H^∞ Control of Microgrids Involving Gas Turbine Engines and Batteries

Masaaki Nagahara, Yutaka Yamamoto, Seiya Miyazaki, Takahiro Kudoh, and Naoki Hayashi

***Abstract*— This paper proposes a new power management control method for microgrids based on H^∞ control theory. Microgrid systems consist of distributed power sources such as cogeneration systems and photovoltaic systems with batteries. In general, power generation by photovoltaic systems and power consumption of various loads cause large fluctuations depending on weather conditions and varied lifestyles. Moreover, efficient management of battery capacity is a critical issue to prolong the battery life. Therefore, in power management control of microgrids, it is necessary to take account of a number of aspects such as power balancing performance, maintaining battery capacity, and robustness against power fluctuations. For such multiobjective control problems, we apply H^∞ control theory which offers a unified robust control method with desirable power balancing performance and efficient battery management. The experimental results illustrate the effectiveness of the proposed control method.**

I. Introduction

Tackling global warming is the most urgent issue on all levels of scientific and engineering fields. The IEA (International Energy Agency) reported that about 41[%] of current energy-related CO_2 emissions comes from the power sector [1]. With the growing attention for the realization of sustainable development, smart grids are expected to play a central role to decarbonize the power sector while improving network efficiency and reliability [2], [3]. Microgrids are small-scale smart grids that can operate independently from commercial utility grids as electrically isolated power networks [4], [5]. In the most common configuration, a microgrid is connected to a utility grid at a single point. The point that connects a microgrid and a utility grid is called a point of common coupling (PCC). The power consumed in a microgrid is mainly supplied by distributed power sources such as photovoltaic systems, storage batteries, and cogeneration systems. In addition, a microgrid can also be supplied power from a utility grid through a PCC when needed. The supplied power from a utility grid at a PCC is predetermined according to a demand prediction. If there is a considerable difference between the predetermined power and the actually supplied power from a utility grid, power flow in the entire network including the microgrid and the utility grid can become unstable. Therefore, power balancing control that adjusts power flow at a PCC to a predetermined set point as close as possible is essential to stabilize the entire network.

The main problem encountered in power balancing control is that power generation by distributed power sources and power consumption of various loads are difficult to control and cause large fluctuations of power flow in microgrids. Moreover, such fluctuations are unpredictable because of sudden changes of weather conditions and varied lifestyles. Therefore, in power control of microgrids, it is important to reduce power fluctuations and achieve power balancing by appropriately controlling batteries and cogeneration systems. In this paper, we propose power balancing control based on H^∞ control theory by regarding power fluctuations as disturbances added to microgrids. H^∞ control theory has been developed to provide a quantitative way of simultaneously mitigating the effect by uncertainty of parameters and stabilizing control systems [6]. The objective of the proposed H^∞ control method is to achieve robust power balancing even under unpredictable power fluctuations.

Another problem of power balancing control is how to assign power generation among distributed power sources. For example, storage batteries can track relatively high frequency fluctuations but they cannot provide enough power used in the entire microgrid because of their limited capacities. On the other hand, gas turbine engines can supply more power than batteries but they generally have a slow response. In this paper, we take account of these operational characteristics of batteries and gas turbine engines. More precisely, we separate power fluctuations in a microgrid into two subsignals so that gas turbine engines can control lower frequency fluctuations and batteries can control higher frequency fluctuations. However, tracking for high-frequency fluctuations causes large variation of state-of-charge (SOC) of batteries and this results in shorter battery lifetime. In this paper, we take battery capacity into account when designing controllers for batteries to reduce such variation of SOC.

There have been proposed a number of power balancing control methods [7]. Yoshimoto and co-workers proposed the SOC feedback control to regulate power flow in microgrids and keep a battery capacity within a certain range [8]. Bolognani and Zampieri considered distributed control of reactive power in microgrids [9]. They proposed a randomized gossip-like algorithm to solve a convex optimization problem of reactive power compensation. Kim and co-workers proposed PI (Proportional-Integral) control strategy with two layered control architecture for power balancing

M. Nagahara is with Department of Applied Analysis and Complex Dynamical Systems, Graduate School of Informatics, Kyoto University, Japan. nagahara@i.kyoto-u.ac.jp

Y. Yamamoto is with Department of Applied Analysis and Complex Dynamical Systems, Graduate School of Informatics, Kyoto University, Japan. yy@i.kyoto-u.ac.jp

S. Miyazaki is with Energy Solutions Development Center, Panasonic Corporation, Japan. miyazaki.seiya@jp.panasonic.com

T. Kudoh is with Energy Solutions Development Center, Panasonic Corporation, Japan. kudoh.takahiro@jp.panasonic.com

N. Hayashi is with Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka University, Japan. n.hayashi@eei.eng.osaka-u.ac.jp

[10]. Guo and Lee proposed PI-based control of regulating power flow in micrograms with fuel-cell and micro-turbine engines [11]. Although the PI-based control approach is demonstrated to achieve desirable power control, it requires repetitive parameter tuning and it is difficult to evaluate the effect of parameter variation in a systematic way. To remedy such a drawback, H^∞ control approach has been considered in a control problem of regulating inverters in microgrids. Yang and co-workers considered H^∞ control scheme that achieves desirable tracking performance on an output voltage of threephase inverters under parameter variation [12]. However, the objective considered in [12] is different from ours in that we consider power balancing control of the entire microgrid system instead of just voltage control of specific inverters.

The paper is organized as follows: Section II presents a model of a microgrid that consists of photovoltaic panels, batteries, and gas turbine engines as distributed power sources. In Section III, we formulate a power balancing problem. Then we propose power balancing control based on H^∞ control theory in Section IV. Section V shows numerical examples for the proposed power balancing control. In Section VI, we present some experimental results on a microgrid testbed. Finally, we give a conclusion in Section VII.

II. Model of Microgrids

In this paper, we consider a microgrid that consists of photovoltaic panels, batteries, and gas turbine engines as distributed power sources. The microgrid is connected to a utility grid at a PCC as shown in Fig. 1. A difficulty in power balancing control of microgrids is to smooth out fluctuations caused by photovoltaic systems and various loads. Figs. 2 and 3 show typical examples of the photovoltaic power generation $P_{\rm pv}$ and the load power consumption $P_{\rm ld}$ over 24 hours, respectively. As observed in these figures, power generation by photovoltaic systems and power consumption of loads cause large fluctuations in power flow of microgrids. To overcome such power fluctuations, we propose power balancing control based on H^∞ control theory by regarding the power fluctuations as disturbances added to the microgrid.

In this paper, we assume that the battery $G_{\rm bt}$ and the gas turbine engine $G_{\rm ge}$ of the microgrid can be modeled as first-order systems (see e.g., [13]):

$$G_{\rm bt}(s) = \frac{1}{T_{\rm bt}s+1}, \quad T_{\rm bt} = \frac{0.1}{2\pi}, \tag{1}$$

$$G_{\rm ge}(s) = \frac{1}{T_{\rm ge}s+1}, \quad T_{\rm ge} = \frac{10}{2\pi}. \tag{2}$$

Note that the time constant of the battery is 100 times faster than that of the gas turbine engine. This reflects the fact that batteries can track higher frequency fluctuations but gas turbine engines can only track lower frequency fluctuations because of their slow responses. In this paper, we take account of these operational characteristics of batteries and gas turbine engines when designing controllers in Section IV.

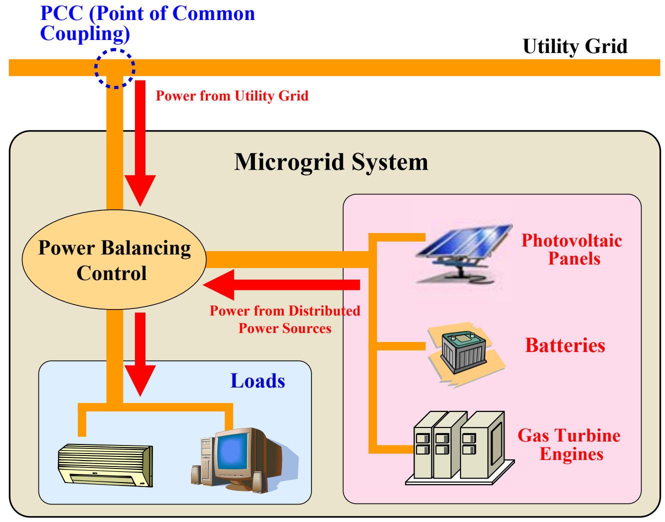

Fig. 1. Configuration of a microgrid system.

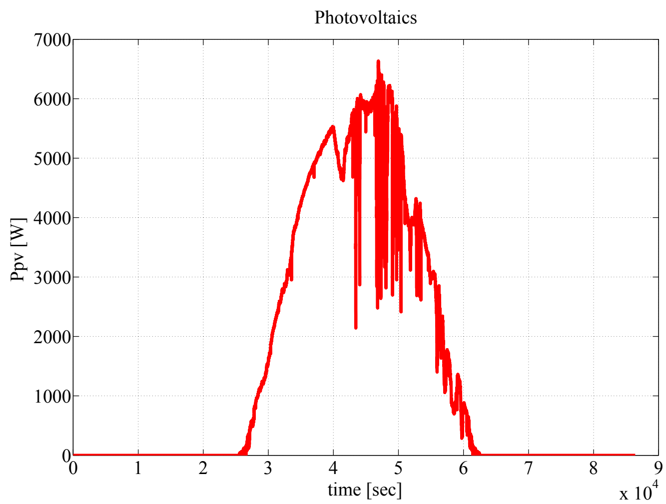

Fig. 2. Photovoltaic power generation $P_{\rm pv}$.

III. Problem Settings

In this section, we formulate a power balancing problem of the microgrid modeled in the previous section. The power supplied to the microgrid from a utility grid at a PCC is predetermined according to a demand prediction. In this paper, we refer to the predetermined power supplied from a utility grid as the reference power. The goal of the power balancing problem is to appropriately regulate distributed power sources in order to track the reference power even under large power fluctuations.

Let $P_{\rm pv}(t)$, $P_{\rm bt}(t)$, and $P_{\rm ge}(t)$ be the power generation of the photovoltaic system, the battery, and the gas turbine engine at time t (≥ 0). Note that $P_{\rm pv}(t)$ and $P_{\rm ge}(t)$ have always nonnegative real values for all $t \geq 0$, and

$$\begin{cases} P_{\rm bt}(t) \geq 0 & \text{if batteries are discharging,} \\ P_{\rm bt}(t) < 0 & \text{if batteries are charging.} \end{cases}$$

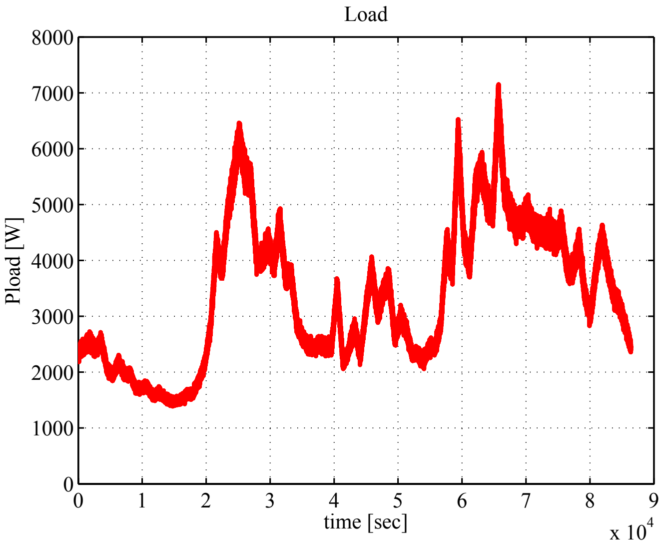

Fig. 3. Load power consumption $P_{\rm ld}$.

Then the supplied power from a utility grid $P_{\rm net}(t)$ is equal to the difference between the power consumption of loads $P_{\rm ld}(t)$ and the total power generation of the distributed power sources; that is,

$$P_{\rm net}(t) = P_{\rm ld}(t) - P_{\rm bt}(t) - P_{\rm ge}(t) - P_{\rm pv}(t), \quad t \geq 0.$$

If $P_{\rm net}(t) > 0$, distributed power sources cannot supply enough power to loads and the necessary power $P_{\rm net}(t)$ is supplied from a utility grid. On the other hand, $P_{\rm net}(t) < 0$ means that the power demand of loads is less than the total power generation of distributed power sources and the redundant power is sold to a utility grid. Then the power balancing problem can be summarized as follows:

Problem 1 (Power Balancing Problem): Given the reference power $P_{\rm ref}$, find the power generation of the battery $P_{\rm bt}$ and the gas turbine engine $P_{\rm ge}$ to minimize the tracking error (3) at each time t (≥ 0):

$$e(t) = |P_{\rm ref}(t) - P_{\rm net}(t)|, \quad t \geq 0. \tag{3}$$

IV. H^∞ Control of Batteries and Gas Turbine Engines

In this section, we design controllers that stabilize and balance power flow in the microgrid. Fig. 4 shows the block diagram of the proposed microgrid system, where

$$r(t) := P_{\rm ld}(t) - P_{\rm pv}(t) - P_{\rm ref}(t),$$
$$y(t) := P_{\rm bt}(t) + P_{\rm ge}(t), \quad t \geq 0.$$

In Fig. 4, $K_{\rm bt}$ and $K_{\rm ge}$ are controllers for the battery and the gas turbine engine, and $G_{\rm bt}$ and $G_{\rm ge}$ represent plant models for the battery (1) and the gas turbine engine (2).

Then the power balancing problem can be restated as follows:

Problem 2: Given the input signal r, find the controllers $K_{\rm bt}$ and $K_{\rm ge}$ in order to minimize the tracking error (4) at

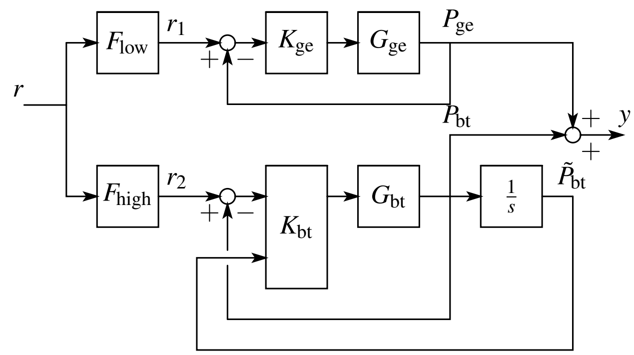

Fig. 4. Block diagram of the proposed microgrid system.

each time t (≥ 0):

$$e(t) = |r(t) - y(t)|, \quad t \geq 0. \tag{4}$$

As shown in Figs. 2 and 3, the input signal r contains various frequency components. In general, batteries can track high-frequency fluctuations but their storage capacity is limited. On the other hand, gas turbine engines can supply more power than batteries but they can track only relatively lower frequency fluctuations. Considering such operational characteristics of batteries and gas turbine engines, we separate the signal r into two subsignals using the low-pass filter $F_{\rm low}$ and the high-pass filter $F_{\rm high}$. Let

$$T_{\rm c} := \frac{T_{\rm ge} + T_{\rm bt}}{2}$$

be the common time constant for the filters. In this paper, we give $F_{\rm low}$ and $F_{\rm high}$ as

$$F_{\rm low}(s) = \frac{1}{T_{\rm c}s + 1}, \quad F_{\rm high}(s) = \frac{T_{\rm c}s}{T_{\rm c}s + 1}.$$

Fig. 5 shows the Bode gain plots of the low-pass filter $F_{\rm low}$ and the high-pass filter $F_{\rm high}$. Then r_1 contains lower frequency fluctuations that are regulated by the gas turbine engine and r_2 contains higher frequency fluctuations that are regulated by the battery.

In addition to power fluctuations, battery life is of great concern in microgrids because of the high costs of battery replacement. In this paper, we consider a battery capacity to reduce variation of SOC. The battery capacity $\tilde{P}_{\rm bt}$ is computed by the integral of the charged/discharged power $P_{\rm bt}$. In the proposed microgrid system, $\tilde{P}_{\rm bt}$ is modeled by using an integrator $1/s$ as shown in Fig. 4.

The controllers $K_{\rm bt}$ and $K_{\rm ge}$ are designed as H^∞ controllers. Fig. 6 shows the block diagram for designing the controller $K_{\rm ge}$. The weights $W_{\rm ge1}$, $W_{\rm ge2}$, and $W_{\rm ge3}$ are the weighting functions for tracking performance, gain margin of the microgrid system, and robustness for power fluctuations. For example, we need to choose $W_{\rm ge1}$ to have a higher gain in an appropriate bandwidth to achieve better tracking performance. In this paper, we set these weights as

$$W_{\rm ge1}(s) = \frac{1}{s} \cdot \frac{1}{\frac{10}{2\pi}s + 1}, \quad W_{\rm ge2}(s) = \frac{0.005s}{0.1s + 1},$$
$$W_{\rm ge3}(s) = 0.01\frac{\frac{5}{2\pi}s}{\frac{5}{2\pi}s + 1}.$$

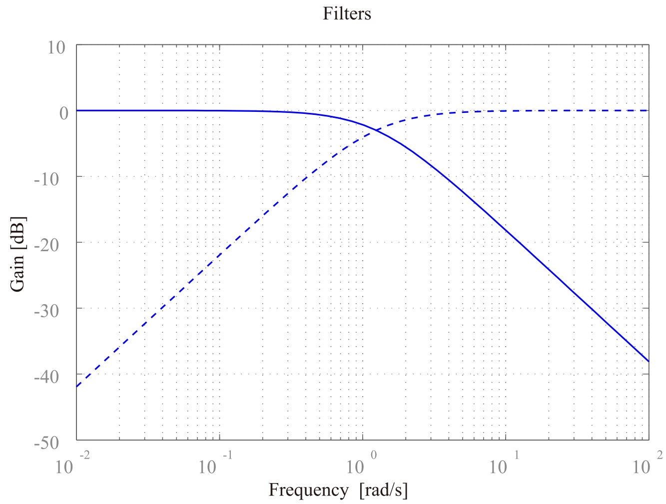

Fig. 5. Bode gain plots of the low-pass filter F_{low} (solid line) and the high-pass filter F_{high} (dashed line).

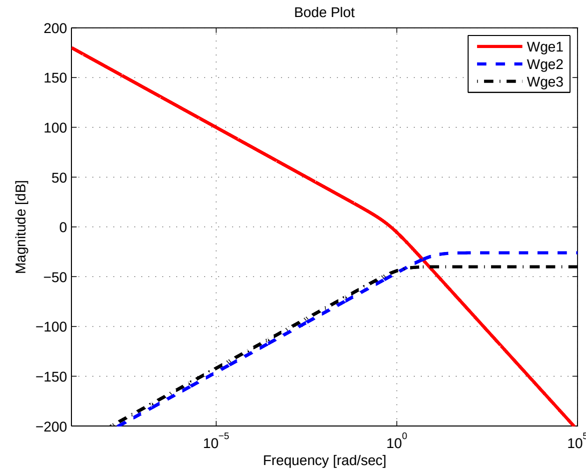

Fig. 7. Bode gain plots of the weights W_{ge1} (solid line), W_{ge2} (dashed line), and W_{ge3} (dashed-dotted line).

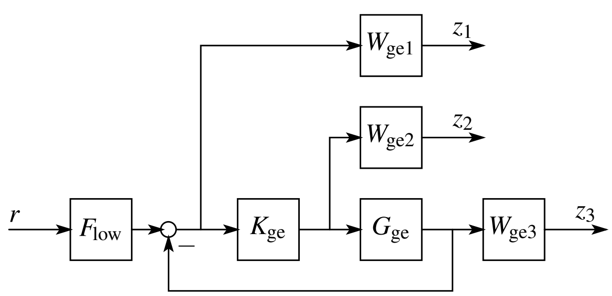

Fig. 6. Block diagram for the controller K_{ge}.

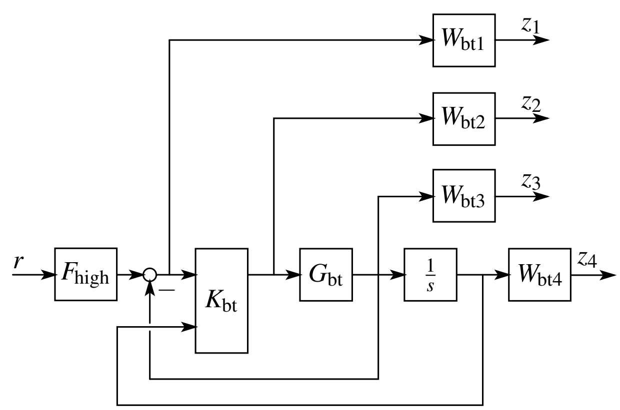

Fig. 8. Block diagram for the controller K_{bt}.

The Bode gain plots of the weights are shown in Fig. 7. Then the controller K_{ge} can be obtained by solving the following H^∞ problem.

Problem 3 (H^∞ Problem for Controller K_{ge}): Find the controller K_{ge} that minimizes the H^∞ norm of the system from r to $z = [z_1\ z_2\ z_3]^\top$.

Note that Problem 3 is a standard H^∞ problem and we can find the controller K_{ge} using Robust Control Toolbox of MATLAB.

The block diagram for designing the controller K_{bt} is shown in Fig. 8. We set the weights of the block diagram as

$$W_{\mathrm{bt1}}(s) = \frac{1}{\frac{0.5}{2\pi}s+1}, \quad W_{\mathrm{bt2}}(s) = 0.001,$$
$$W_{\mathrm{bt3}}(s) = 0.01\frac{\frac{0.5}{2\pi}s}{\frac{0.5}{2\pi}s+1}, \quad W_{\mathrm{bt4}}(s) = 1.$$

The purposes of the weights W_{bt1}, W_{bt2}, and W_{bt3} are the same as those of the weights W_{ge1}, W_{ge2}, and W_{ge3}, respectively. The weight W_{bt4} is for the battery capacity. The higher the gain of the weight W_{bt4} is, the more likely we must consider variation of the battery capacity. Fig. 9 shows the Bode gain plots of these weights. The controller K_{bt} can be obtained by solving the following H^∞ problem:

Problem 4 (H^∞ Problem for Controller K_{bt}): Find the controller K_{bt} that minimizes the H^∞ norm of the system from r to $z = [z_1\ z_2\ z_3\ z_4]^\top$.

Problem 4 is also a standard H^∞ problem and solved by Robust Control Toolbox of MATLAB.

V. Simulation

In this section, we show some numerical examples of the proposed power balancing control.

Fig. 10 shows the Bode plots of the H^∞-optimal controllers K_{ge} and K_{bt} obtained by solving Problems 3 and 4 with MATLAB. Note that the controller K_{ge} has a pole at $s = 0$ since the weight $W_{\mathrm{ge1}}(s)$ has a pole there. On the other hand, the controller K_{bt} has a higher gain in a high frequency domain. This shows that low-frequency fluctuations are mainly controlled by the gas turbine engine while high-frequency fluctuations are controlled by the battery.

To show the effectiveness of the proposed method to the battery life, we also design a controller by solving the H^∞ control problem of the system from r to $z = [z_1\ z_2\ z_3]^\top$. This controller does not take account of the state of capacity

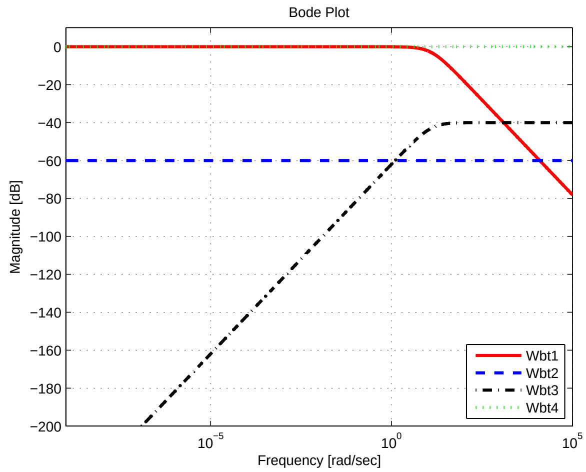

Fig. 9. Bode gain plots of the weights W_{bt1} (solid line), W_{bt2} (dashed line), W_{bt3} (dashed-dotted line), and W_{bt4} (dotted line).

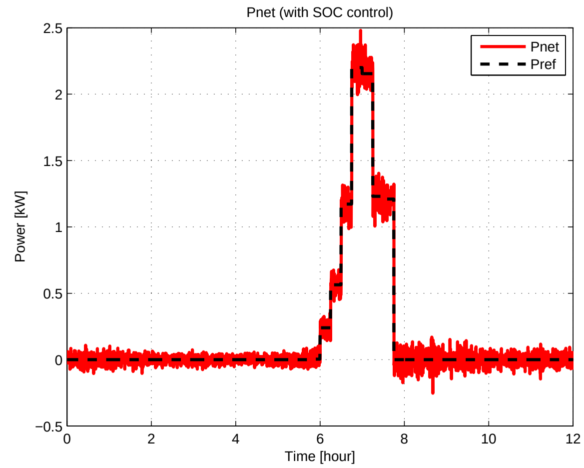

Fig. 11. P_{net} for 12 hours with SOC control

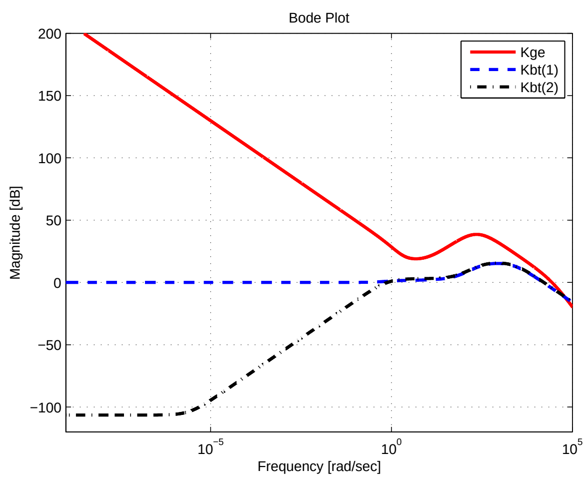

Fig. 10. Bode gain plots of the controllers K_{ge} (solid line) and K_{bt} (dashed line and dashed-dotted line).

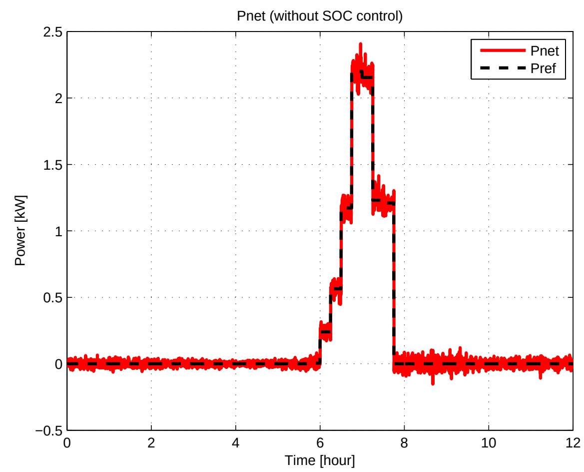

Fig. 12. P_{net} for 12 hours without SOC control

(SCO) of the battery. Fig. 11 shows the reference power P_{ref} and the net power P_{net} with SOC control, while Fig. 12 shows that without SOC control. The RMS (root mean square) value of the error is 0.086 [kW] with SOC control and 0.077 [kW] without SOC control. The difference is just 0.09 [kW].

Fig. 13 shows the SOC [%] of the battery. The initial SOC is 50 %. From Fig. 13, we can see that the SOC is maintained closer to the initial SOC with SOC control than that without SOC control.

VI. Experimental Results

We developed a microgrid testbed that consists of a gas turbine engine, a lead battery, and 3 units of photovoltaic inverters. The maximum power of the gas turbine engine is 5 [kW]. The H^∞ controller of the gas turbine engine K_{ge} is implemented in the testbed. The total capacity of the lead battery that is regulated by a PI controller is 10 [kWh]. In the microgrid testbed, we used a photovoltaic simulator that emulates the behavior of real photovoltaic inverters. We assume that the maximum powers of the photovoltaic inverters are 15 [kW], 10 [kW], and 4 [kW]. The power consumption of 2 loads are also generated by a simulator. The peak power consumption of these loads are assumed to be 10 [kW] and 8 [kW].

Figs. 14 and 15 show the results of the experiment on the testbed with a conventional PID controller and with the H^∞ controller K_{ge} for the gas turbine engine. We can see that the tracking performance for the reference signal is significantly improved by using the H^∞ controller K_{ge}.

VII. Conclusion

In this paper, we proposed power balancing control for microgrids based on H^∞ control theory. We designed H^∞ controller for gas turbine engines and batteries to smooth out power fluctuations caused by photovoltaic systems and loads.

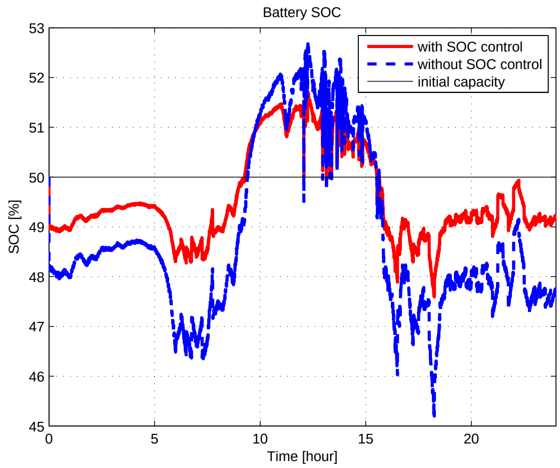

Fig. 13. SOC (state of capacity) of the battery with SOC control (solid line) and without SOC control (dashed line).

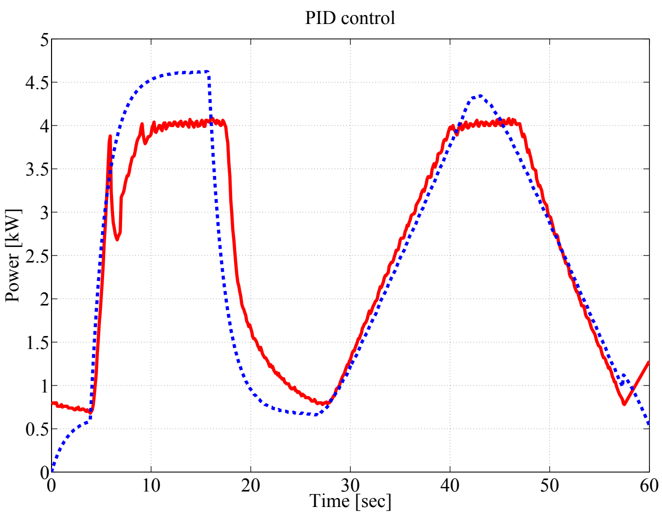

Fig. 14. PID control for the gas turbine engine: reference signal (dashed line), power generation (solid line).

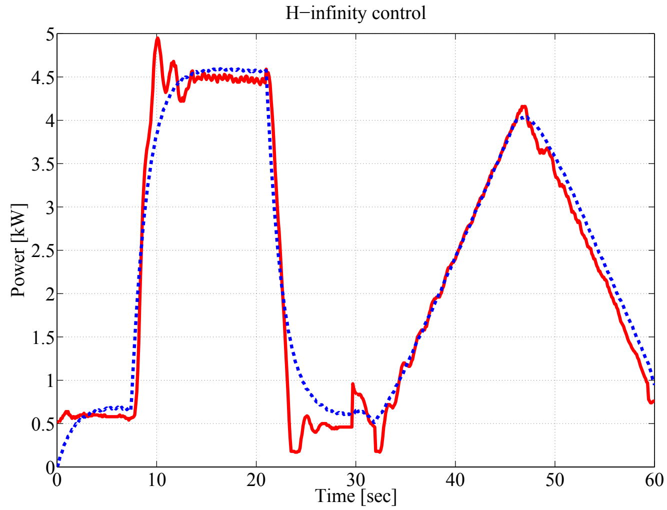

Fig. 15. H^∞ control for the gas turbine engine: reference signal (dashed line), power generation (solid line).

The obtained controllers can appropriately assign power generation based on operational characteristics of batteries and gas turbine engines. Numerical examples showed that the proposed method can achieve power balancing control considering SOC of the batteries. We also implemented the obtained H^∞ controller for a gas turbine engine on a microgrid testbed. The experimental results showed that the proposed H^∞ control method can achieve better tracking performance compared to a PID-based control.

In the experiment on the testbed, we only implemented a H^∞ controller for a gas turbine engine. The evaluation of a H^∞ controller for a battery on the testbed is a target of our subsequent work.

References

[1] OECD/IEA, *Energy Technology Perspectives 2010: Scenarios & Strategies to 2050*. OECD/IEA, 2010.

[2] S. M. Kaplan, *Smart Grid: Modernizing Electric Power Transmission and Distribution*. The Capitol.Net, 2009.

[3] X. Yu, C. Cecati, T. Dillon, and M. Simõs, "The New Frontier of Smart Grids," *IEEE Industrial Electronics Magazine*, vol. 5, no. 3, pp. 49–63, 2011.

[4] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids: An Overview of Ongoing Research, Development, and Demonstration Projects," *IEEE power & energy magazine*, vol. 5, no. 4, pp. 78–94, 2007.

[5] R. Zamora and A. K. Srivastava, "Controls for microgrids with storage: Review, challenges, and research needs," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 7, pp. 2009–2018, 2010.

[6] M. Green and D. J. Limebeer, *Linear Robust Control*. Prentice Hall, 1995.

[7] A. Llaria, O. Curea, J. Jiménez, and H. Camblong, "Survey on microgrids: Unplanned islanding and related inverter control techniques," *Renewable Energy*, vol. 36, no. 8, pp. 2052–2061, 2011.

[8] K. Yoshimoto, T. Nanahara, and G. Koshimizu, "New Control Method for Regulating State-of-Charge of a Battery in Hybrid Wind Power/Battery Energy Storage System," in *Proc. of IEEE PES Power Systems Conference & Exposition 2006*, pp. 1244–1251, 2006.

[9] S. Bolognani and S. Zampieri, "Distributed control for optimal reactive power compensation in smart microgrids," in *Proc. of the 50th IEEE CDC-ECC*, pp. 6630–6635, 2011.

[10] J.-Y. Kim, J.-H. Jeon, S.-K. Kim, C. Cho, J. H. Park, H.-M. Kim, and K.-Y. Nam, "Cooperative Control Strategy of Energy Storage System and Microsources for Stabilizing the Microgrid during Islanded Operation," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 3037–3048, 2010.

[11] Z. Guo and K. Y. Lee, "Modeling and Simulation of a Power Conditioning System for the Hybrid Fuel Cell/Turbine Power Plant," in *Proc. of the 50th IEEE CDC-ECC*, pp. 3658–3633, 2011.

[12] S. Yang, Q. Lei, F. Peng, and Z. Qian, "A Robust Control Scheme for Grid-Connected Voltage-Source Inverters," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 202–212, 2011.

[13] S. K. Yee, J. V. Milanovic, and F. M. Hughes, "Overview and comparative analysis of gas turbine models for system stability studies," *IEEE Trans. Power Systems*, vol. 23, no. 1, pp. 108–118, 2008.