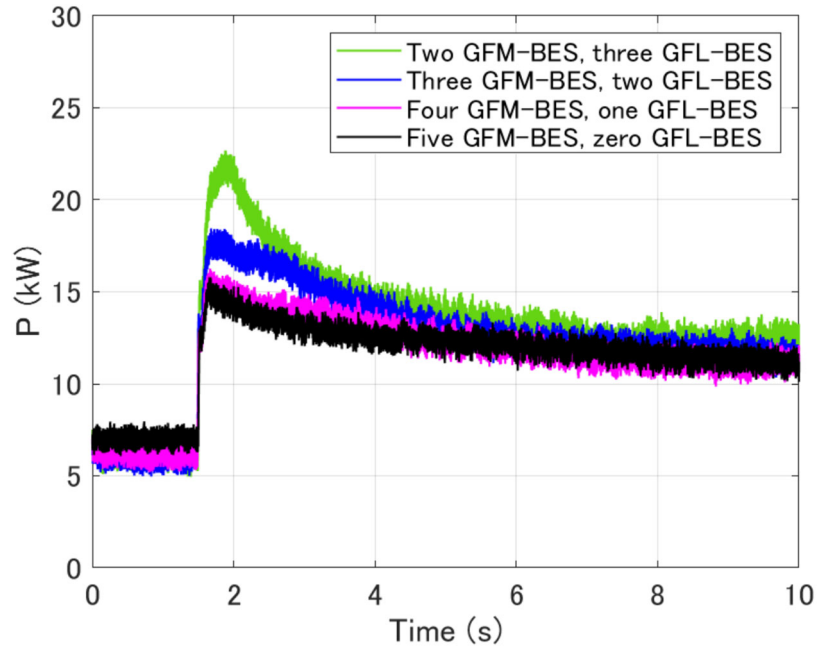


Fig. 4.19 Load sharing of one GFM-BESS with different penetrations of GFM-BESS.

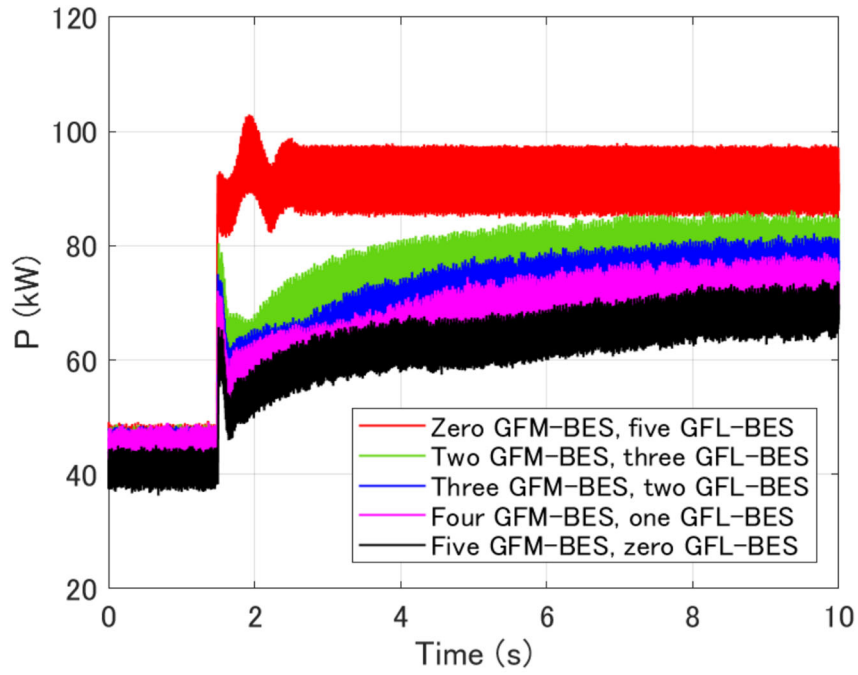


Fig. 4.20 Load sharing of SG with different penetrations of GFM-BESS.

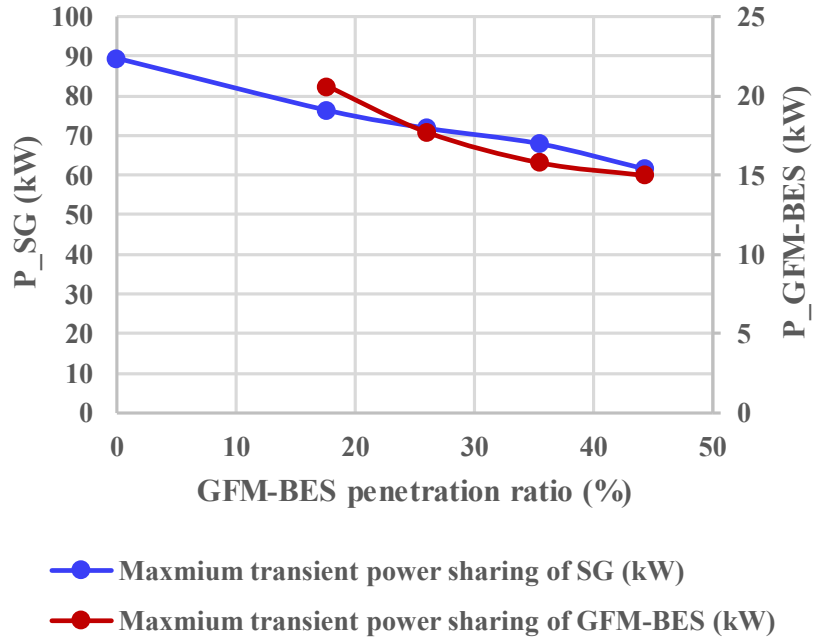


Fig. 4.21 Transient load sharing of SG and GFM-BESS with different penetrations of GFM-BESS.

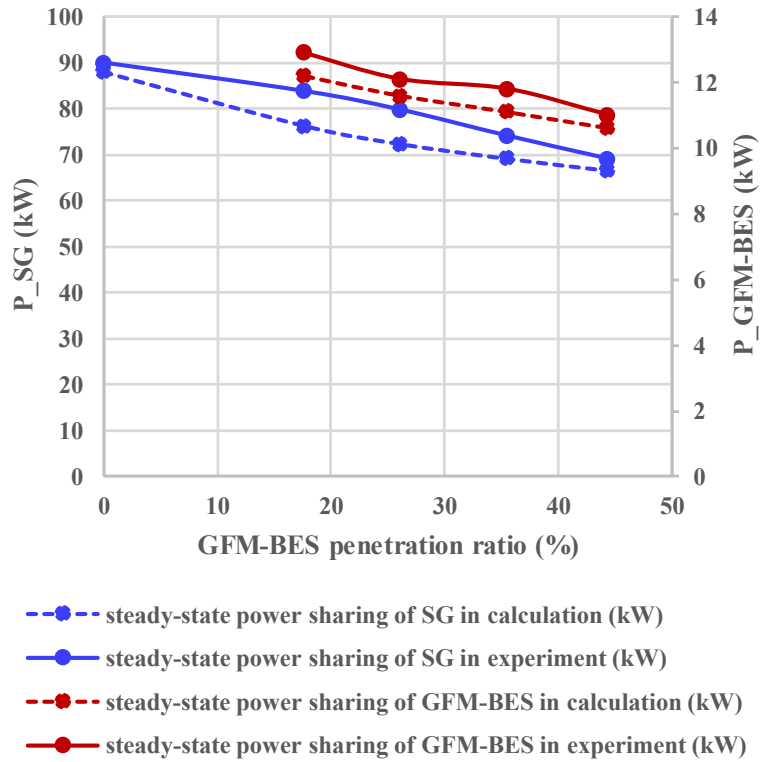


Fig. 4.22 Steady state load sharing of SG with different penetrations of GFM-BESS

4.5. Conclusion

In this chapter, a large-scale power grid simulating an actual microgrid in Mutsuzawa, Japan was built according to the actual microgrid architecture and simulated with an approximately 1:1 power capacity scale. The grid contains SGs and inverter-BES units. In the simulated grid, the power generation penetration of the inverter-BES units reached 44.4%. Autonomous operation of the simulated grid to achieve frequency regulation was demonstrated without relying on a communication network. Many advanced functions, namely grid forming, synchronization, frequency regulation, and power sharing, were demonstrated through field tests. Improved system inertia and power sharing were demonstrated by increasing the penetration of GFM-BESS units for different cases. The inertia constant of a diesel SG was inferred from simulations and experiments to be approximately 1.12 s, which is very small. An unexpected problem also occurred, during the step load change experiment, in which the GFM-BESS shut down when the GFM-BESS penetration ratio was low because of the low inertia of the SG.

In the microgrid of this study, the penetration ratio of the GFM-BESS needs larger than 20 % to meet the RoCoF standard for system stability. With the proposed evaluation scheme, the transient and steady state characteristics of each power generation device will be clarified. Even if there are different load fluctuations on different scales, the results can be predicted without conducting a demonstration experiment.

The field trial demonstrated that the GFM-BESS improved grid stability, reliability, security, and resiliency without relying on communication networks. In the future, if the proportion of renewable energy power sources increases, it should be possible to compensate for the decrease in inertial force by using the GFM-BESS technology. This project is expected to demonstrate a new lifestyle, with natural sustainable resources for improved resiliency.

4.6. Reference

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Chapter 4

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Chapter 5. System Stability Evaluation on GFM with Virtual Synchronous Generator Control Applied to Photovoltaic Power Systems

5.1. Introduction

Renewable energy sources such as photovoltaic (PV) power are increasingly being introduced into power grids instead of thermal power generation that relies on fossil fuels in order to realize a low-carbon society. However, conventional current-controlled PV inverters operate in maximum power point tracking (MPPT) mode, which cannot provide inertia support for the power system. As a result, power systems that contain a large amount of PV suffer from a lack of inertia, and thus frequency fluctuations occur during large disturbances [1]-[5]. To solve these issues, some advanced power and frequency control methods have been proposed by researchers. A constant power generation (CPG) method is proposed in [1]-[2]. The output power of the PV system is limited by a constant power command value for PV power overloading and fluctuation suppression. However, power reserved by the CPG that is not used during operation is wasted power. Another solution is the virtual synchronous generator (VSG) strategy, which improves the stability of the system by emulating the inertia and damping characteristics of a synchronous generator [2]-[13]. The photovoltaic virtual synchronous generator (PV-VSG) is implemented as a combination of PV and VSG. The energy buffer between PV and VSG used for grid frequency modulation is provided by energy storage devices and active power reserves of PV arrays. Control strategies that use energy storage devices have been studied in [3]-[13]. [3] uses a supercapacitor energy management system that has a good instantaneous charge and discharge performance, thus realizing good inertial frequency modulation. Battery energy storage systems have also been integrated into the DC side [4]-[6] or AC side [7]-[13], providing inertial and primary frequency modulation by coordinated power control of the bidirectional battery energy storage. However, energy storage devices increase costs and need additional space for installation. Active power reserved PV-VSG was proposed [14]-[15] based on the CPG strategy that uses the reserved active power during operation for grid forming and was able to achieve frequency regulation without any energy storage devices. However, all the methods above are implemented in the current control inverters, and little effort has been reported on the experimental evaluation of inertia.

In this paper, an improved voltage-controlled GFM-PV using MPPT limit (MPPTL) control is proposed. PV power is reserved by MPPTL control to provide a power buffer, and a voltage-controlled VSG algorithm is implemented for grid forming. The proposed GFM-PV realized frequency regulation

with inertial characteristics without any energy storage devices. The effect of the proposed method for improving the virtual inertia is experimentally tested by comparing it with conventional GFL-BESS in a 165-kVA microgrid system that contains a 125-kVA diesel synchronous generator.

5.2. Control Method of GFM-PV

In this paper, the GFM-PV consists of a PV array (PV simulator in the experiment), a DC / DC converter, and a three phase 202-V/20-kVA inverter. These were installed in a $1,200 \times 530 \times 1,715$ mm frame. This configuration is the same as the general GFL-PV inverter. The main circuit of the GFM-PV is shown in Fig. 5.1, where u_{abc} , e_{abc} , and i_{abc} are the GFM-PV three-phase output voltage, induced electromotive force, and three-phase output current, respectively. R_s and L_s are the equivalent stator resistors and equivalent synchronous inductors, respectively, and P_e and Q_e are the real power and reactive power output by the GFM-PV, respectively.

GFM-PV uses a voltage-controlled inverter, has an inertia emulated unit inside, and operates in synchronization with the grid system. Furthermore, it is equipped with an MPPTL control, which is an improvement on the MPPT control implemented in conventional GFL-PV. Fig. 5.1 shows a schematic block diagram of the MPPTL GFM-PV control algorithm.

The primary control stage is equipped with droop control to maintain the frequency of the grid system. In the converter control stage, the operating power command value P_{PV_ref} of the MPPTL is a combination of the command value received from the upper control system P_{ref} and the frequency modulation power command value from droop control as shown in (1). MPPTL is a function that performs conventional MPPT operation when the operating power command value P_{PV_ref} is larger than the PV array output possible value P_{PV_MPP} and outputs the operation command value P_{PV_ref} when P_{PV_ref} is smaller than P_{PV_MPP} , as shown in Fig. 5.2. The operation mechanism of the MPPTL control can be explained easily by the flowchart shown in Fig. 5.3. The block without shadow is the same as the conventional MPPT control method. The block with the shadow is the MPPTL control which lets the PV output the command value P_{PV_ref} and operates on the right side of the PV curve shown in Fig. 5.2.

$$P_{PV_ref} = P_{ref} + D_p(f_{ref} - f_{mea}) \quad (1)$$

VSG control is implemented in the inverter control stage shown in Fig. 5.1. Active power and frequency control is realized by emulating the electromechanical equation in (2), where the P_m , P_e , and P_d are the virtual mechanical power, output power, and damping power, J is virtual moment inertia, and ω_0 and ω are grid angular velocity and mechanical angular velocity. In the proposed method, the input DC voltage of the inverter E_{inv} is regulated to a constant value. Virtual mechanical power P_m is calculated through the integration of the DC voltage deviation as shown in (3).

Chapter 5

$$P_m - P_e - P_d = J\omega_0 \frac{d\omega}{dt} \quad (2)$$

$$P_m = G(s) * (E_{inv_ref} - E_{inv_mea}) \quad (3)$$

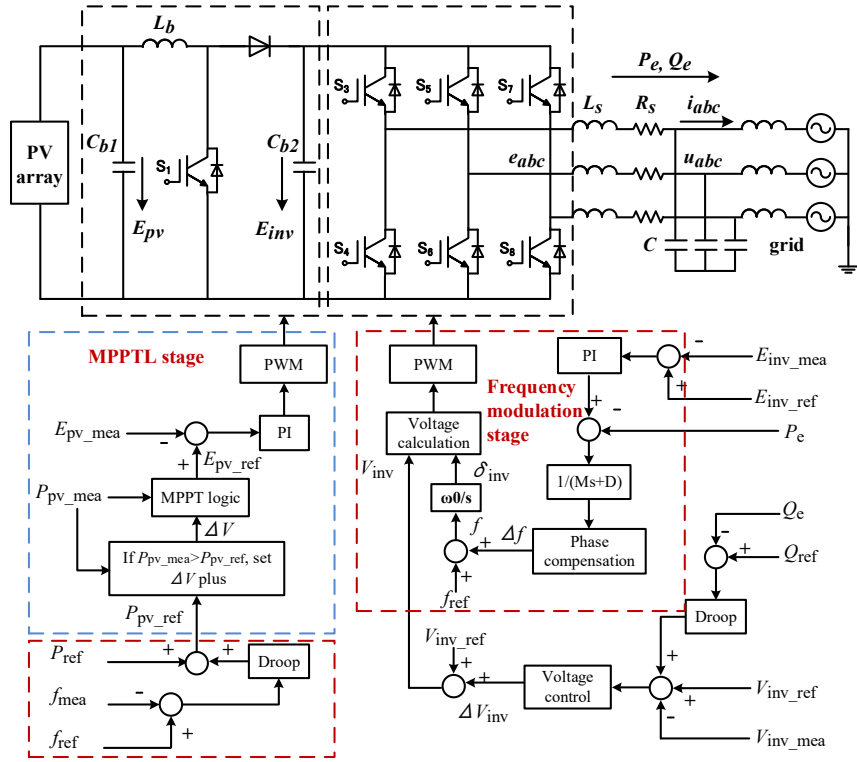


Fig. 5.1 Configuration and control algorithm of GFM-PV

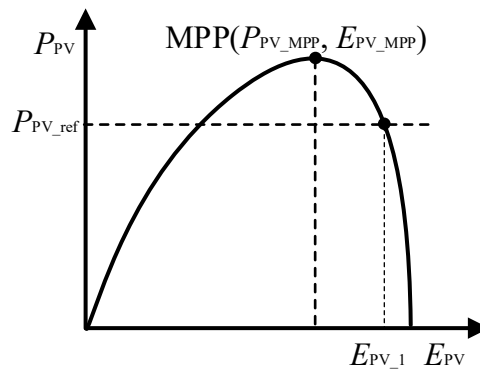


Fig. 5.2 PV array output power curve

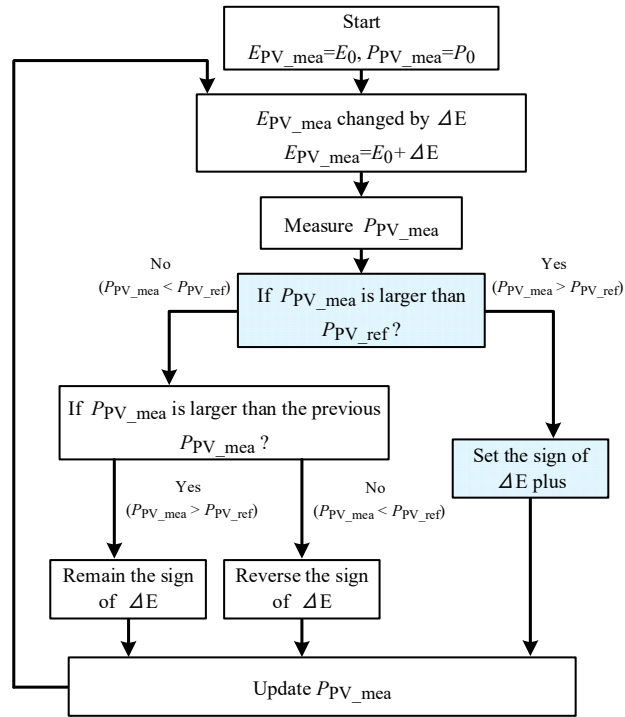


Fig. 5.3 Flowchart of MPPTL control scheme

Chapter 5

Table 5.1 Experimental Details

Case#	Consist of microgrid	Load change
1	125 kVA SG + 20 kVA GFL-BESS (command active power 10 kW)	70 to 80 kW
2	125 kVA SG + GFM-PV (solar radiation power 10 kW; command active power 10 kW)	70 to 80 kW
3	125 kVA SG + GFM-PV (solar radiation power 20 kW; command active power 10 kW)	70 to 80 kW

Table 5.2 Parameters of GFM-PV and Diesel SG

Parameter	Value	Parameter	Value
V_{base_GFM}	200 V	M_{GFM}	2 s
S_{base_GFM}	20 kVA	D_{GFM}	1.0
f_{base_GFM}	50 Hz	Droop gain (GFM-BES)	-4%
L_s	0.05 pu.	Xslope gain	-4%
Phase compensation	(1+0.08s)/ (1+0.02s)	Voltage control	20/s
V_{base_SG}	400 V	S_{base_SG}	125 kVA
f_{base_SG}	50 Hz	Droop gain (SG)	-4%

5.3. Microgrid Configuration

An experimental microgrid as shown in Fig. 5.4 was constructed to verify the validity of the proposed control strategy. A diesel synchronous generator (SG) with a rated power of 125 kVA, droop gain of 4%, rated voltage of 400 V, and rated frequency of 50 Hz is implemented to simulate a weak grid. The proposed MPPTL GFM-PV for a rated power of 20 kVA, inertia coefficient of 2 s, damping coefficient of 1, and droop gain of 4% is investigated experimentally. A conventional current-controlled 20-kVA grid following inverter with battery energy storage system (GFL-BESS) is implemented for comparison. The grid voltage is regulated at 6.6 kV, the rated power is 165 kVA, and the load change is 10 kW. The experimental platform is shown in Fig. 5.4. Field operation of the microgrid was performed to demonstrate the operation of the system: (1) GFL-BESS and GFM-PV in parallel with diesel SG to respond automatically to load fluctuations within a few seconds without relying on a communication network; (2) Characteristics GFM-PV, namely grid forming, synchronization, frequency regulation, and power sharing; (3) Confirmation of the inertial effect of GFM-PV on frequency fluctuations according to sudden load changes under the cases of different

reserved power. (4) Confirmation of power sharing in transient and steady states. The test details are shown in Table 5.1. The parameters of GFM-PV and the SG are shown in Table 5.2.

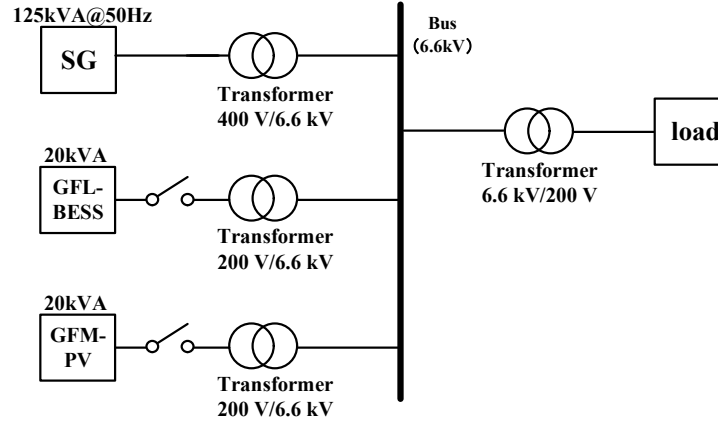


Fig. 5.4 Emulated microgrid used in experiment



Fig. 5.5 Experimental platform

5.4. Results from Field Demonstration

The initial load was 70 kW. each of the active power reference values of the inverters was set to 10 kW, with the remaining 60 kW shared by the SG. The rotor speed of the SG was adjusted by operating the operation panel of the SG until a grid frequency of 50 Hz was achieved. At this moment, the active power command value of the SG was 60 kW theoretically. This is considered the initial state.

5.4.1. GFL-BESS in Parallel with a Diesel SG

In case 1, an SG operating in parallel with the GFL-BESS is implemented as a comparison benchmark. The load changed from 70 kW to 80 kW at $t=1.5$ s, and the power sharing and frequency change are shown in Fig. 5.6. Because the GFL-BESS unit does not have inertia, it was found that

even if the load fluctuated at $t=1.5$ s, the GFL-BESS output followed the reference value of 10 kW without sharing the load. The load sharing of the SG is 80 kW. As the load increases, the grid frequency gradually drops due to the inertia of the SG, and finally has a significant transient drop to 48.9 Hz. After this, the synchronous force of the SG accelerates the rotor, and the grid frequency returns to 49.8 Hz due to the frequency drooping characteristics in steady state.

5.4.2. GFM-PV in Parallel with a Diesel SG when Irradiation Power less than Command Power

In case 2, the SG operates in parallel with MPPTL mode GFM-PV which the irradiation power of PV is less than the command active power. The power sharing and frequency change are shown in Fig. 5.7. The active power reference value of the GFM-PV is 10 kW. Because the grid frequency is 50 Hz until $t=1.5$ s, the actual output of the GFM-PV is also 10 kW, as commanded. After the load change at $t=1.5$ s, the load is shared by the GFM-PV unit and the SG together. However, the irradiation power of PV is less than the command active power so no reserved power existed. The energy in the output capacitor of the PV was recharged for frequency modulation. The output voltage of the PV is unstable. Therefore, an output power oscillation occurred. GFM-PV almost provided no inertia in this situation. The SG contributed to frequency modulation.

5.4.3. GFM-PV in Parallel with a Diesel SG when Irradiation Power larger than Command Power

In case 3, the SG operates in parallel with MPPTL mode GFM-PV which the irradiation power of PV is larger than the command active power. The power sharing and frequency change are shown in Fig. 5.8. The power sharing of GFM-PV is 10 kW as commanded. After the load change at $t=1.5$ s, the load is shared by the GFM-PV unit and the SG together. At the moment of load fluctuation, the GFM-BES and SG share the load fluctuation at the same time by the mutual synchronization force. After this, the output of the GFM-PV gradually increases, and the output of the SG gradually decreases until both reach a steady state. It was confirmed that the GFM-PV unit could share the load power autonomously. When the load suddenly changed at $t=1.5$ s, the frequency gradually decreased to 49.2 Hz due to the inertia of the power generation device, then the frequency increased due to the synchronization force of the power generation device, and the system frequency returned to 49.9 Hz due to the frequency drooping characteristic.

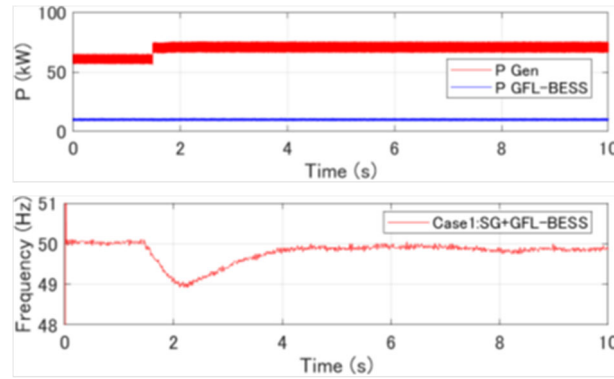


Fig. 5.6 Case 1: Power sharing and grid frequency change for GFL-BESS and SG

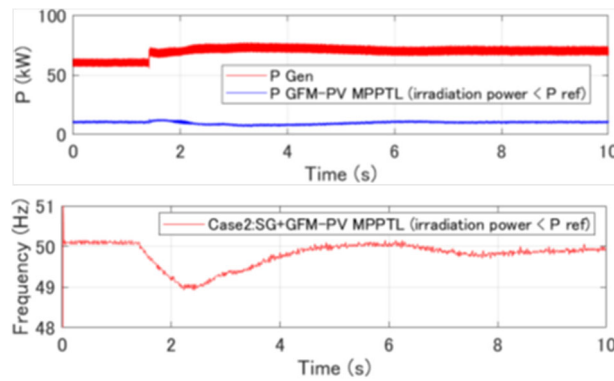


Fig. 5.7 Case 2: Power sharing and grid frequency change for GFM-PV (irradiation power less than command power) and SG

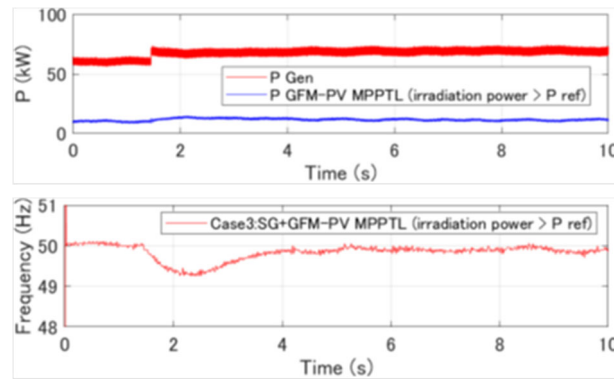


Fig. 5.8 Case 3: Power sharing and grid frequency change for GFM-PV (irradiation power larger than command power) and SG

5.4.4. Power Sharing and Inertia Evaluation

In case 1, an SG operating in parallel with the GFL-BESS is implemented as a comparison benchmark, while in cases 2 and 3, the SG operates in parallel with GFM-PV under different reserved power. For all 3 cases, the virtual inertia and primary frequency modulation of MPPTL GFM-PV are

Chapter 5

Table 5.3 Inertia Evaluation

Metric	Case 1	Case 2	Case 3
Frequency nadir (Hz)	48.9	48.9	49.2
Maxmium Frequency deviation (Hz)	1.1	1.1	0.8
RoCoF (Hz/s)	1.78	1.78	1.28
Steady state frequency (Hz)	49.8	49.8	49.8

evaluated in comparison with GFL-BESS. Fig. 5.9 shows a comparison of the active power response between case 1 and case 2. Since GFM-PV operates without active power reserved. The frequency fluctuation is the same as GFL-BESS because the output is the same as GFL-BESS even if load fluctuation occurs, as shown in Fig. 5.10. Fig. 5.11 shows a comparison of the active power response between case 1 and case 3. GFM-PV operates immediately when a load change occurs because GFM-PV operates with the reserved active power of 10 kW. When the frequency drops due to a load fluctuation, the output follows the droop characteristics provided by the GFM-PV, which is effective for frequency modulation as shown in Fig. 5.12. The minimum frequency drop decreased by 0.3 Hz, and the RoCoF decreased by 0.5 Hz/s. The frequency Nadir and RoCoF for inertia evaluation are summarized in Table 5.3 Inertia Evaluation. This clearly shows the proposed strategy increases the virtual inertial.

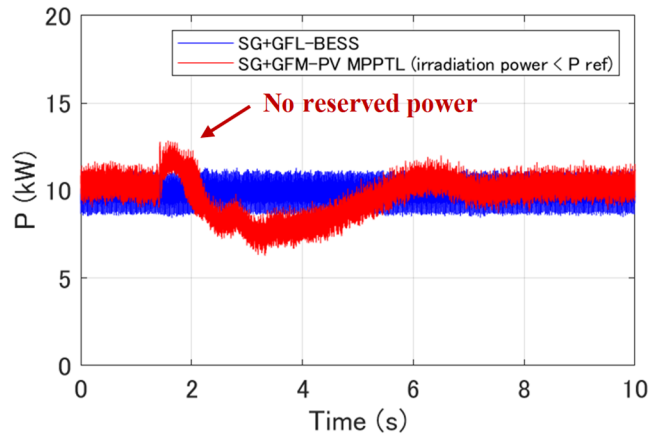


Fig. 5.9 Active power comparison between Case 1: GFL-BESS (blue) and Case 2: GFM-PV (red)

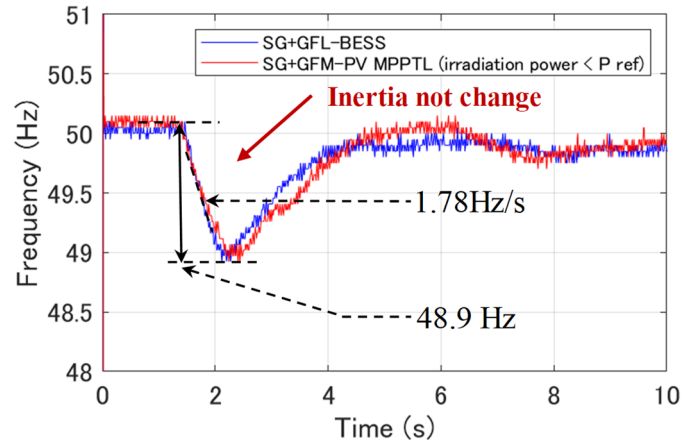


Fig. 5.10 Frequency comparison between Case 1 (blue) and Case 2 (red)

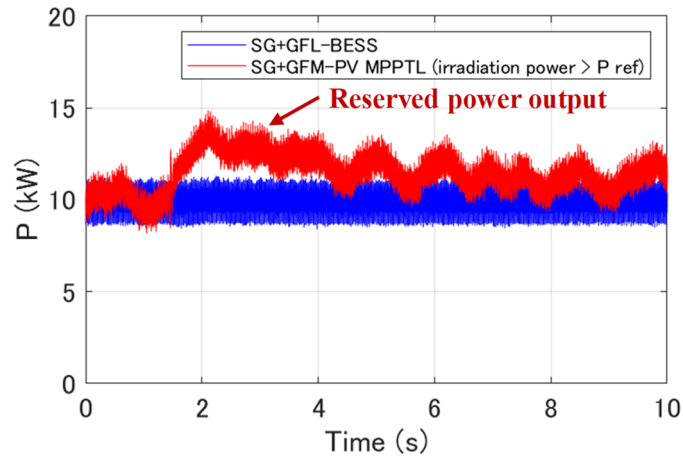


Fig. 5.11 Active power comparison between Case 1: GFL-BESS (blue) and Case 3: GFM-PV (red)

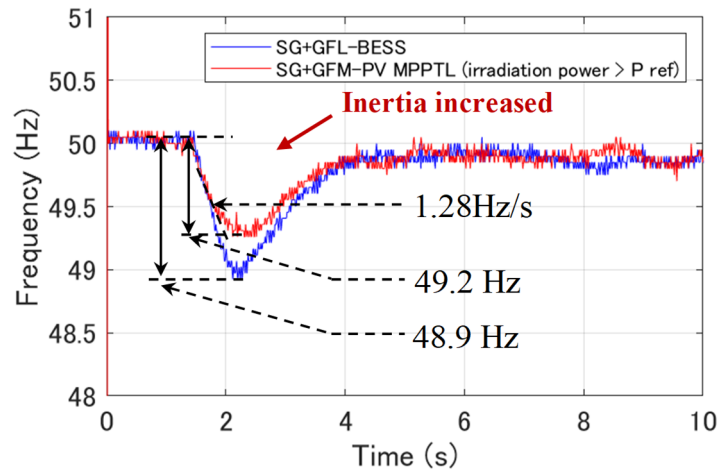


Fig. 5.12 Frequency comparison between Case 1 (blue) and Case 3 (red)

5.5. Conclusion

This paper introduced a grid forming strategy for PV inverters using the MPPTL VSG algorithm. Active power of PV is reserved to provide a power buffer between PV power and inverter for grid frequency forming. The advantages of the proposed strategy include the following: firstly, virtual inertial frequency modulation ability can be improved under load fluctuations compared to conventional GFL-BESS; secondly, no additional energy storage devices are needed; thirdly, the voltage-controlled inverter supports the grid voltage, thus improving grid stability. The effectiveness and validity of the proposed method are verified experimentally.

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Chapter 6. EMI Measurement and Reduction of IBR

6.1. Introduction

Compared to the large-capacity power supplies installed in a large restricted area in the past, with the miniaturization and decentralization of renewable energy power supplies, the distance from broadcasting and communication is getting closer, and there is a growing concern that electromagnetic interference (EMI) will occur. In this chapter, the EMI of GFM-BESS was measured and the reduction method was taken. Conducted EMI reduction method has improved EMI to meet CISPR 11 class A, which is intended for use in industrial environments. In addition, we analyzed the EMI generation mechanism of a general inverter, evaluated the EMI reduction effect by balancing the circuit in comparison with the reduction effect by the conventional noise filter, and confirmed the reduction effect by up to 20 dB.

6.2. EMI Measurement and Reduction for GFM-BESS

The EMI of the developed GFM-BESS is evaluated. As shown in Fig. 6.1, it is measured in a 10m anechoic chamber and compared with the allowable value of the conduction interference wave of CISPR 11, power supply without power failure UPS, JIS C 4411-2: 2019. Fig. 6.2 shows the results of conducting EMI measurement. Conducted EMI meets the UPS-equivalent tolerances of Category C3 where EMC-savvy professionals or organizations need to install and tune storage systems. Since high conduction interference waves were measured at the switching frequency of the inverter and the frequency corresponding to its harmonic components, it is considered that the switching of the inverter is the main factor. As a reduction method against conduction EMI, a line filter was properly loaded and a common mode choke was added. The measured values after the reduction method against conduction interference cleared the allowable values of CISPR 11 class A intended for use in an industrial environment and were improved to a noise level of about class B. Fig. 6.3 shows the measurement of radiated interference waves (electric field strength) of 30 MHz or more at a distance of 10 m. It was confirmed that the values other than 30MHz were below the permissible values of CISPR 11 class A and group 1.

However, there is an issue that the EMI reduction method increased the cost very much. The EMI suppression method without an EMI filter is desirable. In the next section, the EMI generation mechanism in the general inverter will be analyzed and the EMI reduction method that does not use the noise filter will be discussed.

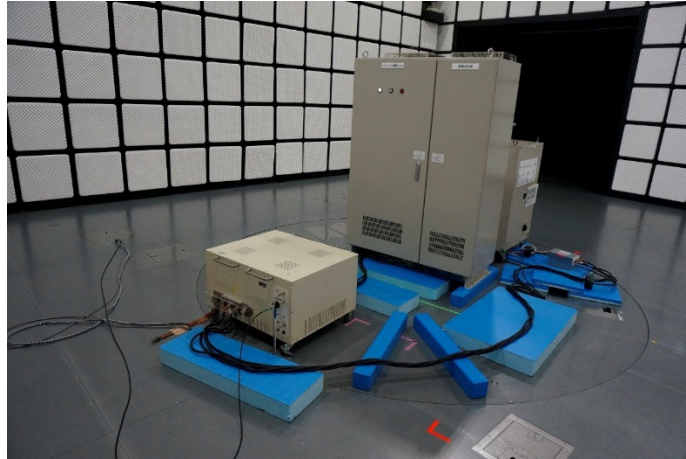


Fig. 6.1 Measurements of EM disturbances

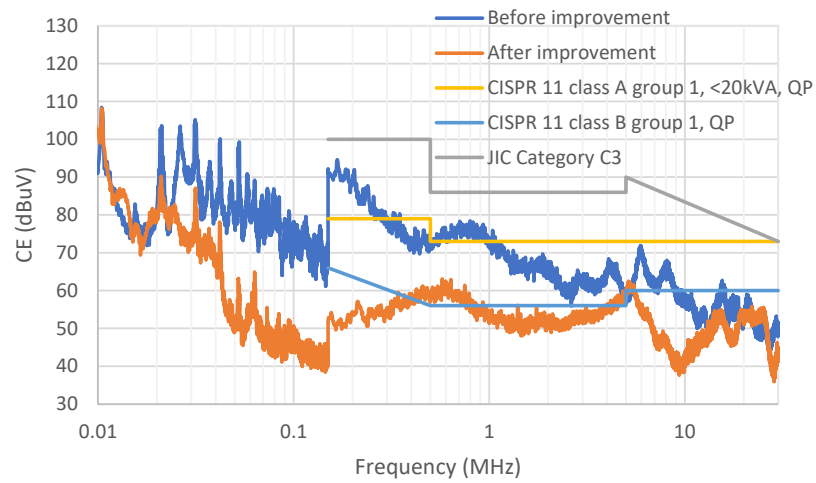


Fig. 6.2 Measurements of conducted disturbances

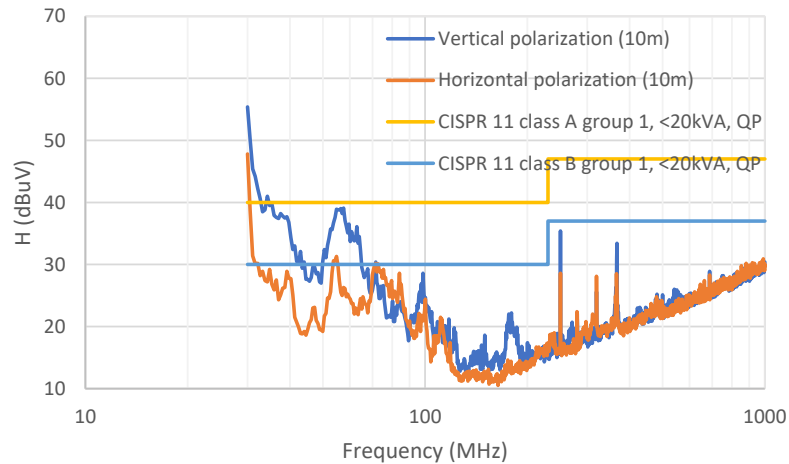


Fig. 6.3 Measurements of radiated disturbances

6.3. Analysis of Noise Issues in General IBR

A general single phase transformer-less PV system is consist of a boost step-up stage and a full bridge inverter with an ac harmonic filter, as shown in Fig. 6.4. A heatsink is usually used with the MOSFET, so the parasitic capacitance is formed between the drain of the MOSFET and the frame ground FG through its heatsink. In this case, where small size and a low profile are strongly required for the converter, the metal frame ground itself may be used as a heatsink so that the parasitic capacitance becomes very large. Parasitic capacitance in a PV system is mainly considered as follows:

- 1) The capacitance between the drain of the switch to the heatsink and the capacitance between the heatsink to the ground (C_{1g} , C_{2g} , and C_{dg} as shown in Fig. 6.4).
- 2) The capacitance between the panels to the frame ground (C_{pv} as shown in Fig. 6.4).

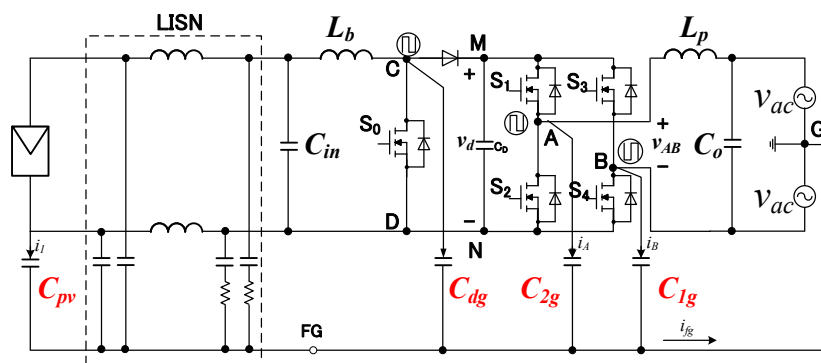


Fig. 6.4 Singled phase transformer less PV system

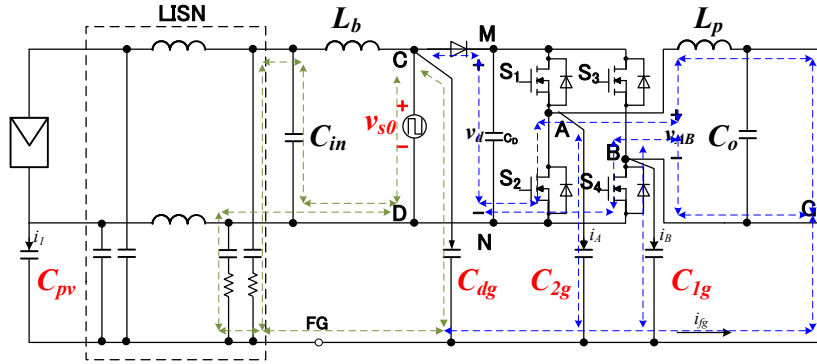


Fig. 6.5 Common mode noise current path caused by V_{s0}

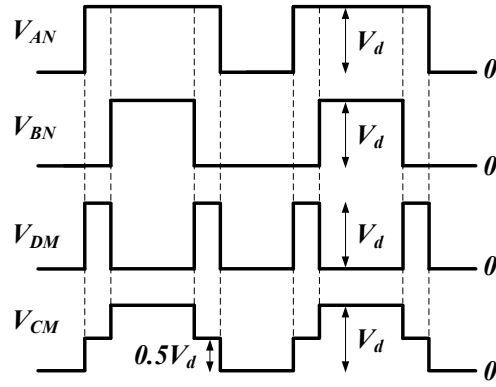


Fig. 6.6 Terminal voltage of each phase leg, CM and DM voltage of inverter part with unipolar modulation

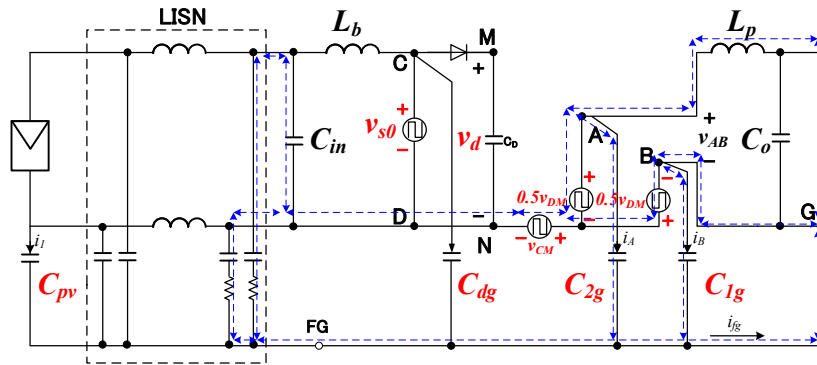


Fig. 6.7 Common mode noise current path caused by V_{AN} and V_{BN}

6.4. Noise Generation Mechanism

In the unbalanced boost converter, the drain voltage changes very rapidly in the switching time as denoted by the symbol next to the drain. A large current pulse flows through the parasitic capacitance C_{dg} . Consequently, this causes the large common mode noise current to lead to serious problems. The common mode noise current path caused by boost converter switching is shown in Fig. 6.5. Noise current flow through both boost part (green line) and inverter part (blue line) need to be reduced.

The common mode of the inverter output voltage is the average value of the voltages between the outputs and a common reference. For this system, the negative terminal of the dc bus, point N is considered as the common reference. V_{AN} and V_{BN} are terminal voltages of two phase legs with respect to the N point. Therefore, the common mode voltage of the converter, V_{CM} is defined as (1). The differential mode output voltage, V_{DM} is defined as the voltage between both converter outputs as (2). From (1) and (2), the voltage between the converter outputs and the N point can be derived as (3) and (4).

$$V_{CM} = \frac{1}{2}[V_{AN} + V_{BN}] \quad (1)$$

$$V_{DM} = [V_{AN} - V_{BN}] \quad (2)$$

$$V_{AN} = [\frac{1}{2}V_{DM} + V_{CM}] \quad (3)$$

$$V_{BN} = [-\frac{1}{2}V_{DM} + V_{CM}] \quad (4)$$

The effects of different PWM schemes can be evaluated by exploring the generated DM and CM terminal voltages as defined in (1) and (2). The unipolar PWM modulation is usually used in full bridge inverter. Fig. 6.6 shows the unipolar modulation scheme and its corresponding CM and DM terminals in two switching periods. The terminal voltages V_{AN} and V_{BN} step up/down between 0 and dc link voltage V_d during the switching period. A high frequency leakage current will generate and flow through the parasitic capacitances to ground.

Substitution V_{AN} and V_{BN} based on (3) and (4). Path of common mode noise current generated by the V_{CM} is shown in Fig. 6.7. These noise currents flow into the grid will cause malfunction of other circuits and need to be reduced.

6.5. EMI Reduction with EMI Filter

In the previous section, the analysis shows that both boost converter and inverter will generate large common mode noise current flow through the system. To reduce the conducted noise current, the following suppressing methods are considered:

- 1) Increase CM/DM impedance by adding a noise filter between LISN and boost converter.

- 2) Use a balanced technique to cancel the noise.
- 3) Revise the PWM modulation scheme to reduce the value of the noise source.

In this paper, a common mode choke, two Y capacitors, two X capacitors are used as a noise filter connected between LISN and boost converter as shown in Fig. 6.8. As we know, common mode choke works as a large inductor for the common mode component which will reduce the common mode current efficiently. Y capacitors also provide a bypass path for the common mode component. X capacitors are available to suppress normal component effectively.

Fig. 6.9 shows the noise spectrum result of adding a noise filter comparing with the noise spectrum of the original circuit. From the result, by adding a noise filter the conducted noise could be suppressed effectively, especially from 150 kHz to 7MHz. However, it has the drawback of increasing the size and weight, need a special design for high-frequency noise reduction. So the method that without noise filter or only use small noise filter to achieve the same suppression effect is required.

Table 6.1 EMI filter parameters

Symbol	Value
L_{CMC}	1.3mH
C_{x1}, C_{x2}	0.1 μ F
C_{Y1}, C_{Y2}	1nF

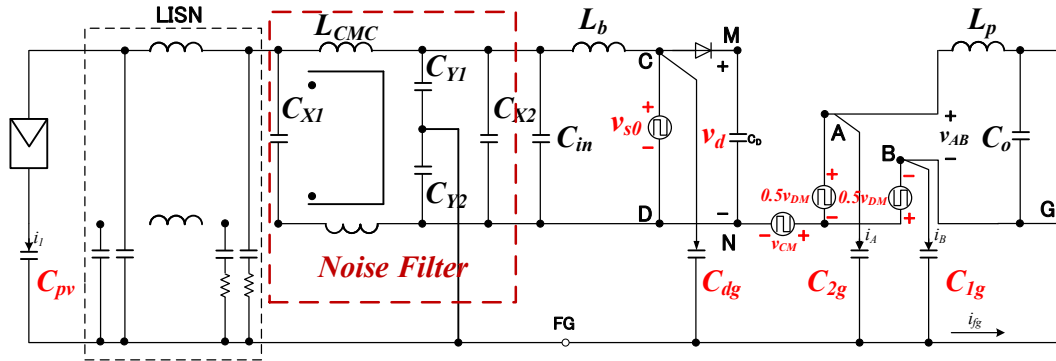


Fig. 6.8 PV system with noise filter

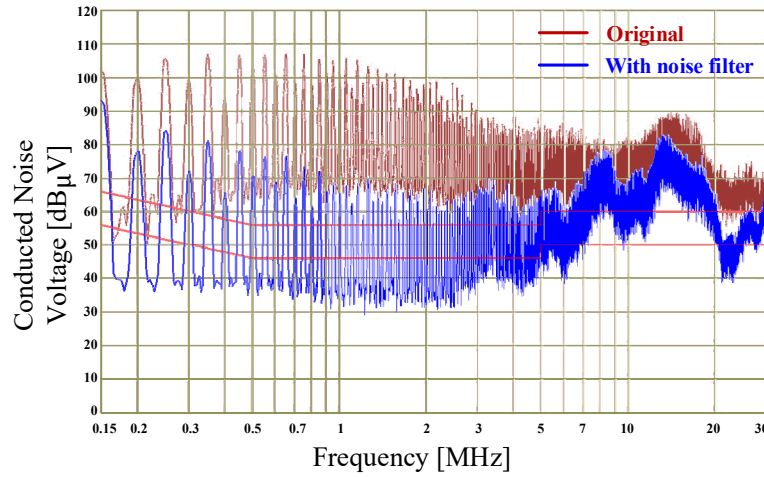


Fig. 6.9 Conducted noise sepectrum measurement of original circuit and circuit with noise filter

6.6. EMI Reduction with Balanced Technique

In order to solve the noise generated from the boost converter, we used a balanced switching converter as shown in Fig. 6.10. The circuit operation is essentially the same as that of the conventional unbalanced boost converter. The winding of the inductor is equally split into two parts. So ideally, the balanced circuit almost does not increase size and weight by using coupled inductor. Actually, the parasitic capacitance C_{dg} (red and blue) are not exactly the same, an auxiliary capacitance can be added to equalize their values to achieve a good balance loop.

In the balanced converter, the drain voltage and the source voltage of the switch change symmetrically. This is ideally achieved by balanced the inductors. As a result, no noise current will conduct to ground, they are canceled in the loop.

It could also be explained by Wheatstone bridge as shown in Fig. 6.11. If the inductor and capacitor equals each other, the current generated by V_{s0} will only flow around the loop, so the leakage current to the ground will be reduced.

In order to solve the noise problem generated from the inverter, the balanced inverter is used as shown in Fig. 6.12. The LC filter is split into two identical parts, having the same inductance value. They are distributed into the two switching legs as shown in Fig. 6.13. Because of the symmetrical circuit configuration, high frequency current will not flow to the load for the large impedance of each leg.

Comparing with the conventional PWM modulation scheme, bipolar PWM modulation scheme is implemented to generate a drain-source voltage of each leg switch with opposite phase as shown in Fig. 6.12. According to equation (1), the common mode voltage with a bipolar modulation scheme is approximately half of the dc link voltage. So it is substituted with a dc voltage source in Fig. 6.13. Common mode noise is reduced from the source in theory.

The common mode noise current generate from $0.5V_{DM}$ flows through the parasitic capacitor C_{2g} , C_{1g} , $-0.5V_{DM}$, then back to $0.5V_{DM}$. Noise current flow inside of the loop. No current will leak the ground. The conducted noise current path caused by V_{AN} and V_{BN} in balanced inverter is shown in Fig. 10.

Features of the proposed method are as follow:

- 1) No additional circuit is required. By adjusting the balanced element and using a coupled inductor, noise could be reduced without using noise filter or another additional circuit. Therefore, this method can contribute to downsizing the system.
- 2) No complex modulation technique is required.

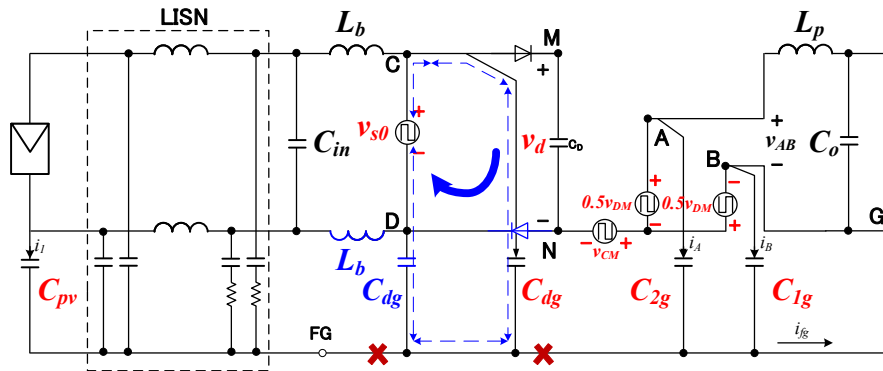


Fig. 6.10 Conducted noise current path caused by V_{s0} in balanced boost converter

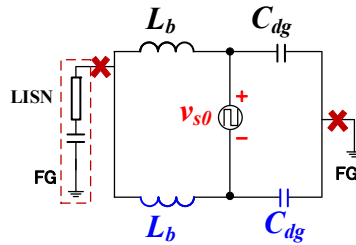


Fig. 6.11 Balaced wheatstone bridge of boost converter

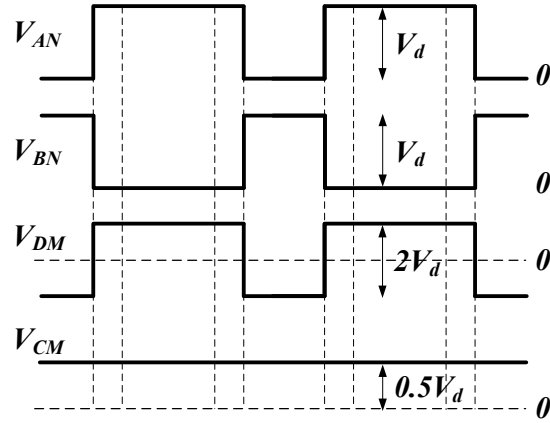


Fig. 6.12 Terminal voltage of each phase leg, CM and DM voltage of inverter part with bipolar modulation

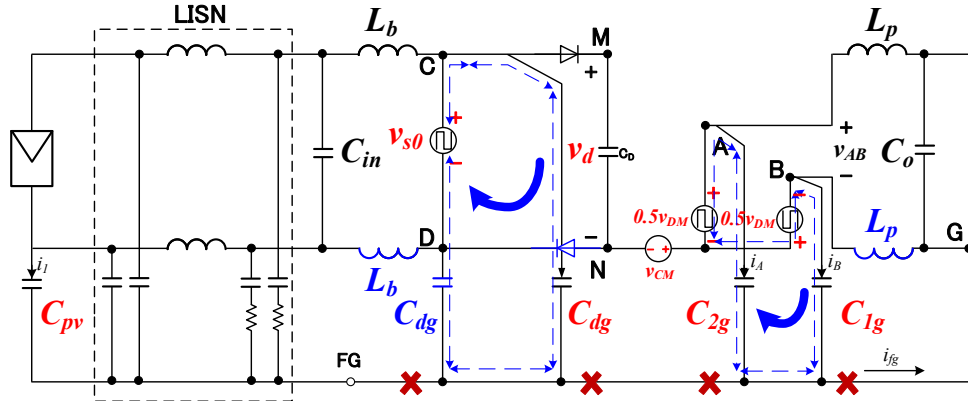


Fig. 6.13 Conducted noise current path caused by V_{AN} and V_{BN} in balanced inverter

6.7. Experiment

The experiment was done with a resistor load. The circuit parameters are shown in Table 6.2. The EUT is connected with a DC power source through the line impedance stabilization network (LISN) for input impedance stability and noise measurement. The experiment is performed by balancing the circuit step by step. The conducted noise spectrum was measured, respectively.

Fig. 6.14 shows the noise spectrum measurement result of the original circuit and balanced boost circuit. The method reduced conducted noise effectively from 600 kHz to 30 MHz. The conducted noise reduced up to 30dB in 15 MHz. It is considered that the inverter dominates the noise from 150 kHz to 6 MHz.

Fig. 6.15 shows the noise spectrum measurement result of a balanced boost circuit and balanced the whole circuit. The conducted noise is suppressed from 150 kHz to 3 MHz. By applying the proposed method, the conducted noise could be reduced up to 30dB during 150kHz to 30Mz. Fig. 6.16 shows the conducted noise spectrum measurement of the original circuit, the circuit with noise filter and balanced the whole circuit. Compared with the result of adding noise filter, the proposed method performed the same ability below 3MHz and have a better performance at high frequency.

Table 6.2 Experimental conditions

Symbol	Value
V_{in}	10V
f_{sw}	50kHz
C_{in} ,	100uF
L_B	150uH
Duty ratio of boost	0.6
C_D ,	470uF
L_P	180uH
C_O	1uF
C_{1g} C_{2g} C_{dg}	1nF
Output frequency	50Hz
load	50 Ω

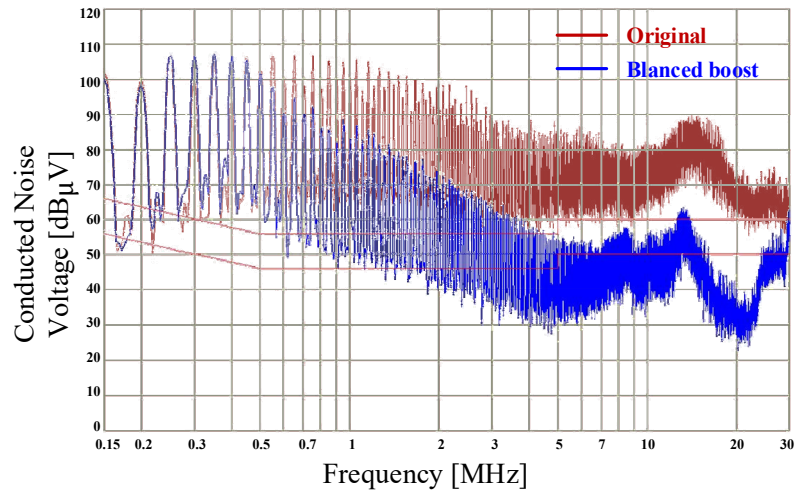


Fig. 6.14 Conducted noise spectrum measurement of original circuit and balanced boost circuit

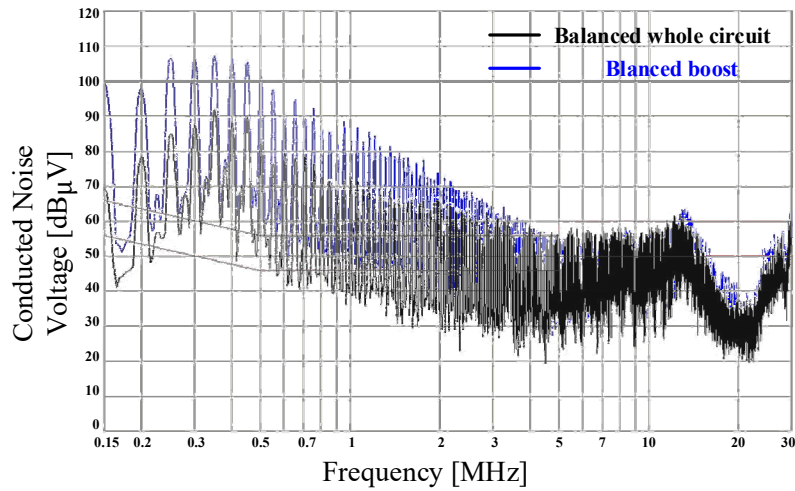


Fig. 6.15 Conducted noise spectrum measurement of balanced boost circuit and balanced the whole circuit

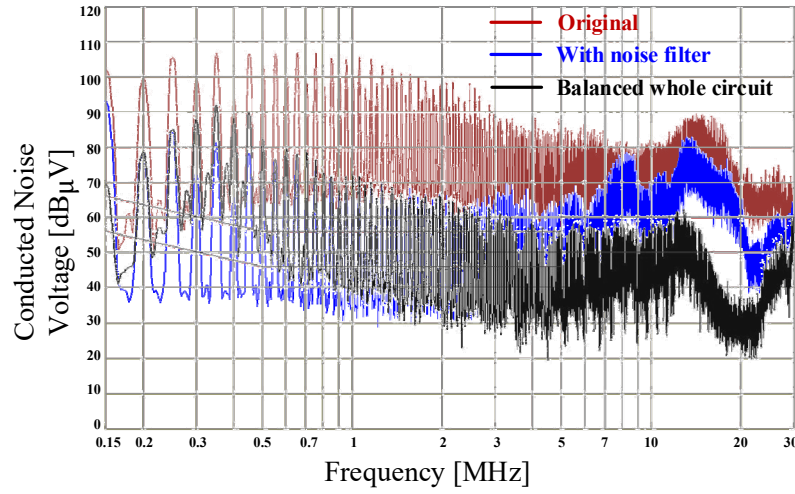


Fig. 6.16 Conducted noise spectrum measurement of original circuit, circuit with noise filter and balanced the whole circuit

6.8. Conclusion

In this chapter, the EMI of GFM-BESS was measured and the reduction method was taken. Conducted EMI reduction method has improved EMI to meet CISPR 11 class A, which is intended for use in industrial environments. However, an EMI filter will increase the total cost. The EMI reduction method without an EMI filter is discussed in a general PV inverter. The common mode generation mechanism in general PV inverter is analyzed. A balanced technique is implemented to reduce the common mode noise compared with the conventional method using a noise filter. The effectiveness of the noise reduction method is verified by experiment. By applying a balanced technique, the conducted noise can be suppressed effectively to a maximum of 30dB in the whole frequency range. Compared with the conventional method using a noise filter, the proposed method performed the same ability below 3MHz and have a better performance at high frequency area.

Chapter 7. Evaluation of the Effect of Synchronous Reactance on Synchronization Power

7.1. Introduction

In GFM-BESS, the effect of the inductance of the line filter and EMI filter on the transient load sharing of GFM-BESS will be evaluated. Since the synchronization force in GFM-BESS changes depending on the inductance value of the internal filter, the mounting status of the line filter and the synchronization force are related. Therefore, the relationship between the synchronization force and the line filter will be examined. A method of predicting the overload sharing immediately after the load fluctuation is presented by the synchronization force. Two microgrids consisting of a synchronous generator and GFM-BESS were evaluated by simulation and demonstration experiments.

7.2. Synchronization Power

The load sharing immediately after load fluctuation will be analyzed in the system shown in Fig. 7.1. The SG (synchronous generator) and GFM-BESS are connected to the same bus, and the internal voltage of the generator is $E = E \angle \delta_n$ (δ_n : internal phase difference angle of the generator), and the bus voltage (phase reference) is $V = V \angle \delta_B$, the SG and GFM-BESS output the power of P_{SG} and P_{GFM} respectively, supplies them to the load P_L , and if $X_{SG} = X_{d1} + X_{tra1}$ and $X_{GFM} = X_{d2} + X_{tra2}$, the relationship between the generated power of the following generator and the synchronous reactance and phase difference is obtained as the formula below:

$$P_{SG} = \frac{E_1 V}{X_{SG}} \sin(\delta_1 - \delta_B) \quad (1)$$

$$P_{GFM} = \frac{E_2 V}{X_{VSG}} \sin(\delta_2 - \delta_B) \quad (2)$$

Assuming that the load sharing of SG and GFM-BESS immediately after the load fluctuation ΔP_L is ΔP_{SG} and ΔP_{VSG} , respectively, the strength of the restoring force that tries to restore this when the phase deviation increases by $d\delta$ with respect to the load fluctuation. Therefore, it is called synchronizing power in the sense that it is the power to maintain synchronization between power generation devices. The mutual synchronization force of SG, GFM-BESS showed in Fig. 7.1 are K_{SG} and K_{VSG} , representing the following equations, respectively.

$$K_{SG} = -\frac{\Delta P_{SG}}{\Delta \delta_B} = \frac{E_1 V}{X_{SG}} \cos(\delta_1 - \delta_B) \quad (3)$$

$$K_{GFM} = -\frac{\Delta P_{GFM}}{\Delta \delta_B} = \frac{E_2 V}{X_{GFM}} \cos(\delta_2 - \delta_B) \quad (4)$$

Then, the following equations for load sharing and mutual synchronization force can be derived.

$$\Delta P_L = \Delta P_{SG} + \Delta P_{GFM} = -(K_{SG} + K_{GFM})\Delta\delta_B \quad (5)$$

It can be seen that the overload sharing immediately after the load fluctuation is shared in proportion to the mutual synchronization force.

$$\Delta P_{SG} = \frac{\Delta P_{SG}}{\Delta P_{SG} + \Delta P_{GFM}} \Delta P_L = \frac{K_{SG}}{K_{SG} + K_{GFM}} \Delta P_L \quad (6)$$

$$\Delta P_{GFM} = \frac{\Delta P_{GFM}}{\Delta P_{SG} + \Delta P_{GFM}} \Delta P_L = \frac{K_{GFM}}{K_{SG} + K_{GFM}} \Delta P_L \quad (7)$$

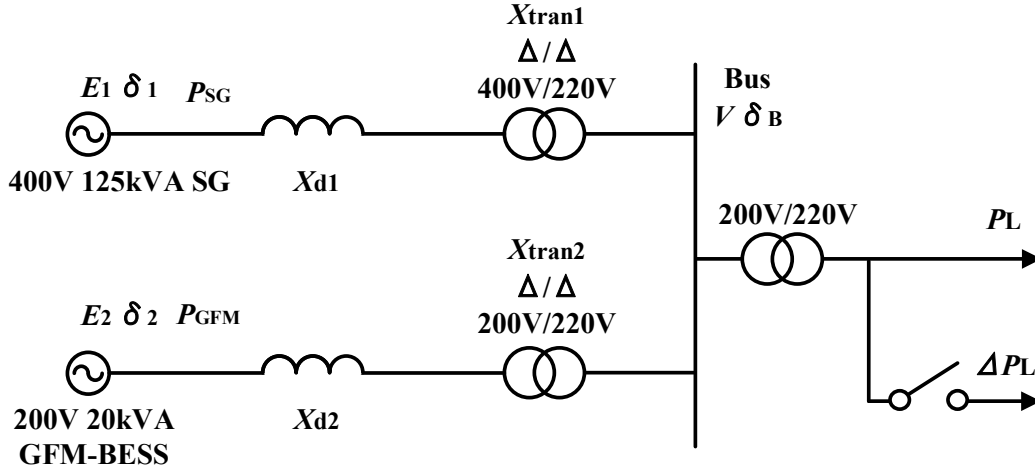


Fig. 7.1 Two-machine parallel operation system

7.3. Evaluation of Transient Load Sharing Effected by Synchronization Power

7.3.1. Configuration of the simulated microgrid

Fig. 7.2 shows a 125 kVA synchronous generator, which is the main power generator of the microgrid, two 20 kVA GFM-BESS units, a 150 kW three-phase load device that corresponds to a power consumer, a transformer that corresponds to a power transmission and distribution transformer, and protective safety devices. Table 7.1 shows the parameters of the diesel generator and GFM-BESS used in this section. The test environment and the diesel generator are shown in Fig. 7.3 and Fig. 7.4, respectively.

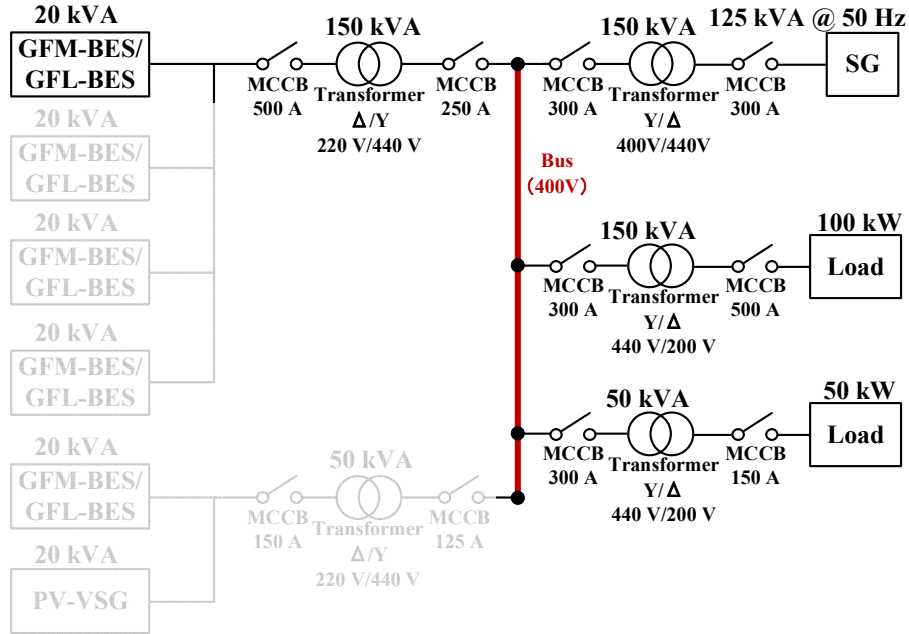


Fig. 7.2 Simulated microgrid

Table 7.1 Experimental conditons

Parameter	Value	Parameter	Value
V_{base_GFM}	200 V	M_{GFM}	8.0 s
S_{base_GFM}	20 kVA	D_{SSI}	1.0
f_{base_GFM}	50 Hz	Droop gain (GFM-BESS)	-4%
L_s	0.05 pu.	Xslope gain	-4%
V_{base_SG}	400 V	S_{base_SG}	125 kVA
f_{base_SG}	50 Hz	Droop gain (SG)	-4%



Fig. 7.3 Indoor



Fig. 7.4 Outdoor

7.3.2. Evaluation of Transient Load Sharing in One IBR and One SG System

There is no big difference between the excess internal voltage E and the phase angle δ of each generator by the pu (per unit) method, and the synchronization force ratio roughly matches the ratio of the excess synchronization reactance. To confirm the analysis in the above section, the tests of Cases 2, 3 and 4 were performed. Case 2 and Case 1 have different load fluctuations, Case 3 and Case 2 have different GFM-BESS command values, and Case 4 and Case 1 have different initial states. The overload sharing in each situation is evaluated. The content and results of the test are summarized in Table 7.3. The active power outputs of Cases 2, 3, and 4 are shown in Fig. 7.5, Fig. 7.6, and Fig. 7.7, respectively.

From the results of the four cases, it can be confirmed that the overload sharing between SG and

GFM-BESS is proportional to the mutual synchronization force and roughly proportional to the synchronous reactance. For further confirmation, the simulation is performed using the hyper-synchronized reactance of SG set together with the test conditions of Case 4.

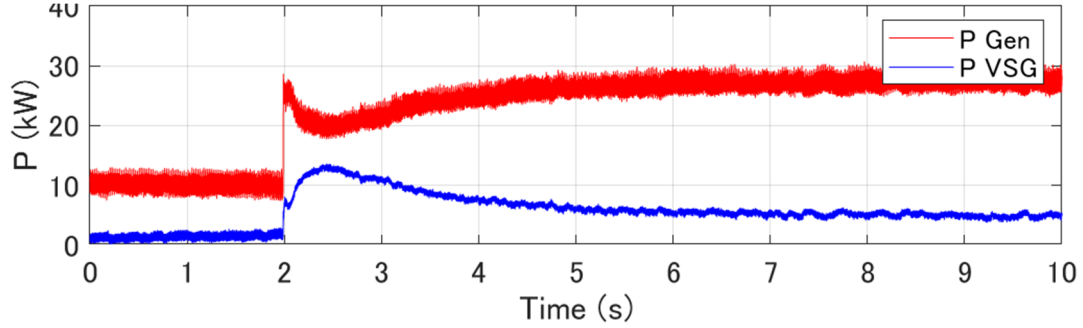


Fig. 7.5 Case2 : Load sharing between SG and GFM-BESS due to load fluctuation 10⇒30kW

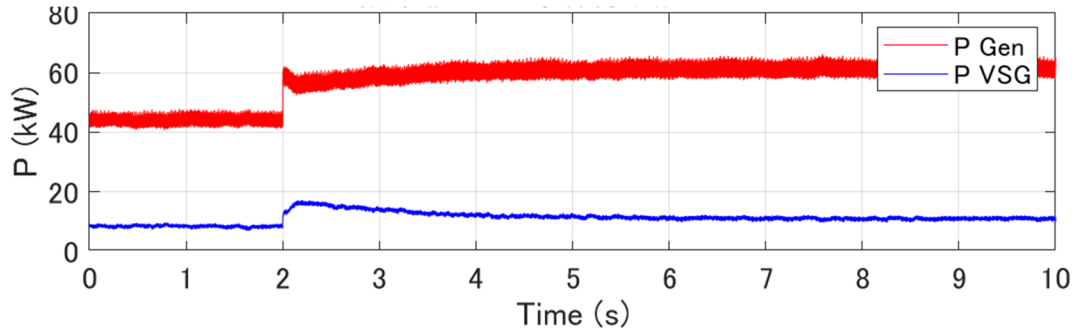


Fig. 7.6 Case3 : Load sharing between SG and GFM-BESS due to load fluctuation 50⇒70kW

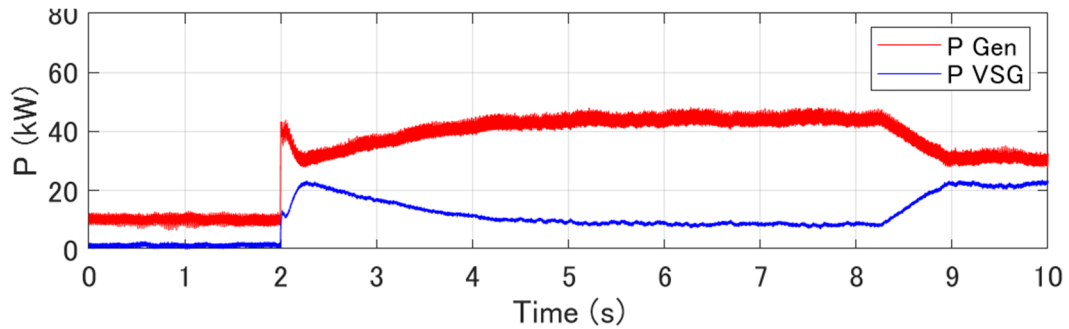


Fig. 7.7 Case4 : Load sharing between SG and GFM-BESS due to load fluctuation 10⇒50kW

Table 7.2 Evaluation of transient power sharing

Case	Case 1	Case 2	Case 3	Case 4
GFM-BESS command value (kW)	0	0	10	0
SG command value (kW)	0	0	0	0
load (kW)	0⇒40	10⇒30	50⇒70	10⇒50
GFM (primary load sharing) (kW)	-0.9	1.7	8.5	1.7
GFM (transient load sharing) (kW)	9.1	7.3	13.1	11.7
ΔP_{GFM} (kW)	10	5.6	4.6	10
SG (primary load sharing) (kW)	2.4	10.1	44.3	10.6
SG (transient load sharing) (kW)	32.3	26.0	58.9	39.8
ΔP_{SG} (kW)	29.9	15.9	14.6	29.2
Synchronous power ($K_{\text{VSG}}/K_{\text{SG}} = \Delta P_{\text{VSG}}/\Delta P_{\text{SG}}$)	1:2.9	1:2.8	1:3.2	1:2.9

7.4. Evaluation of the Effect of Inductance on Synchronization Power

When the synchronous reactance of SG and GFM-BESS are matched, it was confirmed by simulation whether the load sharing in the excessive state is the same as the theory. The simulation conditions are the same as above, but the 1.83mH reactor is added to the 400 side of the generator, and the synchronous reactance of SG and GFM-BESS is 0.68 pu together. Compared with the original condition, the simulation results are shown in Fig. 7.8 and Fig. 7.9. The results match theoretical, and when the synchronous reactance is the same, the overload sharing is also the same, and the accuracy of the analysis can be further confirmed.

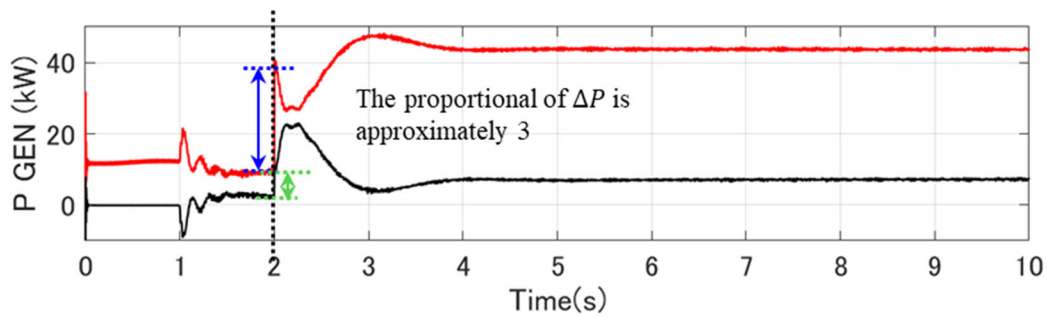


Fig. 7.8 Simulation: Load sharing between SG and GFM-BESS due to load fluctuation 10⇒50kW (the same condition with the experimental test)

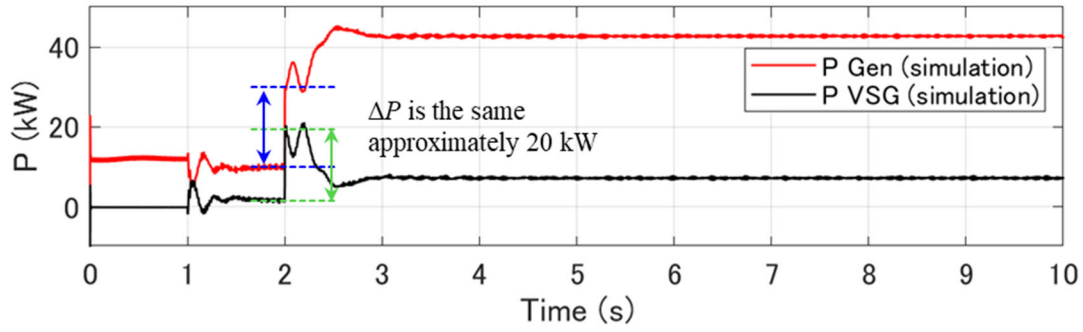


Fig. 7.9 Simulation: Load sharing between SG and GFM-BESS due to load fluctuation 10⇒50kW (1.83mH reactor is added to the 400 side, and the over synchronized reactance of SG and GFM-BESS is combined)

7.5. Evaluation of Transient Load Sharing by Synchronization Power in a Five IBR and One SG Microgrid

Using the above-mentioned relational expression of overload sharing and synchronization force, we will consider overload sharing in a multi-machine system. As shown in Fig. 7.10, the test system configuration consists of one SG and five inverters. The inverter is a mixture of GFM-BESS with synchronization power and GFL-BESS without synchronization power. By adjusting the penetration rate of GFM-BESS with synchronization power, we considered the overload sharing of a multi-machine system with and without synchronization power in three cases where the inverter is congested. The test content is summarized in Table 7.3.

The test results of the three cases are shown in Fig. 7.11, Fig. 7.12 and Fig. 7.13, respectively. Since Case 1 uses 5 GFM-BESS units, the synchronization power of the system is maximized. As shown in Fig. 7.11, it can be seen that GFM-BESS and SG share the excessive load of 9.9 kW and 50.5 kW immediately after the load change at $t = 2$ s. In Case 2, only 3 GFM-BESS units with synchronization power are used, so the synchronization power of the system is reduced. As shown in Fig. 7.12, it can be seen that GFM-BESS and SG share the excessive load of 11.4 kW and 56 kW immediately after the load change at $t = 2$ s. By reducing the synchronization power, each generator has more overload sharing. In Case 3, there is no GFM-BESS with synchronization power, and 5 GFL-BESS units without synchronization power are used. As shown in Fig. 7.13, GFL-BESS does not share the overload because it has no synchronization power. SG shares all overload and the output fluctuates. Before building a microgrid system, it is meaningful to understand the synchronization power and overload sharing. In the test results of Case 2, the above analysis is used to show an example of the calculation of overload sharing. The mutual synchronization power of GFM-BESS and SG is about 1:3. The load sharing immediately after the load fluctuation of 40 kW is:

$$\Delta P_{SG} = \frac{K_{SG}}{K_{SG} + K_{GFM}} \Delta P_{SG} = \frac{3}{3 + 3} 40 = 20 \text{ kW}$$

$$\Delta P_{GFM} = \frac{K_{GFM}}{K_{SG} + K_{GFM}} \Delta P_{SG} = \frac{1}{3+3} 40 = 6.7 \text{ kW (One IBR)}$$

The measured and calculated values of GFM-BESS and SG overload sharing are summarized in Table 7.4, respectively. The error between the calculated value and the measured value is within 10%. The excessive load sharing between the power generation devices is shared in proportion to the mutual synchronization force.

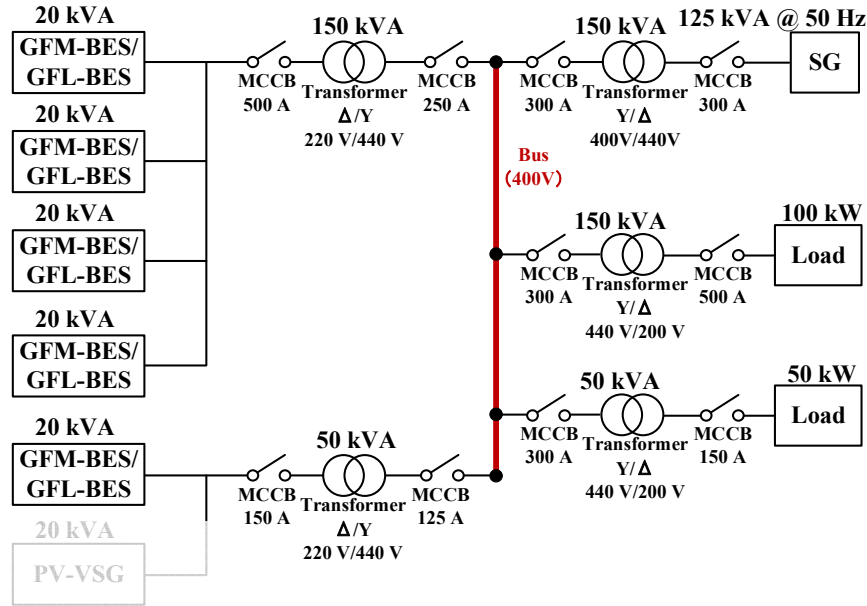


Fig. 7.10 A system that simulates off-the-grid (multi-machine system)

Table 7.3 Evaluation of transient power sharing

Case	Case 1	Case 2	Case 3
GFM-BESS commend value(kW) / numbers	5.5 / five	5.5 / three	0
GFL-BESS commend value(kW) / numbers	0	5.5 / two	5.5 / five
SG commend value (kW)	34	34	34
Load change (kW)	62⇒102	62⇒102	62⇒102

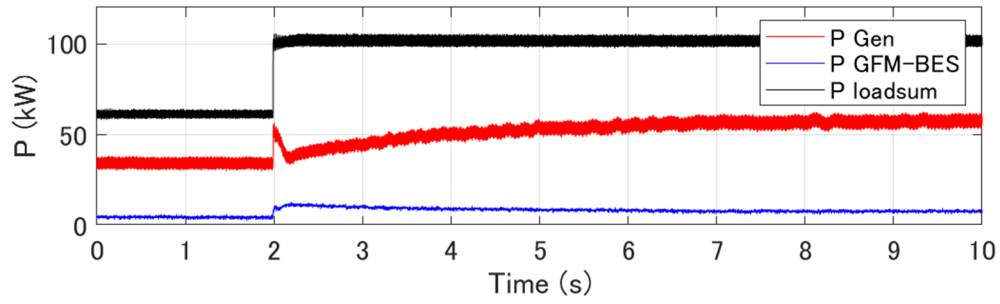


Fig. 7.11 Case1 : Load sharing between SG and GFM-BESS due to load fluctuation 60⇒100kW

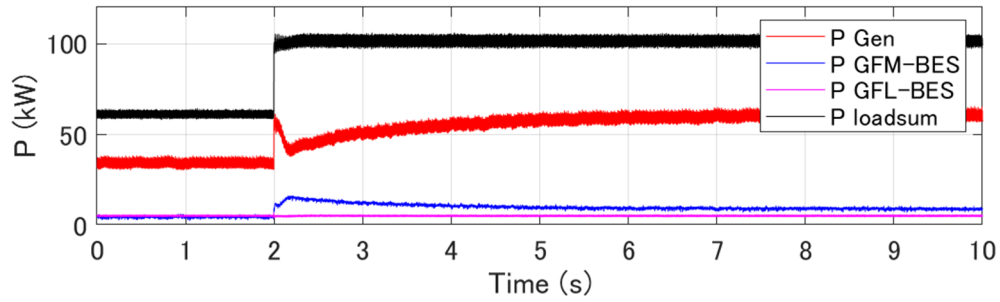


Fig. 7.12 Case2 : Load sharing between SG and GFM-BESS due to load fluctuation 60⇒100kW

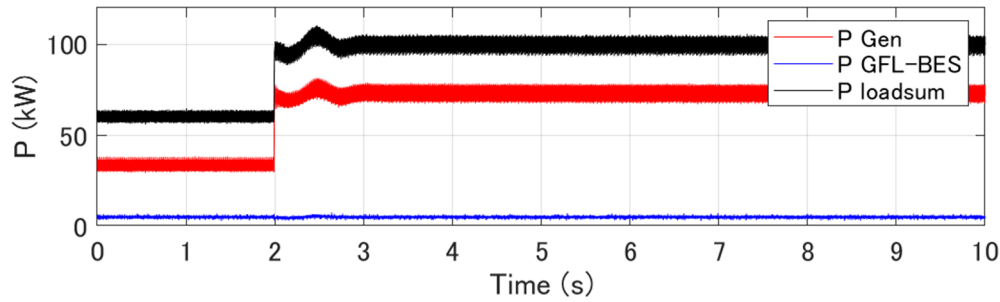


Fig. 7.13 Case3 : Load sharing between SG and GFM-BESS due to load fluctuation 60⇒100kW

Table 7.4 Evaluation of transient power sharing

Case	Case 1	Case 2	Case 3
GFM (primary load change) (kW)	5.1	5.4	
GFM (transient load change measured) (kW)	9.9	11.4	
GFM (transient load change predicted) (kW)	10.1	12.0	
SG (primary load change) (kW)	34.8	34.4	34.1
SG (transient load change measured) (kW)	50.5	56.0	73.0
SG (transient load change predicted) (kW)	49.8	54.4	74.1
$\Delta P_{\text{GFM}}(\text{kW}) / \Delta P_{\text{SG}}(\text{kW})$ measured	1:3.27	1:3.6	

7.6. Conclusion

The theory of mutual synchronization force between power generation devices was examined, and a method of predicting the overload sharing immediately after load fluctuation was presented by the mutual synchronization force. The synchronous reactance of the diesel generator could be estimated on a microgrid consisting of SG and GFM-BESS. A simulation and a demonstration experiment were conducted, and the accuracy of the analysis was confirmed. In addition, it was further confirmed that the overload sharing immediately after the load change is proportional to the synchronization power in the microgrid system in which 5 GFM-BESS and GFL-BESS units are operated in parallel with SG, in 3 cases.

Chapter 8. Conclusions and Future Works

8.1. Learned from the demonstration experiment

There were some findings learned from the actual tests that were not predicted by the simulations. Because the inertia constant of the 125-kVA SG is very small, a large load change may cause the inverters to shut down for protection in low GFM-BESS penetration ratio cases. The step response delay of the diesel SG is not constant because of its actual mechanical characteristics, and the delay varies between different load changes. The high quality BESS can recharge very quickly to provide inertial energy.

8.2. Conclusions

- 1) The basics of GFL inverters, GFM inverters, and VSGs which belong to IBR were described. the control methods of the VSG domestic and foreign studies are reviewed, and the differences are organized.
- 2) A method for evaluating the effects on the system of a synchronous generator with an internal combustion engine is proposed. The operating characteristics of GFM-BESS were analyzed and evaluated under parallel conditions with different operating modes of synchronous generators.
- 3) As a method for quantitatively measuring and evaluating the inertial force of GFM-BESS, a method for evaluating an actual machine that operates in parallel with a synchronous generator is proposed. The test conditions were determined with reference to the data of the power demand, solar radiation intensity, and PV module temperature of the Mutsuzawa microgrid that is actually in operation. Combined with GFM-BESS and GFL-BESS, the IBR ratio has reached 44.4%. The load fluctuated, the ratio of GFM inverter and GFL inverter was changed for 5 BESS, and the frequency stability, load sharing, and synchronization power were verified on the actual machine. By GFM-BESS, it was confirmed that the overload sharing of the generator was reduced by 30% and the steady load sharing was reduced by 22%. It was also confirmed that GFM-BESS suppresses frequency Nadir by 70%, suppresses RoCoF from 8Hz / s to 2Hz / s or less, and contributes to frequency stability compared to GFL-BESS.
- 4) A GFM inverter applied to photovoltaic power generation with imitated inertia characteristics is proposed and evaluated by the proposed evaluation method, which is named GFM-PV. By updating the control software without adding an energy buffer to supply the inertial force, the frequency Naidr is suppressed by about 30%, the RoCoF is suppressed from 1.78Hz / s to 1.28Hz / s, and the frequency is stabilized by providing the inertial force.

- 5) The electromagnetic interference of GFM-BESS was measured and reduction methods were taken. Conducted electromagnetic interference reduction methods have improved electromagnetic interference to meet CISPR 11 class A, which is intended for use in industrial environments. In addition, we analyzed the EMI generation mechanism of a general inverter, evaluated the EMI reduction effect by equilibrating the circuit in comparison with the reduction effect by the conventional noise filter, and confirmed the reduction effect by up to 20 dB.
- 6) In GFM-BESS, the effect of the inductance of the line filter and EMI filter on the transient load sharing of GFM-BESS were evaluated. Since the synchronization force in GFM-BESS changes depending on the inductance value of the internal filter, the mounting status of the line filter and the synchronization force are related. Therefore, the relationship between the synchronization force and the line filter was examined. A method of predicting the overload sharing immediately after the load fluctuation is presented by the synchronization force. Microgrid consisting of a synchronous generator and GFM-BESS were evaluated by simulation and demonstration experiments.
- 7) The field trial demonstrated that the GFM-BESS improved grid stability, reliability, security, and resiliency without relying on communication networks. In the future, if the proportion of renewable energy power sources increases, it should be possible to compensate for the decrease in inertial force by using the GFM-BESS technology. This project is expected to demonstrate a new lifestyle, with natural sustainable resources for improved resiliency.

8.3. Future works

- 1) We will continue to study the issues of applying the proposed circuit equilibration EMI reduction method to GFM-BESS. The trade-off of EMI filter value and synchronization power will be further evaluated.
- 2) Toward practical use, we will tackle issues such as overcurrent protection, a trade-off between inertial function, and independent operation detection of GFM-BESS.
- 3) Although GFM-BESS which inverters with imitated inertia has been developed, it is also important to grasp the inertia of the system. The continuous system inertia monitoring method will be discussed further.
- 4) When the GFM-BESS is applied to the existing system, the cost of BESS will be increased. To maintain the power quality, the same as that of the existing system, the voltage and frequency maintenance cost will be high, which will be a barrier to the realization of sustainable power infrastructure. Furthermore, in solar power generation, when a phenomenon called a cloud edge phenomenon in which solar radiation is diffracted at the edge of a cloud occurs and the amount of solar radiation fluctuates suddenly, it is difficult to secure the power quality of the system. These issues should be further discussed in the future.