Evaluation of Battery System for Frequency Control in Interconnected Power System with a Large Penetration of Wind Power Generation

Masashi Arita, Akihiko Yokoyama, *Member, IEEE*, and Yasuyuki Tada, *Member, IEEE*

***Abstract*--Recently, a lot of distributed generations such as wind power generation are going to be installed into power systems. However, the fluctuation of these generator outputs affects the system frequency. Therefore, introduction of battery system to the power system has been considered in order to suppress the fluctuation of the total power output of the distributed generation. For frequency analysis, we use the interconnected 2-area power system model. It is assumed that a small control area with a large penetration of wind power plants is interconnected into a large control area. In this system, the tie line power fluctuation is very large as well as the system frequency fluctuation. It is shown that the installed battery can suppress these fluctuations and that the effect of battery on suppression of fluctuations depends on the battery capacity. Then, the required battery capacity for suppressing the tie line power deviation within a given level is calculated.**

***Index Terms*—Battery, Distributed Generation, Frequency, Load Frequency Control (LFC), Power System, Tie Line Power, Wind Power Generation**

I. Introduction

RECENTRY, a strong interest in distributed generations using renewable energy such as wind and solar energy has been attracted because the fossil energy will be exhausted in the future and its use causes the environmental issue [1]. Among them, a wind farm type of power generation is more economic and has been developed at commercial level.

However, the wind power generation is not stable and cannot supply constant electrical output. Since the wind power output depends on wind, as a natural source, the electrical output always fluctuates due to the weather, site conditions and other possible factors.

Imbalance between supply and demand of power causes the fluctuation of the system frequency. In order to suppress the fluctuation within a certain range, outputs of thermal and hydro power plants are controlled automatically (LFC, load frequency control) [2]. However, if a large amount of wind power generation is installed, it is difficult to suppress the fluctuation of the system frequency because of the lack of total LFC capability of the system. On the other hand, installation of advanced electric energy storage system such as NAS battery and Redox flow battery has been proposed to solve this problem.

This research aims at suppressing the system frequency fluctuation due to the wind power generation within a certain range using battery in a power system with a large penetration of wind power generation. In this research, we assume that a small control area with a large penetration of wind power plants is interconnected into a large control area and fluctuations of the system frequency and the tie line power in these 2-area power systems are analyzed. Furthermore, we aim to propose a new method to calculate the optimal battery storage capacity (MWh) and the appropriate power converter capacity (MW) and an effective control method of the battery system for reducing the battery capacity and LFC capacity of the conventional power plants.

In this paper, we analyze the impact of installed wind power generation and battery on the system frequency and the tie line power in order to calculate the required battery capacity.

II. Wind Power Generation

Wind power generation depends largely on wind direction and wind velocity. The fluctuation of wind power output is very large since wind energy is proportional to wind velocity to the 3rd power. An example of fluctuation of wind power output in Japan is shown in Fig. 1.

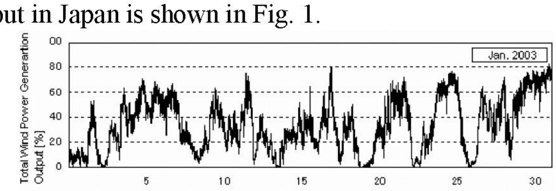


Fig. 1. Example of fluctuation of wind power output.

Wind power energy is exhaustless and clean. However, the energy which can actually be used is restricted due to low energy density in addition to the reason mentioned above. Therefore, it is important to make the most of electric energy obtained from wind power generation.

In Japan, about 900MW of wind power generation has already been in commercial use. As the governmental

---

M. Arita and A. Yokoyama are with the Department of Electrical Engineering, Graduate School of Engineering, University of Tokyo, Tokyo 113-8656, Japan (e-mail:arita@syl.t.u-tokyo.ac.jp; yokoyama@syl.t.u-tokyo.ac.jp).
Y. Tada is with the R&D Center, Tokyo Electric Power Company, Inc., Yokohama, 230-8510, Japan.

1-4244-0111-9/06/$20.00©2006 IEEE.

promoting scheme became available, a growing number of wind power plants will be constructed rapidly in recent years. The Japanese government plans to raise total capacity of wind power generation to 3000MW by the end of 2010 as shown in Fig. 2.

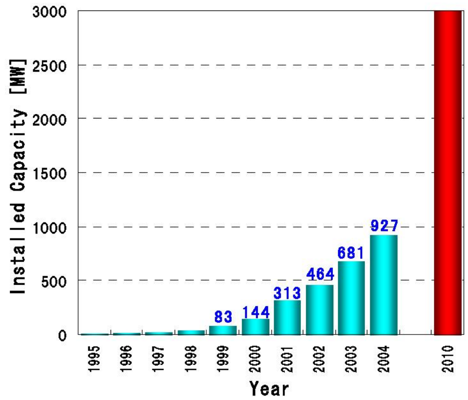


Fig. 2. Wind power generation in Japan.

The fluctuation of wind power generation includes various periodic components. In this research, we aim to suppress the frequency fluctuation caused by short period fluctuation (less than about twenty minutes) by cooperative control of LFC generators and batteries.

III. Analytical Model

A. 2-Area Power System Model

In order to analyze the system frequency, we use the interconnected 2-area power system model shown in Fig. 3. Two control areas (Area 1 and Area 2) are interconnected. We assume that wind power plants and batteries are installed into Area 2. This model is a transfer function model based on the deviation from a given operating point [3]. LFC signals are inputted to the governors of hydro and thermal units. Each turbine output deviation is inputted to the generator model. Wind power fluctuation and battery output are also inputted to the generator model and the system frequency deviation is outputted. It is noted that nuclear unit is operated with a constant output power in Japan. Therefore, output deviation of nuclear unit is constantly zero and not shown in Fig. 3.

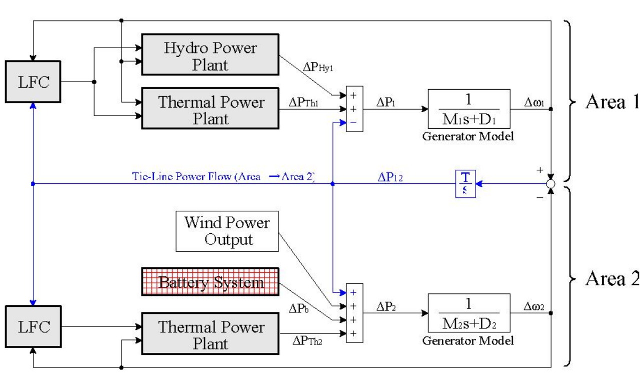


Fig. 3. 2-area power system model for frequency control.

The model shown in Fig. 3 is composed of the generator model, the governor control system model, the LFC model, the tie line model, the wind power plant model and the battery system model.

1) Generator Model

The relationship between supply and demand in power system, in other words, the relationship between the mechanical power ΔP_m and the electrical power ΔP_e is given by

$$M\frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e \tag{1}$$

where $\Delta\omega$ is rotor speed deviation and M is inertia constant.

In general, power system loads are a composite of a variety of electrical devices. For motor loads such as fans and pumps, the electrical power changes with the frequency due to changes in motor speed. The overall frequency-dependent characteristic of a composite load may be expressed as

$$\Delta P_e = \Delta P_L + D\Delta\omega \tag{2}$$

where ΔP_L is non-frequency-sensitive load change and D is load-damping constant.

The block diagram form representation of (1) and (2) is shown in Fig. 4.

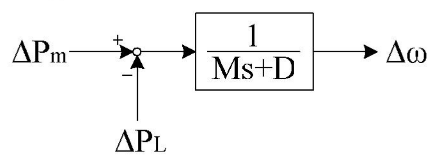


Fig. 4. Relationship between speed and power.

If all generators are assumed to rotate synchronously, the generator model is represented as an equivalent one-machine model shown in Fig. 5 [4], [5].

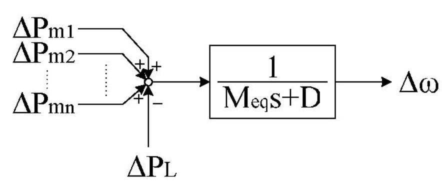


Fig. 5. Equivalent generator model of multi-generator system.

The equivalent generator has an inertia constant M_{eq} equal to the sum of the inertia constants of all generators and is driven by the combined mechanical outputs.

2) Governor Control System Model

Each generator with governor adjusts the turbine valve/gate to bring the frequency back to the nominal value (GF, governor free). The schematics of such governor control system that we use are shown in Fig. 6 (for thermal units) and Fig. 7 (for hydro unit).

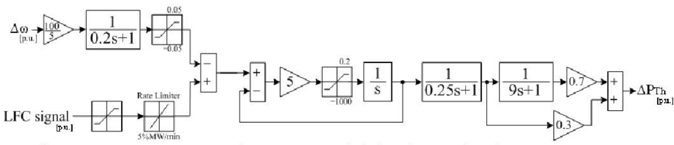


Fig. 6. Governor control system model for thermal unit.

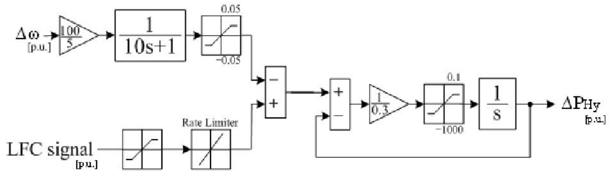


Fig. 7. Governor control system model for hydro unit.

The output change controlled by GF and LFC are limited in order to prevent excessive change.

3) LFC Model

LFC is performed by adjusting load reference points of governors of selected units in the control area and then adjusting their outputs. The central load dispatching center measures the actual frequency of the control area and the actual net interchange power flow between the connected control areas. These measurements are used to evaluate the area requirement (AR); it is the basis for the control signals sent to the generators participating in LFC. LFC model shown in Fig. 8 is used in this research.

The reference output signal of each generator is generated by PI controller based on AR. As LFC control method, FFC (Flat Frequency Control) and TBC (Tie-line Bias Control) are applied.

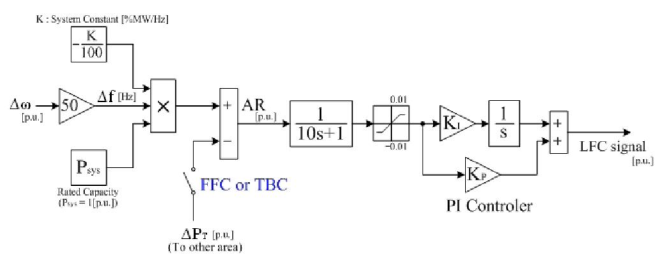


Fig. 8. LFC model.

4) Tie Line Model

The power flow across the interconnecting line can be modeled using DC flow method [5]. Using this method, the tie line power flow P_{12} is given by

$$P_{12} = \frac{1}{X_T}(\delta_1 - \delta_2) \tag{3}$$

where X_T is reactance of a tie line, δ_1 and δ_2 are phase angles of the both terminal of the tie line.

Note that the tie line power flow is defined as going from area 1 to area 2. Then the deviation ΔP_{12} from the nominal flow is given by

$$\begin{aligned}\Delta P_{12} &= \frac{1}{X_T}(\Delta\delta_1 - \Delta\delta_2) \\ &= \frac{T}{s}(\Delta\omega_1 - \Delta\omega_2)\end{aligned} \tag{4}$$

where $T = 100\,\pi / X_T$ (for a 50-Hz system).

This tie line model is shown in Fig. 3.

5) Wind Power Plant Model

The fluctuation data of wind power generation is generated by a block diagram shown in Fig. 9 [6]. The base components multiplied by band-limited white noise are summed up. Since the component with period of shorter than five minutes or longer than thirty minutes is out of LFC control, the component is eliminated by applying filters (HPF and LPF).

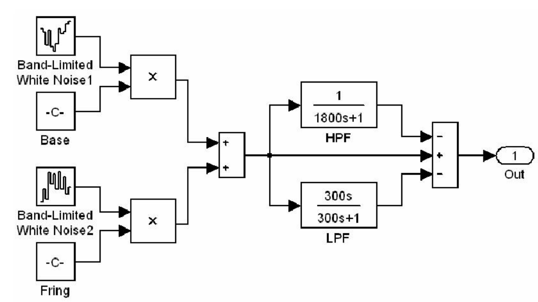


Fig. 9. Wind power plant model.

6) Battery System Model

The battery system model is shown in Fig. 10. Both power converter capacity (MW) and storage capacity (MWh) of the installed battery are limited by the lower and the upper values. Here, we assume that the battery works ideally within the limit.

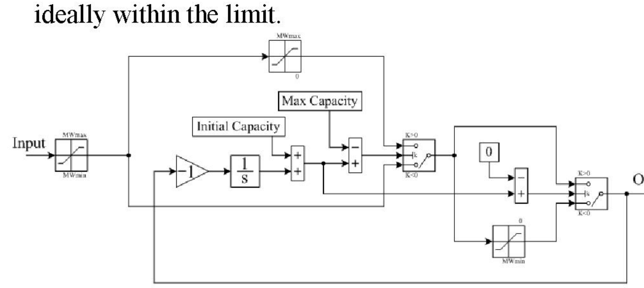


Fig. 10. Battery system model.

B. Application System

In the study, IEEJ East 30-machine model system [7] shown in Fig. 11 is used and this system is divided into two control areas; a large control area (Area 1) and a small control area (Area 2).

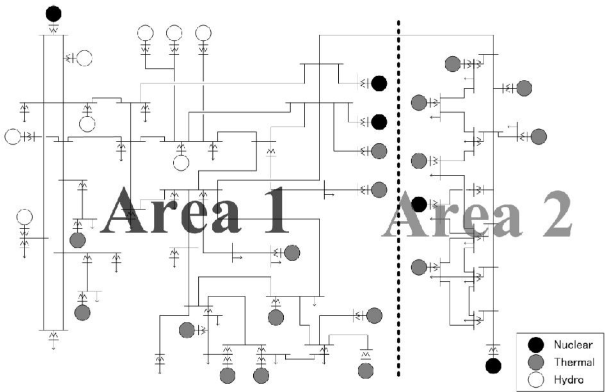


Fig. 11. IEEJ East 30-machine system.

To analyze under the most severe condition of LFC capability, the generation data at night time shown in Table I is used for the analysis.

TABLE I
GENERATION DATA AT NIGHT TIME

		Rated capacity [MW]	Initial output [MW]	Inertia constant [sec]	Total load [MW]
Area 1	Nuclear	18184	17325	8.02	33090
	Thermal	24252	22192	8.23	
	Hydro	11073	-9270	10.3	
	Total	53509	30247	8.58	
Area 2	Nuclear	6000	5800	9.03	7090
	Thermal	5560	4800	9.01	
	Hydro	-	-	-	
	Total	11560	10600	9.02	

It is assumed here that hydro power plant pumps up water at night. Therefore, we assume that output of hydro unit is not controlled by GF or LFC at night time.

IV. IMPACT OF WIND POWER FLUCTUATION AND BATTERY

Using the analytical model mentioned above, the impact of wind power fluctuation and battery on the system frequency and the tie line power in 2-area systems are examined.

The fluctuation of wind power generation shown in Fig. 12 is inputted into area 2. The maximum deviation is about 1600 [MW].

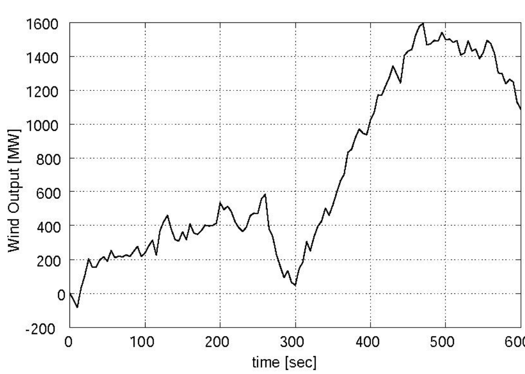


Fig. 12. Deviation of wind power generation.

Simulation condition is shown in Table II. GF capability means a ratio of possible output controlled by GF to the rated capacity. LFC capability means a ratio of possible output controlled by LFC to total outputs of all generators in a system.

TABLE II
SIMULATION CONDITION

		Area 1	Area 2
Reference Frequency [Hz]		50	50
System Constant [%MW/Hz]		9	9
Load-damping Constant [p.u.]		2	2
GF Capability	[p.u.]	0.05	0.05
	[MW]	1213	278
LFC Capability	[p.u.]	0.015	0.015
	[MW]	454	159

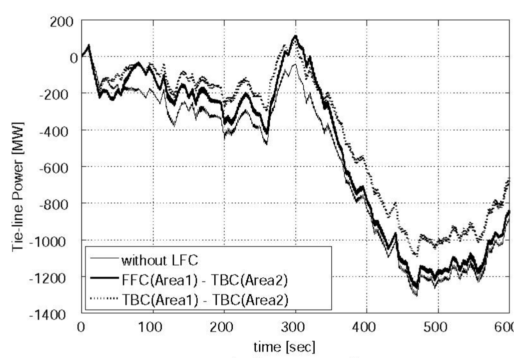
A. *Power System without Battery*

In this section, we consider power systems without battery. The impact of LFC control method on the fluctuations caused by wind power generation is examined. As LFC control method, three cases shown in Table III are compared.

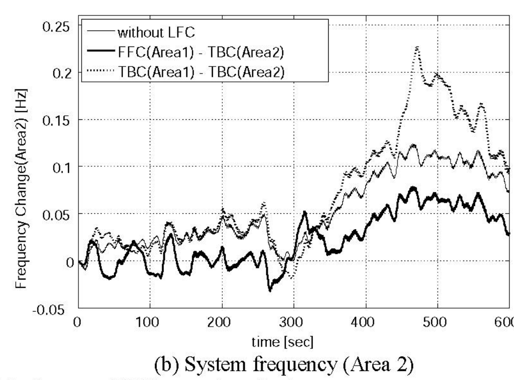
It is seen that the tie line power is suppressed most effectively if both areas adopt TBC (see Fig. 13(a)) and that the system frequency is suppressed most effectively if Area 1 adopts FFC (see Fig. 13(b)).

TABLE III
SIMULATION CASE

Case	Area 1	Area 2
1	FFC	TBC
2	TBC	TBC
3	only GF	only GF



(a) Tie line power flow



(b) System frequency (Area 2)

Fig. 13. Impact of LFC control method.

The tie line power fluctuation is found to be very large; most of the wind power fluctuation flows from Area 2 to Area 1 through the tie line. That is, in case that a small control area with wind power plants is interconnected into a large control area, the tie line power fluctuation is remarkably large as well as the system frequency fluctuation.

B. Power System with Battery

Here, battery is assumed to be installed into Area 2. Battery output is controlled based on a signal from LFC system. As LFC control method, Area 1 adopts FFC and Area 2 adopts TBC. Since LFC capability of thermal unit is small at night, it is compensated by battery control as shown in Fig. 14.

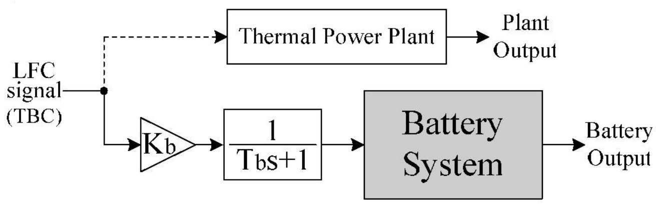
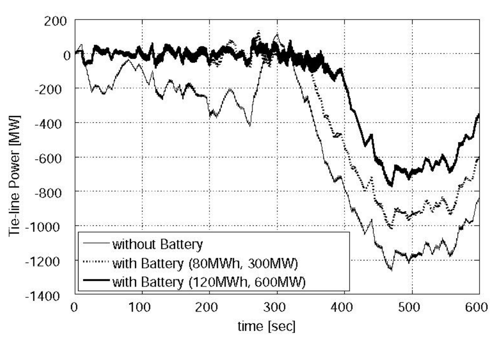
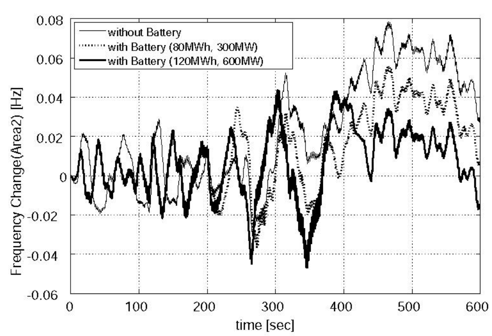


Fig. 14. Control of battery output using LFC signal.

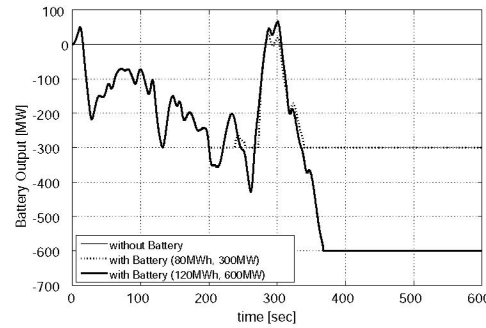
For example, the batteries of 80MWh-300MW or 120MWh-600MW are assumed to be installed. It is noted that the initial stored energy at t = 0 is assumed to be a half of the rated storage capacity (i.e., 40MWh or 60MWh). Fluctuations with/without battery are shown in Fig. 15. It is seen that the installed battery can suppress the fluctuations and that the effect of battery on suppression of fluctuations depends on battery capacity.



(a) Tie line power flow



(b) System frequency (Area 2)



(c) Battery output

Fig. 15. Behaviors of tie line power flow, system frequency and battery output with/without battery (Kb = 0.5, Tb = 0.5).

V. Evaluation of Battery Capacity

A. Impact of Battery Capacity

The impact of battery capacity on the maximum value of the tie line power deviation is analyzed for the wind power generation in Fig. 12. If the storage capacity (MWh) and the power converter capacity (MW) can be set independently, the maximum value of the tie line power deviation varies as shown in Fig. 16.

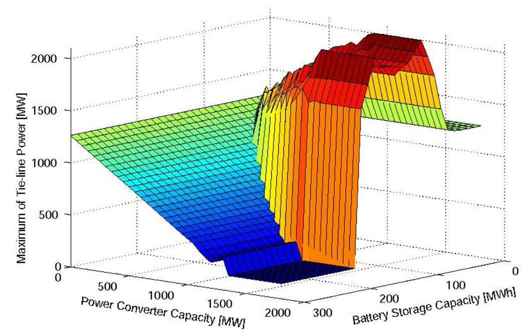
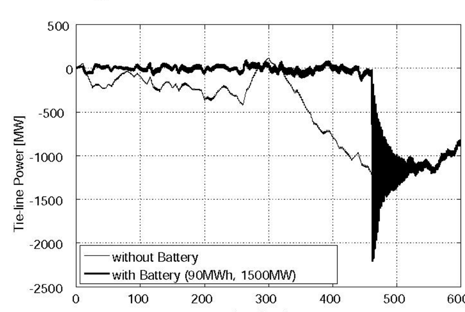
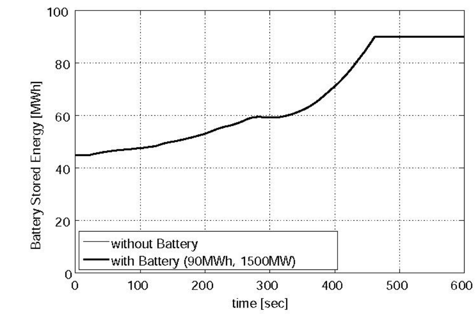


Fig. 16. Impact of battery capacity on the maximum value of tie line power deviation.

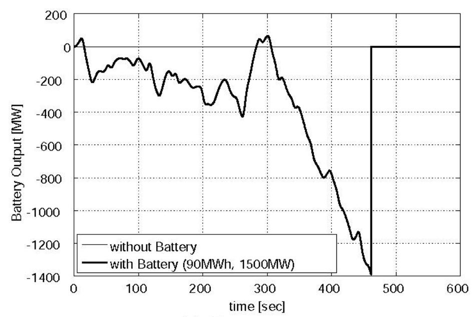
It is shown that battery with a larger capacity doesn't always suppress the deviation more effectively. When MWh capacity is large adequately, the larger MW capacity causes more effective suppression. On the other hand, when MWh capacity is small, the larger MW capacity causes the larger deviation. In order to examine the above result, the behaviors of fluctuations in case of battery of 90MWh and 1500MW are shown in Fig. 17.



(a) Tie line power flow



(b) Battery stored energy



(c) Battery output

Fig. 17 Behaviors of tie line power and output and stored energy of battery (90MWh, 1500MW)

Since the stored energy of battery reaches the full capacity at t = 462 [sec], the battery output changes to zero suddenly and this change causes the fluctuation of tie line power as a disturbance. Therefore, the battery needs to be operated as the stored energy is kept within the storage capacity.

B. Calculation of Required Battery Capacity

In this section, the required battery capacity for suppressing the tie line power deviation within a reference level is calculated. Based on the analysis mentioned above, the required capacity is calculated as follows.

1) Determination of MW capacity

At this step, the battery storage capacity (MWh) is assumed to be infinite. Then the power converter capacity (MW) is increased by 1 [MW] up to the minimum value required for suppressing the tie line power deviation within a reference level. In the example of chapter IV, the reference level is assumed to be 300 [MW], and the required MW capacity is 1137 [MW].

2) Determination of MWh capacity

The obtained MW capacity is set. Then the storage capacity is decreased by 1 [1MWh] from the adequately large value up to the minimum value required for working the storage function within the storage capacity. In the example of chapter IV, the required MWh capacity is 176 [MWh].

C. Coordination of Battery and Thermal Unit

In this research, we aim to suppress the fluctuation of the system frequency and the tie line power caused by wind power generation by cooperative control of LFC generators and battery. As thermal units and battery are controlled by a signal from LFC system, the LFC signal needs to be shared between battery and thermal units effectively from the view point of the coordination. Therefore, the impact of share ratio on the required battery capacity is examined. The ratio of a signal inputted into battery system to that inputted into thermal unit is K_b to K_{th} (= $1 - K_b$). If the reference of the tie line power deviation is assumed to be 300 [MW], the required battery capacity varies according to the share ratio as shown in Table IV.

TABLE IV
REQUIRED BATTERY CAPACITY

Share ratio		Required battery capacity		Maximum value of thermal output deviation [MW]
K_b	K_{th}	Power converter capacity [MW]	Storage capacity [MWh]	
0.1	0.9	1126	173	218
0.2	0.8	1144	180	215
0.3	0.7	1218	191	165
0.4	0.6	1158	189	158
0.5	0.5	1224	198	158
0.6	0.4	1231	203	141

For higher K_b/K_{th} ratio, larger battery capacity is required. On the other hand, the maximum value of thermal output deviation is lower. Therefore, installation of battery with a larger capacity makes it possible to decrease LFC capacity of the conventional generators.

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, we have analyzed the impact of installed wind power generation and battery on the system frequency and the tie line power. In 2-area power systems, the tie line power fluctuation is remarkably large as well as the system frequency fluctuation. It has been made clear that the installed battery can suppress these fluctuations and that the effect of battery on suppression of these fluctuations depends on battery capacity. If the stored energy of battery reaches the full capacity, the battery output changes to zero suddenly and the large fluctuation is caused. Therefore, the stored energy needs to be controlled within the rated storage capacity. Based on this need, the required battery capacity for suppressing the tie line power deviation within a reference level has been calculated. If battery and LFC generator are controlled cooperatively, installation of battery with a larger capacity makes it possible to decrease LFC capacity of the conventional generators.

In the near future, a new method to calculate the optimal battery storage capacity (MWh) and the appropriate power converter capacity (MW) for various kinds of wind power generation patterns and an effective control method of the battery system for reducing the battery capacity and LFC capability of the conventional power plants will be studied.

VII. References

[1] W. El-Khattam and M. M. A. Salama, "Distributed generation technologies, definitions and benefits," *Electric Power Systems Research*, vol. 71, issue 2, pp. 119-128, Oct. 2004.

[2] N. Jaleeli, L. S. VanSlyck, D. N. Ewart, L. H. Fink, and A. G. Hoffmann, "Understanding automatic generation control," *IEEE Trans. Power Syst.*, vol. 7, pp. 1106-1122, Aug. 1992.

[3] A. Murakami, A. Yokoyama, and Y. Tada, "Basic study on battery capacity evaluation for load frequency control (LFC) in power system with a large penetration of wind power generation," *T. IEE Japan*, vol. 126-B, no. 2, pp. 236-242, Feb. 2006. (in Japanese)

[4] P. Kunder, "Power System Stability and Control, " McGraw-Hill, 1994.

[5] A. J. Wood and B. F. Wollenberg, "Power Generation Operation and Control," 2nd ed., Wiley, New York, 1966.

[6] T. Michigami, T. Ishii, "Construction of fluctuation load model and dynamic simulation with LFC control of DC power system and frequency converter interconnection," in *Proc. 2002 IEEE Power Engineering Society Transmission and Distribution Conf.*, vol. 1, pp. 382-387.

[7] "Standard model in the power system," *IEEJ technical report association*, vol. 754, 1999. (in Japanese)

VIII. Biographies

Masashi Arita received the B.Eng. in Electrical Engineering, The University of Tokyo, Japan, in 2004. He is currently a master course student at The University of Tokyo, Japan. His interests include frequency control using battery in power system with wind power generation.

Akihiko Yokoyama (Member) was born in Osaka, Japan, on October 9, 1956. He received B.S., M.S. and Dr. Eng from The University of Tokyo, Tokyo, Japan in 1979, 1981 and 1984, respectively. He has been with Department of Electrical Engineering, The University of Tokyo since 1984 and currently a professor in charge of Power System Engineering. He is a member of IEEJ, IEEE and CIGRE.

Yasuyuki Tada (Member) received the Ph.D. degree in engineering from the University of Tokyo, Tokyo, Japan, in 1998. Currently, he is a Researcher in the Power System Technology Group, Electric Power Engineering R&D Center, Tokyo Power Electric Company (TEPCO), where he has been since 1981.