Coordinated Frequency Control Strategy of Diesel Generator and BESS during Islanded Microgrid and Performance Test using Hardware-in-the-Loop Simulation System

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Abstract

Frequency control is an important problem in the islanded microgrid because an imbalance between power supply and power demand is occurred. The battery energy storage system (BESS) is an effective system for controlling islanded microgrid frequency because of its charge and discharge actions. In addition, a diesel generator can be control the frequency by controlling its output. Recently, the hardware-in-the-loop simulation (HILS) system is used to test controllers, protective devices, and so on. In this paper, a coordinated frequency control scheme of a diesel generator and a BESS during the islanded mode of a microgrid is proposed in the economic viewpoint and is tested on the HILS environment.

Keywords: *Microgrid, Battery energy storage (BESS), Diesel generator, Coordinated frequency control strategy*

1. Introduction

A microgrid is a small scale power system composed of controllable distributed generation (DG) such as diesel generators, non-controllable DG such as photovoltaic (PV) generators and wind turbine generators, distributed energy storage systems (DESSs) such as the battery energy storage system (BESS), and various loads [1-3].

The microgrid can be operated autonomously when it is isolated from the upstream power grid due to fault occurrence of the power grid or geographically isolation. Especially, the frequency control problem is an important problem because the imbalance between power supply and power demand occurs frequently due to renewable energy sources and uncontrollable loads. The frequency can be controlled by battery energy storage systems (BESSs) and diesel generators [4-6].

Meanwhile, the hardware-in-the-loop simulation (HILS) system has been applied to the power engineering studies to test developed controllers, protective devices, and so on [7]. The HILS technique uses a real-time digital simulator to emulate plants such as flexible AC transmission systems (FACTS) and high voltage DC (HVDC) to save costs, time and to overcome physical restrictions [8-10].

In this paper, a coordinated frequency control scheme of a diesel generator and a BESS during the islanded mode of a microgrid is proposed in the economic viewpoint. To test the proposed control scheme, a HILS system based on OPAL-RT real-time digital simulator (RTDS) is developed. The coordinated control scheme is implemented using CompactRIO, which is a general-purpose controller. The CompactRIO-based coordinated frequency controller is tested on the developed HILS system.

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2. Microgrid Configuration & Modeling

2.1 Diesel generator & PV/Wind hybrid generation system

A diesel generator composed of the exciter (IEEE DC1A) and the diesel engine governor is modeled as shown in Figure 1. The diesel generator is operated in the constant power mode. A PV/wind-turbine hybrid generation system based on equivalent current model is applied as shown in Figure 2 in this paper.

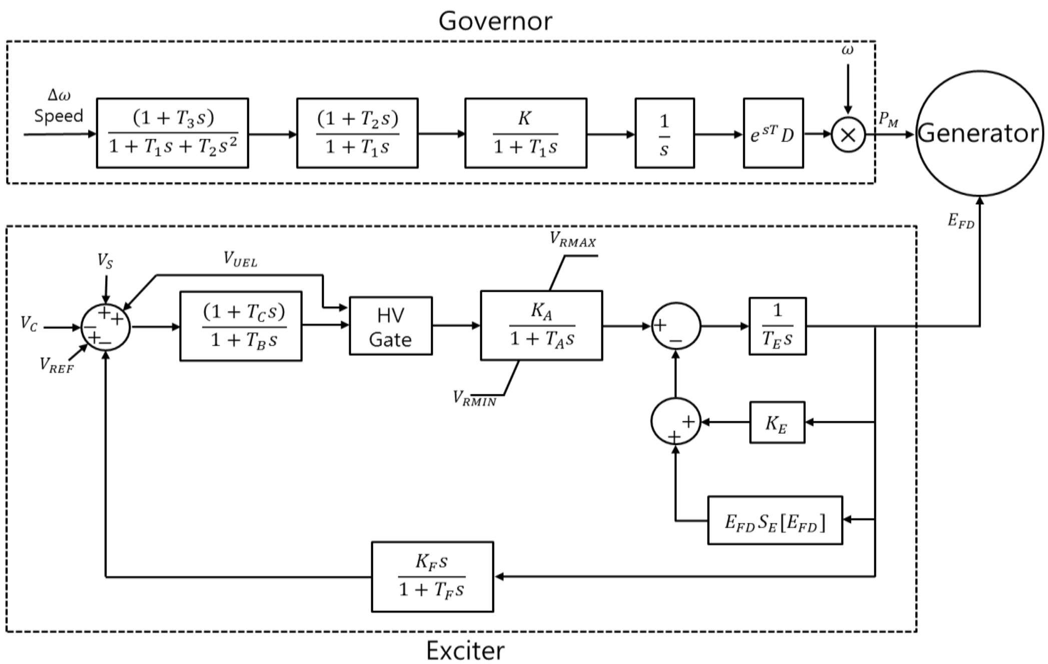


Figure 1. Diesel generation system model

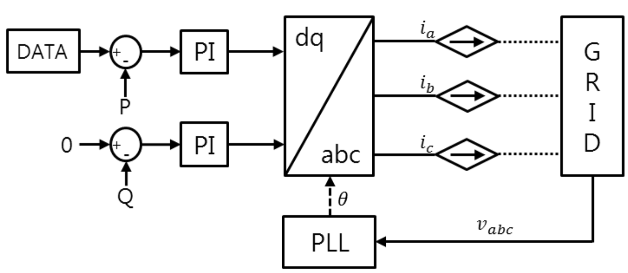


Figure 2. PV/wind-turbine hybrid system model based on equivalent current model

2.2 Battery energy storage system (BESS)

A Lithium-ion (Li-ion) BESS is applied to the microgrid. The Li-ion BESS composed of a transformer, a voltage sourced converter (VSC), and a the Li-ion battery is modeled by a controlled voltage source and internal resistance as shown Figure 3 [11].

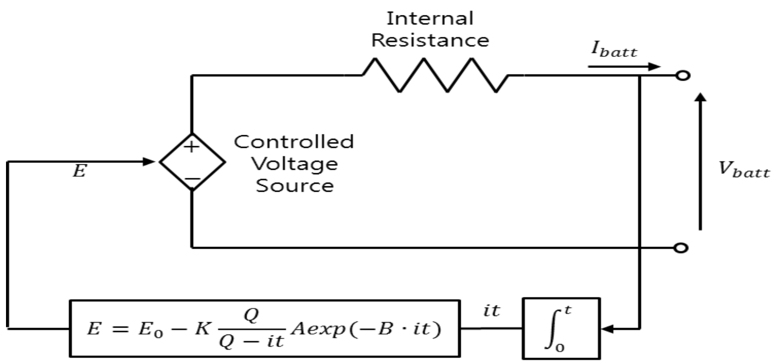


Figure 3. The battery model

A non-linear voltage of the battery model is modeled by Eq. (1).

$$\mathrm{E} = E_0 - K\frac{Q}{Q-it} + Aexp(-B \cdot it), \tag{1}$$

where

E = no-load voltage (V)

E_0 = battery constant voltage (V)

K = polarization voltage (V)

Q = battery capacity (Ah)

$\int$idt= actual battery charge (Ah)

A = exponential zone amplitude (V)

B = exponential zone time constant inverse $(\mathrm{Ah})^{-1}$

V_{batt} = battery voltage (V)

R = internal resistance (Ω)

I = battery current (A).

Although the internal resistance in the battery model is not variable during charging and discharging and self-discharge is not considered [11], the model can be applied with any problem because the state of charge (SOC) of the BESS is considered in the proposed coordinated control scheme.

The VSC is composed of filters, an insulated gate bipolar transistor (IGBT) bridge, and a DC link for power conversion and control as shown in Figure 4 [12].

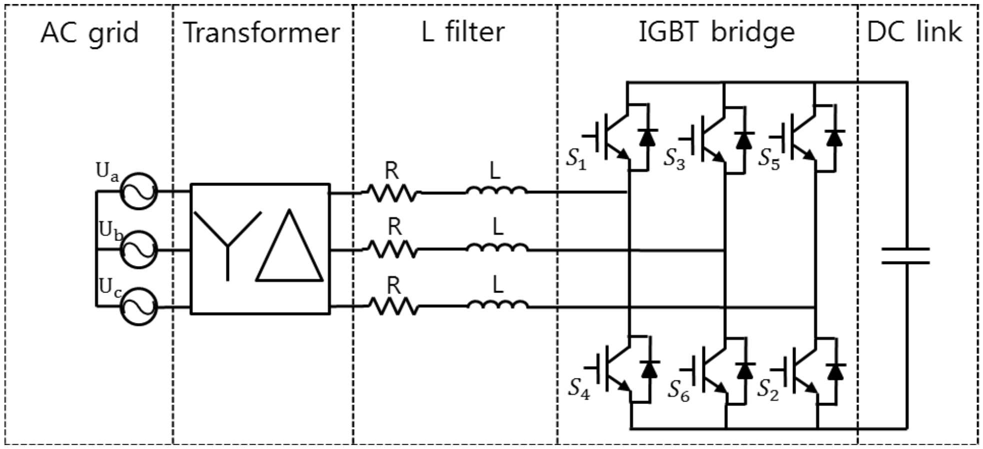


Figure 4. The structure of 2-level VSC

The three-phase line voltage is defined by Eq. (2).

$$U_a = V_s \cos(\omega t + \phi)$$
$$U_b = V_s \cos\left(\omega t + \phi - \frac{2\pi}{3}\right) \quad (2)$$
$$U_c = V_s \cos\left(\omega t + \phi - \frac{4\pi}{3}\right)$$

Equation (1) can be expressed to Eq. (3) by vector relation between αβ-frame and dq-frame as shown in Figure 5.

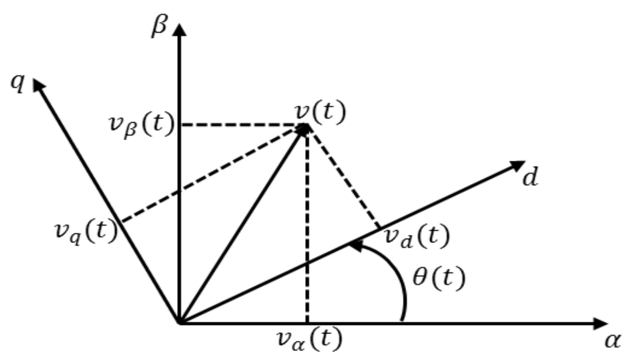


Figure 5. αβ-frame and dq-frame coordinated system

Equation (3) can be expressed by a dq/abc transform and the phase angle thorough the phase lock loop (PLL).

$$L\frac{d}{dt}(i_{dq}) = -j\left(L\frac{d\theta}{dt}\right)i_{dq} - Ri_{dq} + U_{dq} \quad (3)$$

Equation (3) can be subdivided into Eq. (4), which is composed by real and imaginary parts.

$$\mathrm{L}\frac{di_d}{dt} = \left(L\frac{d\theta}{dt}\right) i_q - Ri_d + U_d$$
$$\mathrm{L}\frac{di_q}{dt} = -\left(L\frac{d\theta}{dt}\right) i_d - Ri_q + U_q \quad (4)$$

Equation (4) can be expressed as the control block diagram as shown in Figure 6 [12].

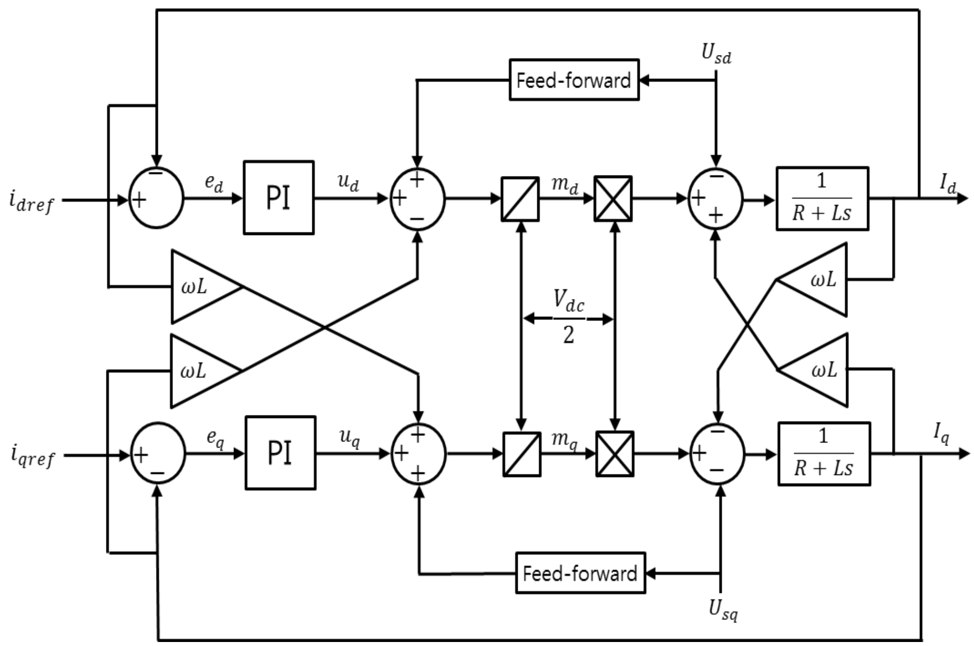


Figure 6. The control block diagram of current controller

2.3 Microgrid modeling

A microgrid, which is dealt with in this paper, is composed of a static switch (STS), a diesel generator, a PV/wind-turbine hybrid generation system, a Li-ion BESS, and a lumped load as shown in Figure 7. The capacity of the components of the microgrid is represented in Table 1.

Table 1. The capacity of components

System	diesel generator	PV/Wind hybrid generation system	Li-ion BESS
Capacity	200kW	100kW	100kW/kWh

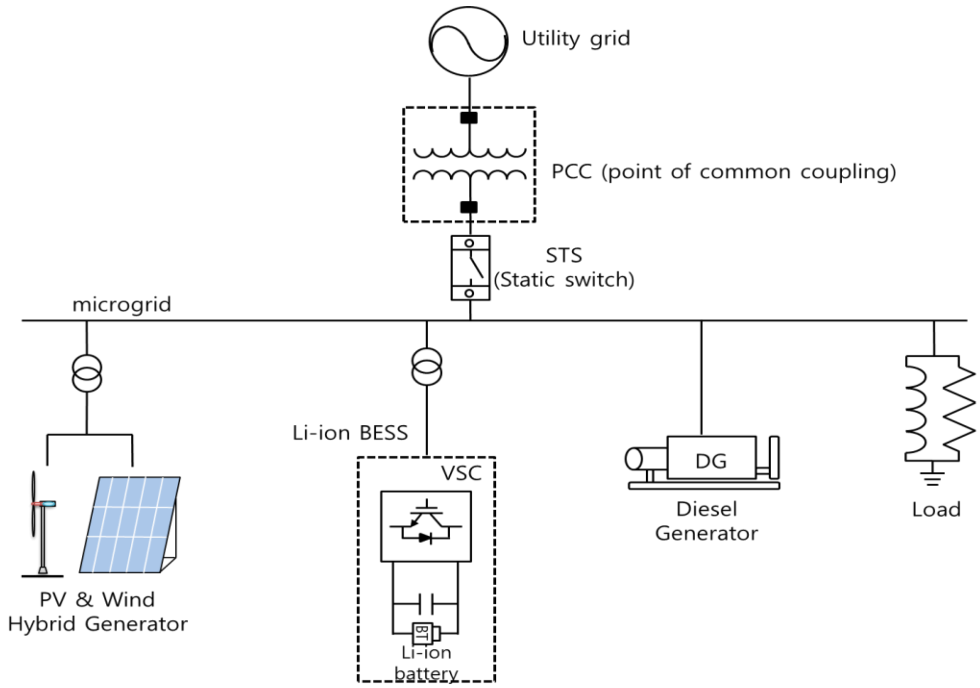


Figure 7. Microgrid structure

3. Design of the Coordinated Control Strategy

Figure 8 shows the proposed coordinated control strategy of a lithium-ion (Li-ion) BESS and a diesel generator for frequency control in the islanded microgrid. The rationale of the strategy is to minimize the output power of the diesel generator because it uses fuel in the economic viewpoint. The detailed is as follows.

In Figure 8, ΔP means the difference between total generation ($\sum$ Generation) and total load ($\sum$ Load). If ΔP>0, the generation should be decreased to meet the power balance. For this, the diesel generator decreases power output firstly because saving the cost. When additional power decrease to meet the power balance, secondly the BESS charges. On the other hand, if ΔP<0, the generation should be increased to meet the power balance. For this, firstly the BESS discharges because of no fuel cost. When additional power is required to meet the power balance, secondly the diesel generator increases power output.

Figure 9 shows configuration of the proposed coordinated frequency controller.

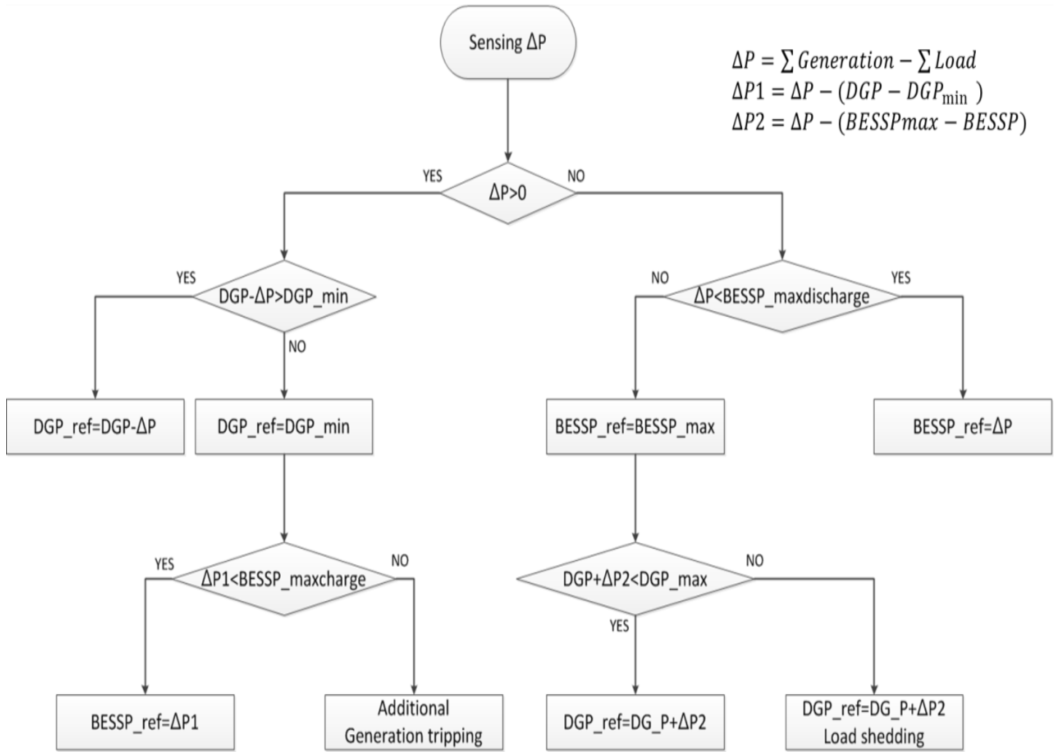


Figure 8. Flow chart of control strategy

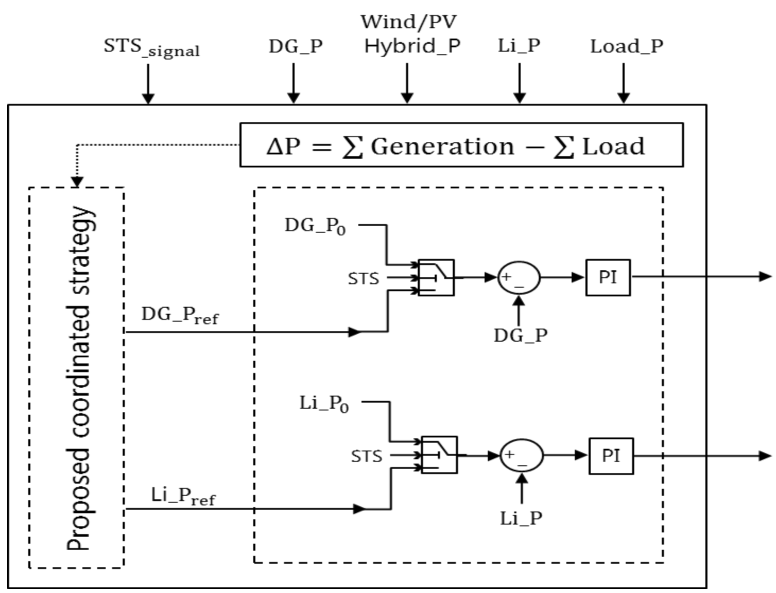


Figure 9. shows configuration of the proposed coordinated frequency controller

4. HILS System

4.1 Designing coordinated frequency controller

The coordinated control strategy shown in Figure 8 is designed using CompactRIO, which a general-purpose controller, as shown in Figure 10.

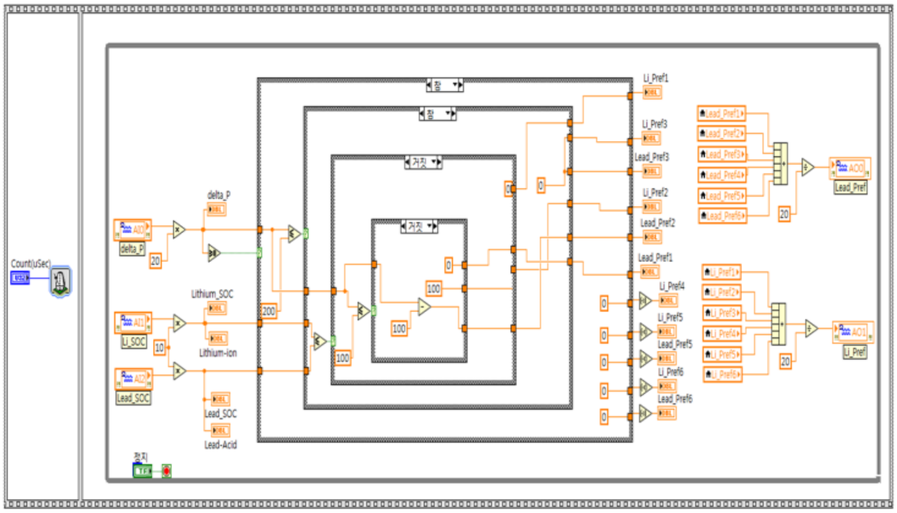


Figure 10. Designed coordinated controller using CompactRIO

4.2 Implementing HILS system based on OPAL-RT RTDS

Figure 11 shows the developed HILS system for emulating a microgrid and the tested CompactRIO-based coordinated controller for microgrid frequency control in the laboratory.

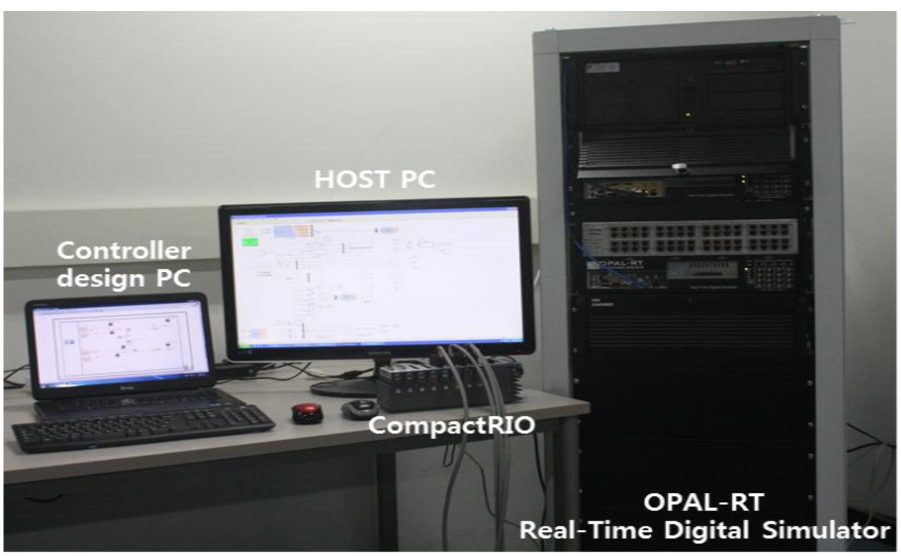


Figure 11. Developed HILS system and tested coordinated controller

5. Coordinated Frequency Controller Test using HILS system

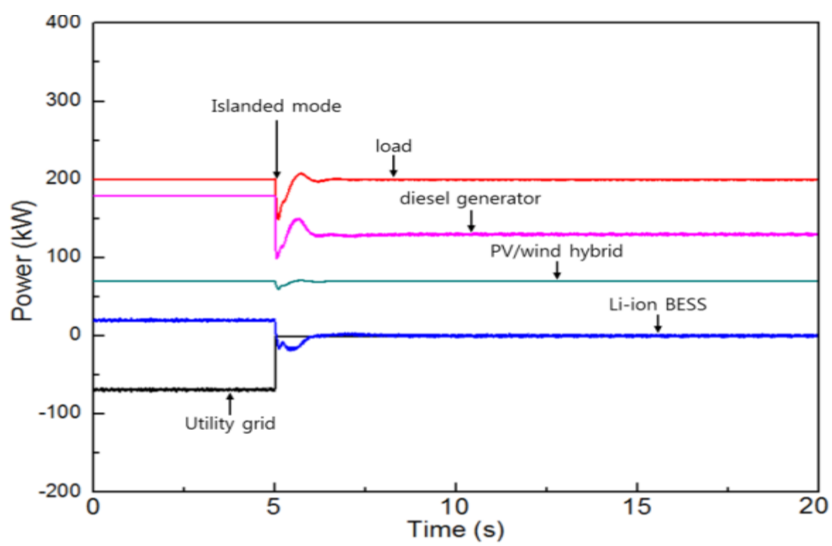
In order to test coordinated frequency control during the islanded microgrid, two operation conditions are tested as shown in the Table 2.

Table 2. Test conditions

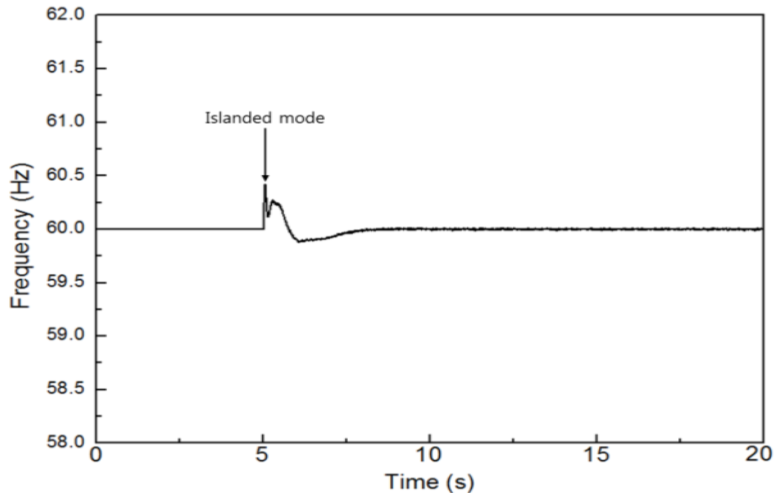
Cases	Conditions
1	DGP=180kW, load=200kW, PV/Wind hybrid=75kW, Li-ion BESS=20kW
2	DGP=140kW, load=280kW, PV/Wind hybrid=75kW, Li-ion BESS=20kW

5.1 Case 1 ($\Delta P > 0$)

In the initial operation condition, the microgrid transmits its excess power to the upstream power grid. The BESS and diesel generators are operated by the constant power mode before 5 sec. An islanded mode is occurred at 5 sec. by opening the STS. Figure 12(a) shows dynamic behavior of microgrid components according to frequency control by the proposed coordinated controller. From the Figure 12(a), it is shown that the output of the diesel generator is decreased and the output of the BESS is decreased to zero. From Figure 12(b), we can see that microgrid frequency is recovered promptly by the coordinated control of the BESS and the diesel generator.



(a) Output power of components.

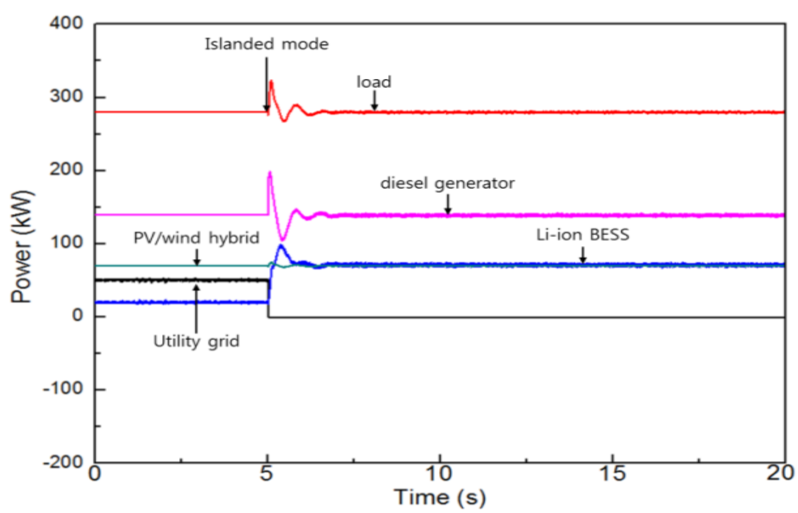


(b) Frequency.

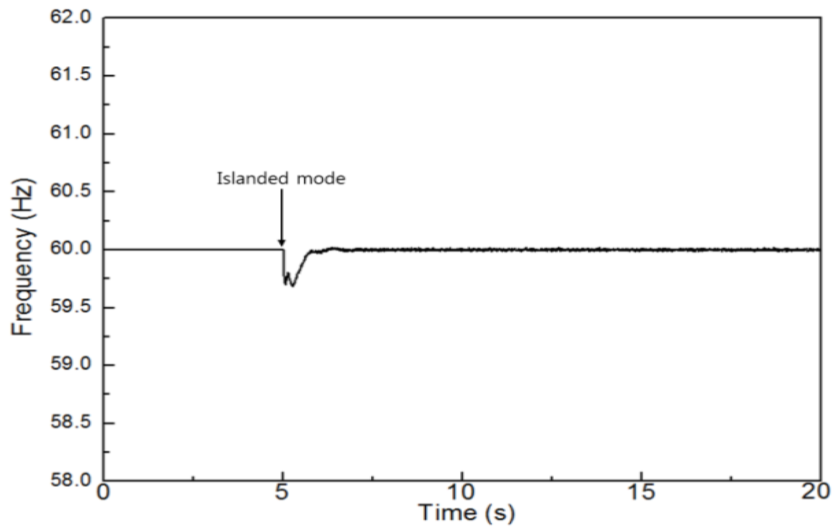
Figure 12. Test result of case 1

5.2 Case 2 ($\Delta P < 0$)

In the initial operation condition, the microgrid receives short power from the upstream power grid. The BESS and diesel generators are operated by the constant power mode before 5 sec. An islanded mode is occurred at 5 sec. by opening the STS. Figure 13 (a) shows dynamic behavior of components by the coordinated controller. From the Figure 13 (a), the output of the diesel generator is not changed but the output of the BESS is increased to meet the imbalance between power supply and power demand in the islanded microgrid. From Figure 12 (b), we can see that microgrid frequency is recovered promptly by the coordinated control of the BESS and the diesel generator.



(a) Output power of components.



(b) Frequency.

Figure 13. Test result of case 2

6. Conclusion

In this paper, a coordinated frequency control scheme of a diesel generator and a BESS based on the economic viewpoint during the islanded mode of a microgrid has been proposed. To test the proposed control scheme, a HILS system based on OPAL-RT RTDS has been developed. The proposed control scheme has been designed using CompactRIO. The test results showed that microgrid frequency has been controlled by designed purpose.

In the near future, we plan to study the coordinated control strategy of multiple ESSs and diesel generators for frequency control during the islanded mode on the developed HILS system.

Acknowledgements

This work was supported partially by the Power Generation & Electricity Delivery of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 20111020400220) and was supported partially by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012R1A1A1011306).

References

[1] H. -M. Kim, T. Kinoshita, Y. Lim and T. -M. Kim, “A Bankruptcy Problem Approach to Load-shedding in Multiagent-based Microgrid Operation”, Sensors, vol. 10, **(2010)**, pp. 8888-8898.

[2] N. D. Hatziargyriou, H. Asano, H. R. Iravani and C. Marnay, “Microgrid”, IEEE Trans. on Power Energy, vol. 5, **(2007)** July/August, pp. 78-94

[3] P. Basak, A. K. Saha, S. Chowdhury and S. P. Chowdhury, “Microgrid: Control Techniques and Modeling”, Proc. of Universities Power Engineering Conference, (2009) September, pp. 1-5.

[4] R. Majumder, A. Ghosh, G. Ledwich and F. Zare, “Power Management and Power Flow Control with Back-to-Back Converters in a Utility Connected Microgrid”, IEEE Trans. on Power System, vol. 25, no. 2, **(2010)**, pp. 821-834.

[5] J. -Y. Kim, H. -M. Kim, S. -K. Jeon and H. -K. Choi, "Designing Fuzzy PID Controller of Energy Storage System for Microgrid Islanded Operation", Energies, **(2011)**, pp. 1443-1460.
[6] H. -M. Kim, T. Kinoshita and M. -C. Shin, "A Multiagent System for Autonous Operation of Islanded Microgrids based on a Power Market Environment", Energies, vol. 3, Issue 12, **(2010)** December, pp. 1972-1990.
[7] J. -H. Jeon, J. -Y. Kim, H. -M. Kim, S. -K. Kim, C. Cho, J. -M. Kim, J. -B. Ann and K. -Y. Nam, "Development of Hardware in-the-Loop Simulation System for Testing Operation and Control Functions of Microgrid", IEEE Trans. on Power Electronics, vol. 25, no. 12, **(2010)** December, pp. 2919-2929.
[8] B. Lu, X. Wu, H. Figueroa and A. Monti, "A Low-Cost Real-Time Hardware-in-the-Loop Testing Approach of Power Electronics Controls", IEEE Trans. on Industrial Electronics, vol. 54, no. 2, **(2007)** April, pp. 919-931.
[9] M. O. Faruque and V. Dinavahi, "Hardware-in-the-Loop Simulation of Power Electronic Systems Using Adaptive Discretization", IEEE Trans. on Industrial Electronics, **(2010)**, pp. 1146-1158.
[10] P. Shi, Q. Zhang, C. Lin and H. Zhang, "Electric Power Steering System Matching and Hardware-in-the-loop Simulation of Economical Cars", Proc. of Electrical Machines and System, **(2011)**, pp. 1-4.
[11] O, Ttrmblay, L. A. Dessaint and A. I. Dekkiche, "A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles", Proc. of IEEE VPPC, **(2007)** September, pp. 284-289.
[12] A. Yazdani and R. Iravani, "Voltage-Sourced Converters in Power System", John Wiley and Sons, **(2010)**.
[13] P. Kundur, Power System Stability and Control, Mcgraw-Hill, NewYork, 1993.
[14] OPAL-RT, OPAL-RT RTDS Manual & Tutorial, **(2011)**.
[15] National Instrument, CompactRIO Manual.

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