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Evaluation of PV output fluctuation suppression by cooperative control of distributed CHP and storage battery

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SUMMARY

This paper discusses quantitatively evaluated result regarding least Battery Energy Storage (BES) capacity necessary to maintain the Fluctuation Suppression (FS) effect derived from 100 case simulator verification tests done on Smart Grid Simulator, together with the simulator model created and FS algorithms.

In order to bring low-carbon emission society to real life, the Japanese government has set an ambitious goal to reduce Carbon Dioxide emission by 25% compared to the emission amount on 1990 by year 2020. A same goal also set in major European countries.

A demonstration regarding distributed energy network called "Smart Energy Network (SEN)" are being realized in Japan. SEN aims to accelerate implementation of renewable energies such as Photovoltaic (PV) to power grid by smoothing PV output fluctuation using simultaneously controlled Combined Heat and Power (CHP). It includes total CHP capacity of 6380kW (i.e. 815kW CHP*7, 520kW CHP, 31kW Micro-CHP (M-CHP)*5), PV capacity of 300kW (i.e. 60kW PV in 5 sites) and other facilities. This demonstration system is made to utilize a part of its output while maintaining the existing benefits of large capacity CHP.

Although CHP uses fuel to generate, it is an efficient generator with controllable output. In the past demonstration carried under SEN, the authors have recognized CHP contribution to FS of PV.

In order to suppress fluctuation caused by PV, BES is well known to be effective due to its rapid charge / discharge ability. However at the current moment, a FS system composed only of BES is still expensive. Therefore, the authors seek possibilities for the combination of CHP and BES to achieve effective FS with lesser capacity of BES.

The authors have recognized the feasibility of PV fluctuation suppression by remote-controlled distributed CHP. According to the verification test results, combination of CHP and BES is able to regulate 6.7 times the capacity of PV. In addition, combination of CHP and BES will reduce the BES capacity necessary to realize fluctuation suppression, yet realizing same quality of FS done only by BES. This is done by dispatching low frequency component control value to CHP, and high frequency component control value to BES, hence enable FS of various frequency domains (such as LFC and EDC) done by CHP and minimum capacity of BES.

The outcome of the verification test will contribute to further implementation of PV as well as smoothing their fluctuant output which may impact future power grid.

KEYWORDS

Smart Energy Network - Smart Grid – PV - Combined Heat and Power - Battery Energy Storage - Load Frequency Control - Energy Management System

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1. Introduction

In order to bring low-carbon society to real life, the Japanese government has set an ambitious goal to reduce Carbon Dioxide (CO2) emission by 25% compared to the emission amount on 1990 by year 2020. A same goal also set in major European countries.
Additional nuclear power plant construction has been regarded as one of the key solutions for CO2 emission reduction; however nuclear power plant accident caused by 2011 Tohoku earthquake and tsunami has made this alternative difficult to select. Along with the existing nuclear power plant operation halt, Japan is facing the need to ensure power supply, and the need to establish low-carbon power system simultaneously.

Having these backgrounds, considerable actions are made from customer sides as below.

First, number of demonstrations regarding demand response using Energy Management Systems implemented in buildings and homes are accelerating, where we see a movement towards customer participation to tackle these arising issues.
Second, more than half of their energy consumption consists of thermal energy consumption [1]. A key technology to efficiently use this thermal energy is "Combined Heat and Power (CHP)". In Japan, more than 4.5million kW of CHP has been implemented by year 2009. Furthermore, it has been decided by the Japanese government to implement CHP to provide 15% of the power generation of year 2030 [2].
Lastly, with the beginning of Feed-in Tariffs, Distributed Energy Resource (DER) such as Photovoltaic (PV) implementation in customer side is increasing. In order to ensure power supply, and establish low-carbon power system, it is inevitable to harmonize with these customer side facilities and participation.

Based on these facts, a demonstration regarding distributed energy network called "Smart Energy Network (SEN)" are undertaken in Japan [3]. SEN aims to smooth PV output fluctuation by simultaneously controlled CHP, hence accelerating PV implementation to the power grid.
Although CHP uses fuel to generate, it is an efficient, output-controllable generator. In the past demonstration carried under SEN, the authors recognized that CHP is capable of contributing to Fluctuation Suppression (FS) of PV.
In order to suppress fluctuation caused by PV, Battery Energy Storage (BES) is well known to be effective due to its rapid charge / discharge ability. However at the current moment, a FS system composed only of BES remains expensive. Therefore, the authors seek possibilities for the combination of CHP and BES that achieves effective FS while reducing the capacity of BES.
This paper will discuss quantitatively evaluated result regarding least BES capacity necessary to maintain the FS effect derived from 100 case simulator verification tests done on Smart Grid Simulator [4], together with the simulator model created and FS algorithms.

2. Approach to simulator verification tests

2.1 Model Grid creation

Below two steps were taken to undergo the verification tests.
Step1: Obtain features of SEN demonstration facilities by modelling distributed PV, large-capacity CHP, and power interchanging system between PV and customer owned CHP. Then, investigated scenarios such as effectiveness of cooperative CHP control to given PV output.
Step2: Create a FS system including batteries, and SEN demonstration facilities with consideration to their features obtained in Step 1. Evaluate necessary CHP and BES capacity to maintain the FS effect.

2.1.1 SEN demonstration experiment facilities

Fig. 1 describes the overview of the SEN demonstration project, composed of total CHP capacity of 6380kW (i.e. 815kW CHP*7, 520kW CHP, 31kW Micro-CHP (M-CHP)*5), PV capacity of 300kW (i.e. 60kW PV in 5 sites) and other facilities. This demonstration system is made to utilize a part of its output while maintaining the existing benefits of large capacity CHP. Data acquisition and Control Value (CV) dispatching is done by using the public communication line.

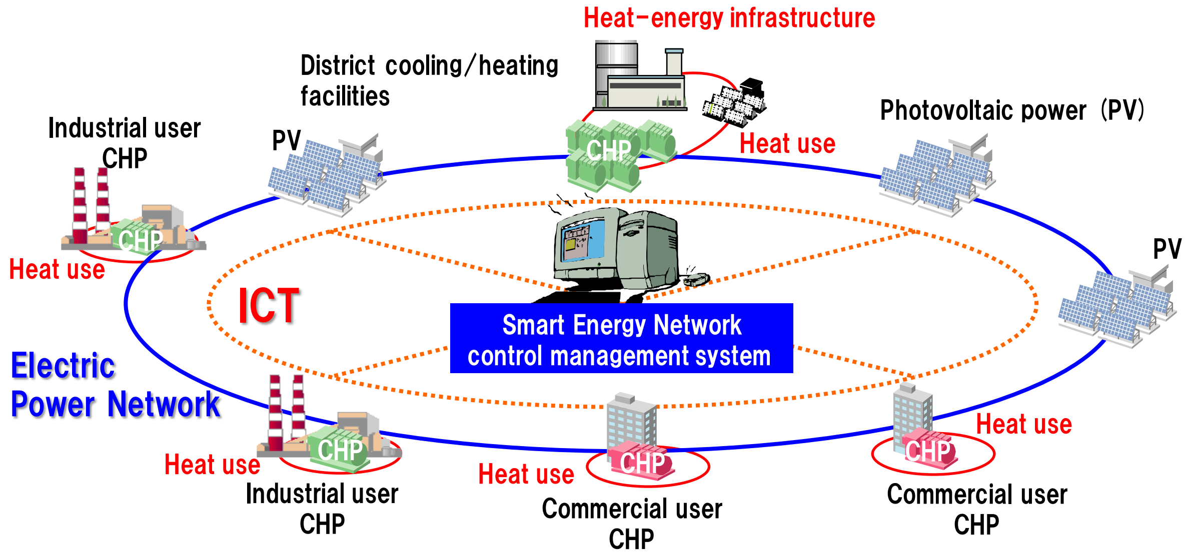


Fig. 1 Overview of the SEN demonstration facilities

2.1.2 Smart Grid Simulator [4][5]

Power grid model is created upon Smart Grid Simulator (SGS). SGS is an analogue-simulator which models actual components in 1/1000 scale capacity. The authors modelled features of each component derived from previous demonstration onto SGS. In this demonstration, the authors focused on the ratio of controlling subject (i.e. PV) and controlling equipment (i.e. CHP and BES), aggregating their features into one device, and undertook experiments by using the devices' capacity as parameters. As a controlling device, the authors used the grid monitoring and control system, "Micro Energy Management System (μEMS)," which is also applicable for actual power grid operation.

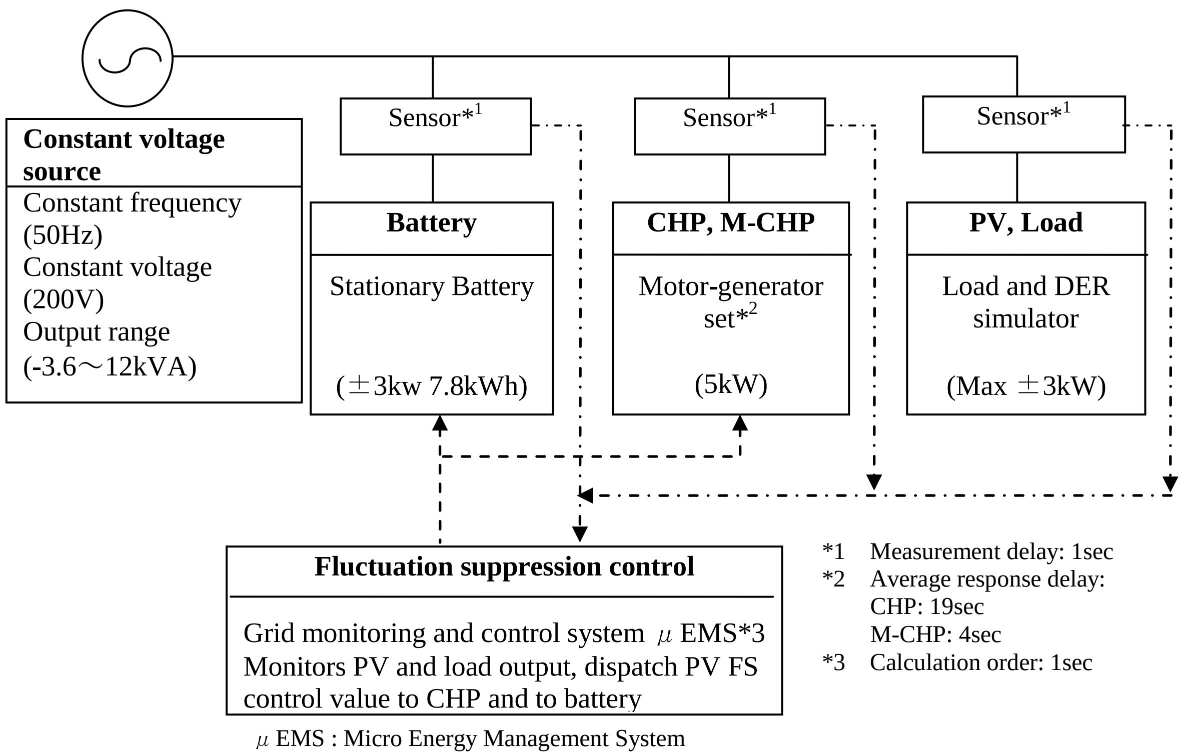


Fig. 2 Simulated grid composed on SGS

2.2 PV model

For verification tests, the authors used data obtained from 14:00 to 15:00 on a cloudy day. This data contains target fluctuation components more than other time range, according to the frequency range analysis. The total output of PV is shown in Fig. 3.

The ratio of fluctuation components are less compared to the individual PV output, due to smoothing effect of the by summation of outputs. Verification test results further on refers to data shown in Fig.3.

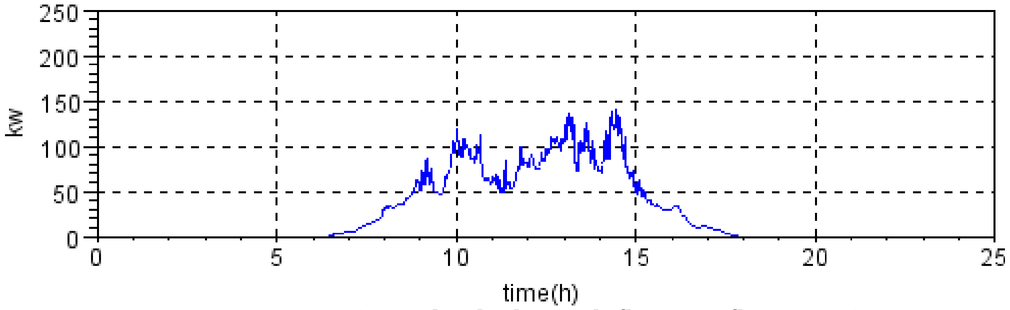


Fig. 3 PV output (on a cloudy day with fluctuant fluctuation)

2.3 CHP model

815kW CHP and 31kW CHP are used in the SEN demonstration. CHP response features are modelled on SGS according to dead time and lamp rate, based on step response simulation done on a real machine (includes control and transmission dead time). Fig. 4 and 5 describes result of step response simulation done on a real machine and a simulator. Different ramp rate is set for increasing and decreasing output order. Parameters used for simulation is described in Table 1.

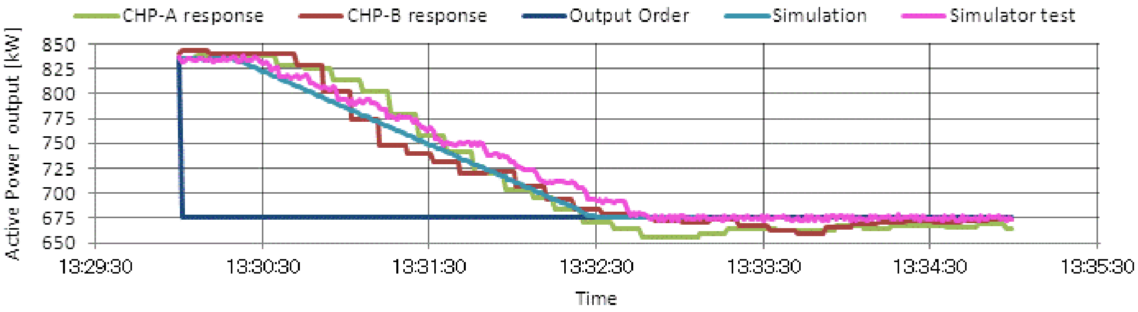


Fig. 4 Step response test result of CHP and simulator（Order decrease: -160kW）

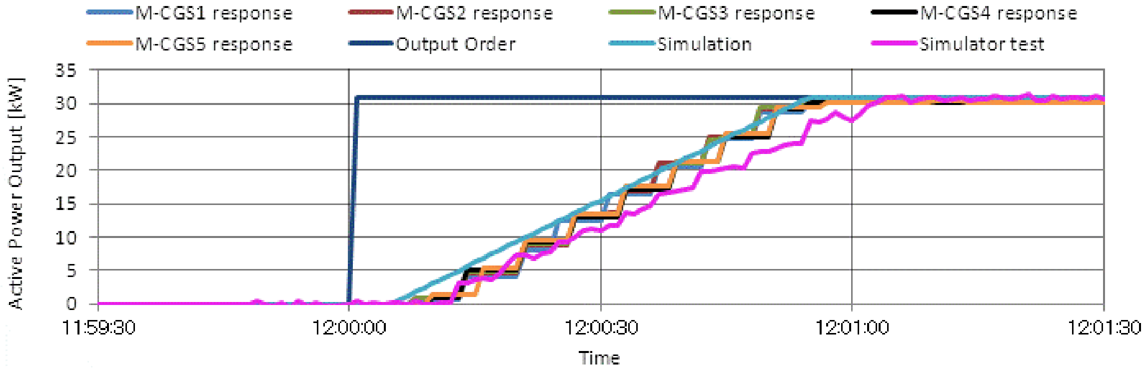


Fig. 5 Step response test result of M-CHPs and simulator (Order increase: 31kW)

Table 1 Parameter of Gas Engine Generator（each unit）

Type	Rated Capacity	Dead time	Ramp rate (increase)	Ramp rate (decrease)
CHP	815kW	19s	1.00kW/s	1.23kW/s
M-CHP	31kW	4s	0.62kW/s	3.44kW/s

2.4 Features of Fluctuation Suppression control block

FS control block is implemented in μEMS of SGS. It obtains PV output, and from that extracts fluctuation element, which then dispatches CV to CHP and BES to smooth the fluctuation element (Fig. 6). Moving average duration necessary to extract fluctuation was set for 20minutes, considering the time range of control target domain. This in this case is the Load Frequency Control (LFC) domain. When using both CHP and BES for FS, the authors applied two control methods as below.

Control method A: Dispatch CV based on capacity ratio of controlling equipment.
Control method B: Within fluctuation component, dispatch CV to regulate low frequency component to CHP, and CV to regulate high frequency component to BES.

Fig. 7 and 8 below describes the control method A and B. In both methods, 20% of CHP rated capacity was set as an adjustment range limit ±160kW.

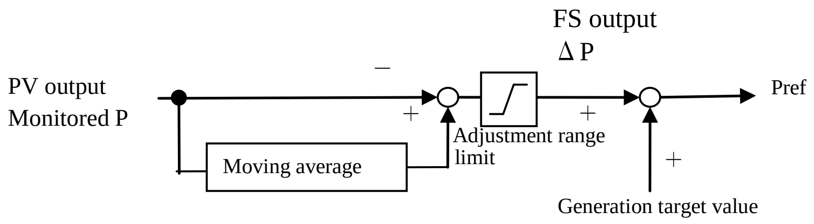


Fig. 6 Basic control block of FS

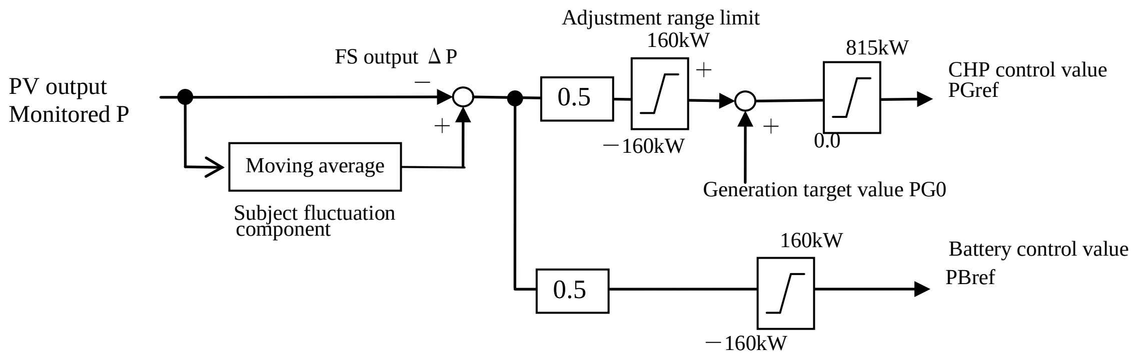


Fig. 7 Control method A control block

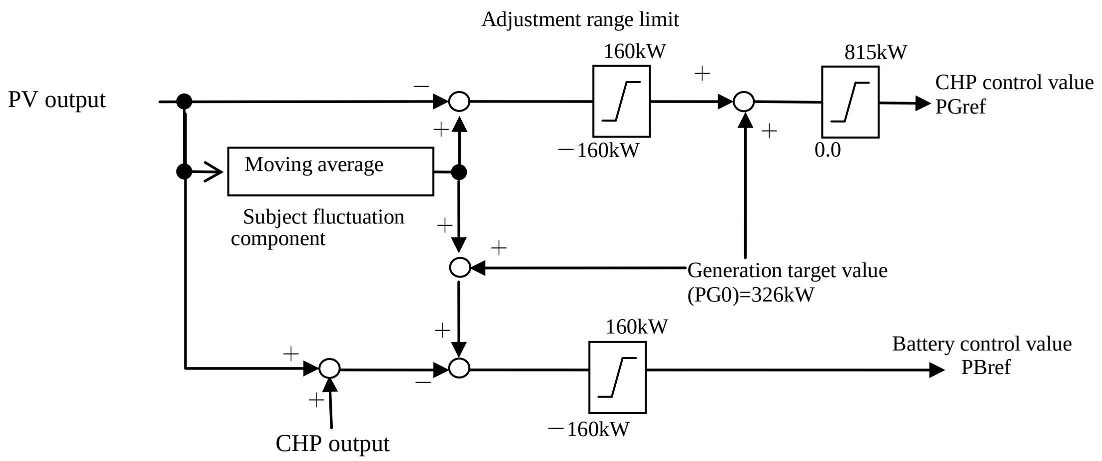


Fig. 8 Control method B control block

3. Result Evaluation

3.1 Result of typical examination case

The result of FS by CHP and BES is described in Fig. 9 and 10. The ratio of PV capacity and adjustment capacity of CHP is set to 2:1 and the ratio of PV capacity and adjustment capacity of BES for FS is set to 6.7:1. By applying control method B, where dispatches CV depending on their frequency domain, medium and low frequency component are reduced by CHP generation (Fig. 9). High frequency component are also being absorbed by BES (Fig. 10).

The authors applied Fluctuation Reduction Rate (FRR) as the evaluation criteria. That is, converting fluctuation component from time domain to frequency domain using Fourier transformation; then extracting the sum of LFC component; and finally quantitatively evaluating the validity of FS. FRR calculation equation is as follows.

$$FRR = (S_{PV} - S_O)/S_{PV}, \quad S_{PV} = \sum_{i=i1}^{i2} C_i^{PV}, \quad S_O = \sum_{i=i1}^{i2} C_i^{O}$$

S_{PV} and S_O each represent the sum of frequency spectrum range before and after FS.

C_i^{PV} and C_i^{O} each represents the frequency component i when converting output signal by using Fourier transformation.

$i1$, $i2$ represents the maximum and the minimum limit of frequency component included in the assessment subject domain (for LFC domain, 1200second and 180second.).

As a result, FS by BES was calculated to be 88% effective, and by CHP, 53% effective (Fig. 11).

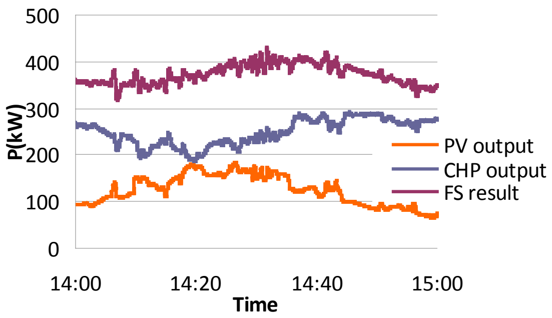


Fig. 9 Result of FS examinations by CHP

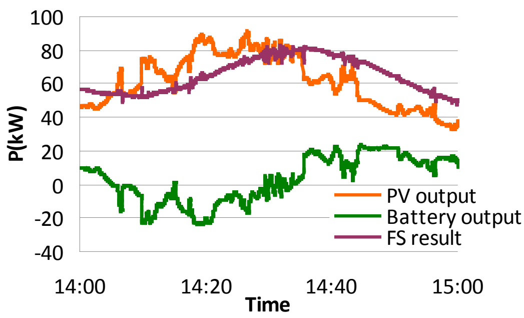


Fig. 10 Result of FS examination by BES

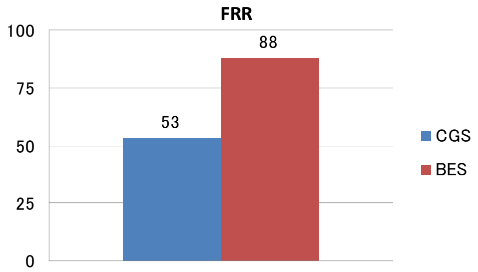


Fig. 11 Evaluation of FRR effect

3.2 Evaluation of FS effect regarding the ratio of PV and control equipment

Fig. 12 shows FRR result of LFC domain, with different capacity of PV and BES, CHP, and M-CHP. In all cases, at certain point the FRR shows a tendency to decrease as the ratio of PV increases. The authors defined this point as saturation point. For FS by CHP, the saturation point was 2, for M-CHP was 3, and for BES was 6.7. In addition, the maximum FRR was below 60% for CHP, greater than 80% for M-CHP and BES.

Possible reason of this tendency of saturation point is as below. The more PV located dispersedly, the more their output will be smoothed when being summed, resulting in the having lesser fluctuation component compared to individual PV output. Therefore capacity ratio of saturation point becomes larger. In terms of CHP, M-CHP with faster response had a higher saturation point.

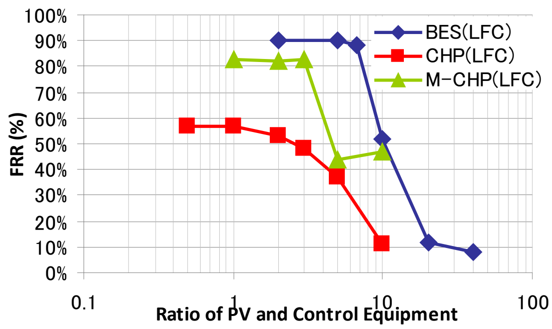
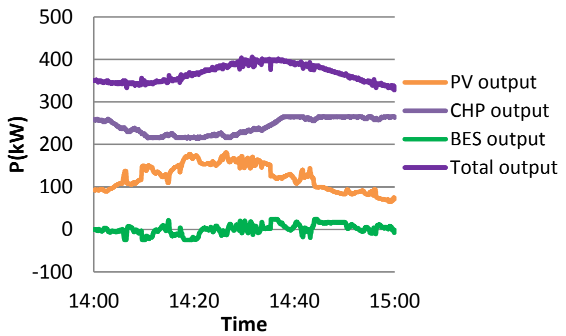


Fig. 12 Capacity ratio of PV and control equipment

3.3 FS evaluation based on BES ratio

The authors derived that 6.7:1 is the saturation point of FS by BES. Considering this result, the authors conducted verification tests by using CHP and M-CHP combination with BES. Fig. 13 describes the verification test results when setting adjustment capacity rate of CHP and BES to 50%. Fig. 14 describes the FRR result calculated when using the ratio used in Fig. 13 as parameter.

When controlling more than one controlling equipments with different features to operate FR, control method B proved to be more effective compared to control method A, due to dispatching adequate control value to all equipment, hence optimizing the performance. In method B, no significant effect to FRR can be seen until CHP ratio increases to 50%, and M-CHP ratio increases up to 75%. Thus it could be concluded that sufficient FS are possible to be carried by the combination of BES and CHP.



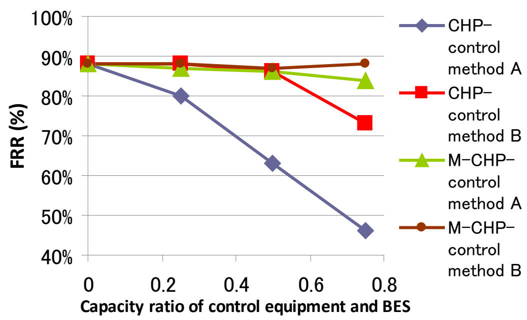


Fig. 13 Result of FS examination by CHP and BES

Fig. 14 Ratio of control equipment and BES

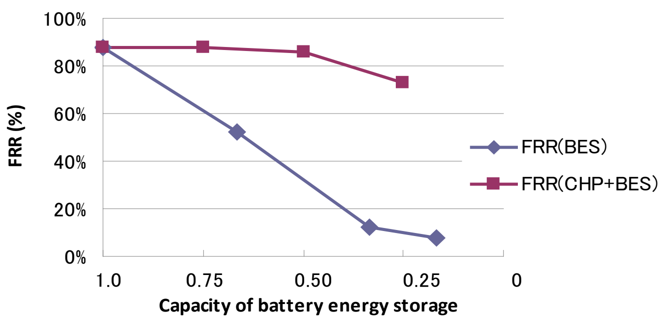


Fig. 15 Relation of FS result and BES implementation

4. Conclusion

This paper discussed quantitatively evaluated result regarding least BES capacity necessary to maintain the fluctuation suppression effect, derived from 100 case simulator verification tests done on Smart Grid Simulator. The authors also discussed details of simulator model and fluctuation suppression algorithms. Through the verification test, the authors have recognized the feasibility of PV fluctuation suppression by remotely controlled and distributed CHP. The authors conclude that it is possible to regulate 6.7times the adjustment capacity of PV by combination of CHP and BES, or by BES alone. In addition, combination of CHP and BES will reduce the BES capacity necessary to

realize fluctuation suppression, yet realizing same quality of FS done only by BES. This is done by dispatching low frequency component CV to CHP, and high frequency component CV to BES. Hence, allowing fluctuation suppression of various frequency domains (such as LFC and EDC) done by CHP and minimum capacity of BES.
The outcome of the verification tests will contribute to mass implementation of PV as well as smoothing their fluctuant output which may impact future power grid quality.

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