http://dx.doi.org/10.11142/jicems.2013.2.3.342
Journal of International Conference on Electrical Machines and Systems Vol. 2, No. 3, pp. 342~348, 2013 **342**

Design of Battery System for Smoothing Wind Power Variations in Power System based on Frequency Response Analysis

Kyouhei Nakajima *, Atsushi Umemura *, Rion Takahashi *, and Junji Tamura *

Abstract – As a number of wind power generation systems have been installed in power systems in the world, frequency fluctuations due to output power variations from wind farms have become a serious problem. Battery systems have been studied for smoothing the output variations and decreasing the resulting frequency fluctuations. Among these studies, efficient design of battery systems is one of the most important subjects from a point of view of cost. This paper presents a comparative analysis of the smoothing effect between the conventional moving average method and a new method based on frequency response analysis.

Keywords: Wind power generator, Power system, Battery system, Frequency response analysis

1. Introduction

In recent years, wind power generation systems are widely being introduced in the world. As the penetration level of wind power into power system increases, however, frequency deviation of the power system due to variations of wind farm output also increases. Therefore some countermeasures are needed to decrease the deviation within the permitted limit. Smoothing control of wind generator output fluctuations is very important.

Battery system is one of the most effective means as a countermeasure for the problem. Therefore, efficient design of battery systems is one of the most important subjects from a point of view of cost. In the design of battery systems, it is very important to determine the frequency range over which the battery system needs to compensate.

This paper examines the characteristics of the frequency variations in the power system by performing a frequency response analysis of the power system model. Sensitivity characteristics of the frequency variation with respect to the oscillating power input to the power system model are obtained by PSCAD/EMTDC simulation analysis. Then, a new design method of efficient battery system is proposed, in which the battery responds only to power fluctuations within a limited frequency range that cannot be compensated by conventional synchronous generators, which can be obtained from the above frequency response analysis. Finally validity of the proposed method is evaluated by a comparative analysis between the conventional moving average method and the proposed method.

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Received 11 July 2013; Accepted 22 August 2013

2. Model System

2.1 Power System Model

The model system used in the simulation analyses is shown in Fig. 1. The power system model consists of a hydro power generator (synchronous generator, SG1, 200MVA), two thermal power generators (SG2, 200MVA, SG3, 300MVA), a nuclear power generator (SG4, 300MVA), and a load (1000MVA) [1]. Additionally, wind generator (Induction Generator, IG) and battery (lead-acid storage battery) are connected to the power system model. Variations of the wind power generator output can cause the frequency variation of the power system. In order to suppress the frequency variation of the power system, SG1 and SG2 are operated under Load Frequency Control (LFC), SG3 is under Governor Free (G.F) and SG4 is under Load Limit (L.L) [2]. L.L is used to output constant power. SG1 is a salient pole type synchronous generator, and SG2, SG3 and SG4 are cylindrical rotor type synchronous generators. Magnetic saturation is not considered in these models. Table 1 shows the parameters of each synchronous generator.

Q_C and Q_{Load} are capacitor banks. Q_C is used at the terminal of wind generator to compensate the reactive power demand of wind generator at steady state. Q_{Load} is used at the terminal of load to compensate the voltage drop due to the impedance of transmission lines. Core saturations of induction generator is not also considered in the analysis.

Details of the wind generator and battery storage unit will be described in the later sections.

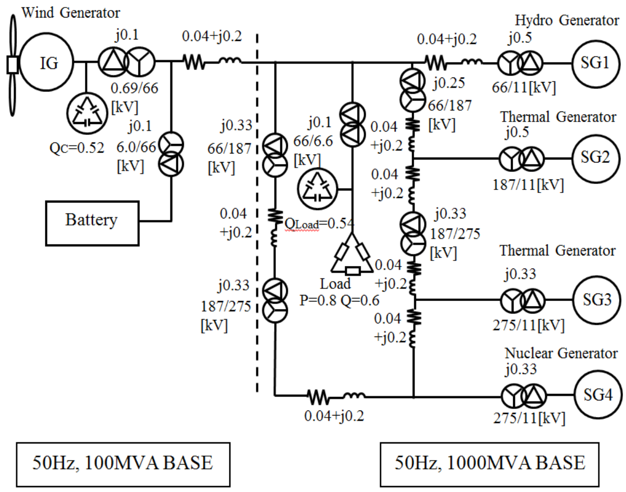

Fig. 1. Power System Model

Table 1. Parameters of Synchronous Generators

	Synchronous Generator			
	Salient pole type (SG1)	Cylindrical rotor type		
		SG2	SG3	SG4
MVA	200	200	300	300
Xd [pu]	1.2	2.11		
Xq [pu]	0.7	2.02		
2H [sec]	10	8		

2.2 Generator

The governor is a device that automatically adjusts the generator output and the rotational speed of the turbine. G.F operation contributes to the suppression of frequency variations in the short period of several seconds. When the frequency drops (rotation speed of the generator decreases), the output of the prime mover increases. When the frequency rises (rotation speed of the generator increases), the output is controlled automatically to decrease.

2.3 Governor Model of each Generator

The Governor model of each generator used in the simulation analyses are shown in Fig. 2 and Fig. 3, in which the values of 65M and 77M are shown in Table 2, where, Sg: the revolution speed deviation [pu]; 65M: the initial output [pu]; 77M: the load limit (65M + rated MW output × PLM[%]); PLM: margin of governor operation [%]; Pm: the turbine output [pu]. PLM for SG3 is set 5[%], and for SG4 PLM is set -20[%] because the nuclear generator output (SG4) is controlled constant (L.L, load limit operation).

2.4 Load Frequency Control Model [3]

Load Frequency Control (LFC) sends the output signal (LFC signal) to each power plant after detecting frequency deviations. Then, governor output value (65M) of each power plant is changed by LFC signal, and the power plant output is changed. The frequency deviation is input into Low Pass Filter (LPF) to remove fluctuations with short period, because the LFC is used to control frequency fluctuations with a long period. The LFC model used in this paper is shown in Fig. 4, where, Tc : the LFC period = 200[s]; ωc : the LFC frequency = 1 / Tc = 0.005[Hz]; ζ : the damping ratio = 1.

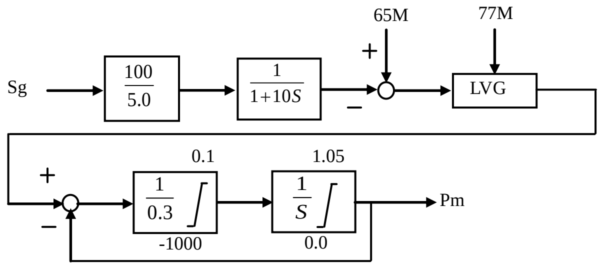

Fig. 2. Hydro Governor

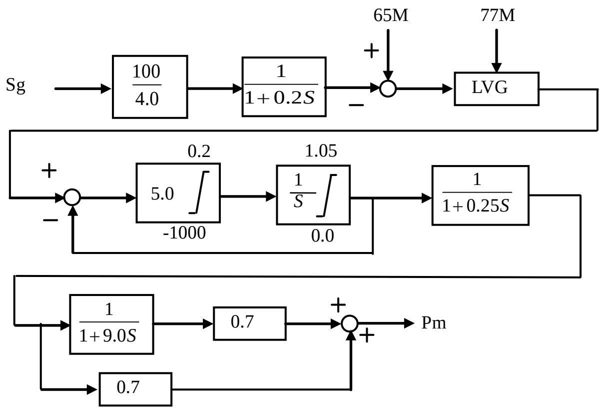

Fig. 3. Thermal and Nuclear Governor

Table 2. Values of 65M and 77M

SG1(Hydro)			SG2(Thermal)		
Frequency control	65M	77M	Frequency control	65M	77M
LFC	LFC signal	1	LFC	LFC signal	1
SG3(Thermal)			SG4(Nuclear)		
Frequency control	65M	77M	Frequency control	65M	77M
G.F	0.8	0.84	L.L	0.96	0.8

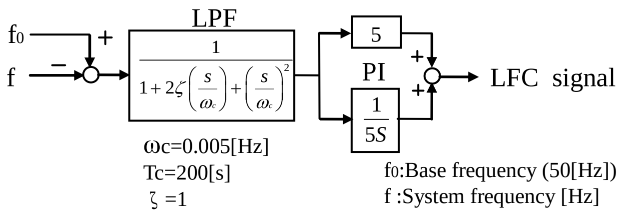

Fig. 4. LFC Model

2.5 Automatic Voltage Regulator (AVR)

To control the terminal voltage of the synchronous generator constant, AVR is needed. In the simulation analyses, AVR is expressed by a first order time delay system as shown in Fig. 5. Parameters of AVR are shown in Table 3.

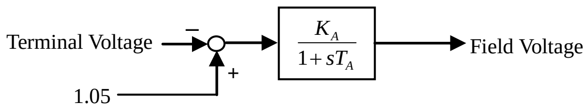

Fig. 5. AVR Model.

Table 3. Parameters of AVR

Gain K_A [pu]	400
Time Constant T_A [sec]	0.02

2.6 Wind Generator Model

In this paper, fixed speed wind turbine with induction generator is used in the simulation analyses. Multiple wind generators are aggregated and expressed by single wind generator approximately, whose rated capacity is 100MVA. The MOD-2 characteristic is used for the wind turbine model. Model equations of MOD-2 are given as follows. The captured power from the wind can be obtained from (1). Tip speed ratio, λ, and power coefficient, C_P, can be expressed as (2) and (3). Since C_P is expressed in feet and mile, Γ is corrected as (4).

$$P_{wtb}=\frac{1}{2}\rho C_P(\lambda)\pi R^2 V_w^{\ 3} \tag{1}$$

$$\lambda=\frac{\omega_{wtb}R}{V_w} \tag{2}$$

$$C_P(\lambda)=0.5(\Gamma-0.022\beta^2-5.6)e^{-0.17\Gamma} \tag{3}$$

$$\Gamma=\frac{R}{\lambda}\cdot\frac{3600}{1609} \tag{4}$$

The torque coefficient and the wind turbine torque are shown as follows.

$$C_t(\lambda)=\frac{C_P(\lambda)}{\lambda} \tag{5}$$

$$\tau_M=\frac{1}{2}\rho C_t(\lambda)\pi R^3 V_w^{\ 2} \tag{6}$$

where, P_{wtb} is the wind generator output [W], R is the radius of the blade [m], ω_{wtb} is the wind generator angular speed [rad/s], β is the blade pitch angle [deg], V_w is the wind speed [m/s], ρ is the air density [kg/m^3], and τ_M is the wind turbine output torque [Nm].

Table 4 shows the parameters of Induction generator.

Table 4. Parameters of Induction Generator

Induction Generator (Squirrel cage type)	
MVA	100
R1 [pu]	0.01
X1 [pu]	0.18
Xm [pu]	10
R2 [pu]	0.02
X2 [pu]	1.22
2H [sec]	1.5

2.7 Battery System Model [4]

The battery system model used in this paper is shown in Fig. 6. It consists of a 6-pulse PWM Voltage Source Converter (VSC), a DC link capacitor, a two quadrant DC-DC chopper, and a Lead-acid battery unit. For controlling DC link voltage constant, voltage source converter (VSC) controls the grid point voltage constant. The two-quadrant chopper controls charging and discharging of the battery unit. Lead-acid battery unit is expressed by a variable DC voltage source with internal resistance [4]. The VSC and the DC-DC chopper are linked by a DC link capacitor. The controller of VSC controls DC link voltage and terminal voltage of wind generator. PWM carrier frequency is 1000 [Hz]. The controller of the two quadrant DC chopper controls active power input/output to/from the battery unit according to the reference signal. Details of the controllers are described in the later sections. Parameters of the battery unit are shown in Table. 5.

2.8 Frequency Response Analysis of Power System

For performing a frequency response analysis of the target power system model (the wind generator and battery system are removed from the original system shown in Fig. 1, responses of the system with respect to input signal (sinusoidal power oscillation) given by (7) have been calculated.

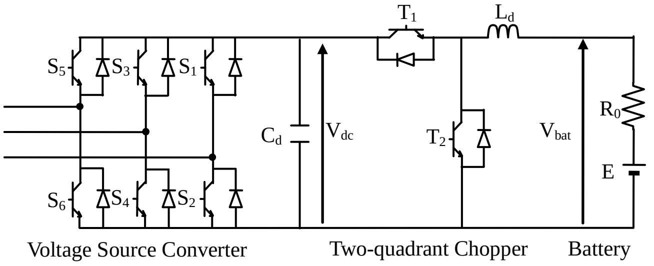

Fig. 6. Battery System Model

Table 5. Parameters of Battery Unit

Capacity	100[MW]
Internal resistance	0.016 [ohm]
Rated storage energy	12000[MJ]
Rated internal voltage	9 [kV]

$$P_{VR}\sin\left(\frac{2\pi}{T_{VR}}t\right)[MW] \quad (7)$$

where, P_{VR} is amplitude of oscillating power input which is varied from 10MW to 200MW; T_{VR} is the period of sinusoidal signal which is changed from 0.1 to 120sec. This signal is input at the connection point between the main power system and the wind farm in Fig.1 (the wind farm and battery are removed in this calculation).

Maximum frequency deviation of the power system with respect to the oscillating power input is calculated by PSCAD/EMTDC. The results are shown in Fig. 7. The horizontal axis is period of the oscillating power, T_{VR} [sec], the vertical axis is maximum frequency deviation [Hz], and the depth axis is amplitude of fluctuation power, P_{VR} [MW]. It is seen from the figure that frequency variations of short period less than about 5sec are suppressed well. This can be regarded to be owing to GF operation. On the other hand, it is seen that frequency variations of long period greater than about 60sec are also suppressed well. This can be regarded to be owing to LFC. However, it is also seen that frequency variations of around 30sec cannot be suppressed well. From these results, it is clear that the target power system cannot compensate power oscillation of the period of around 30sec well and frequency variation becomes large for that period of power oscillation. Therefore it can be said that the battery system with Band Pass Filter (BPF) of around 30sec can be an efficient solution from a view point of cooperative operation with the synchronous generators for frequency control. Control method of the battery system using the frequency response analysis is described in the next chapter.

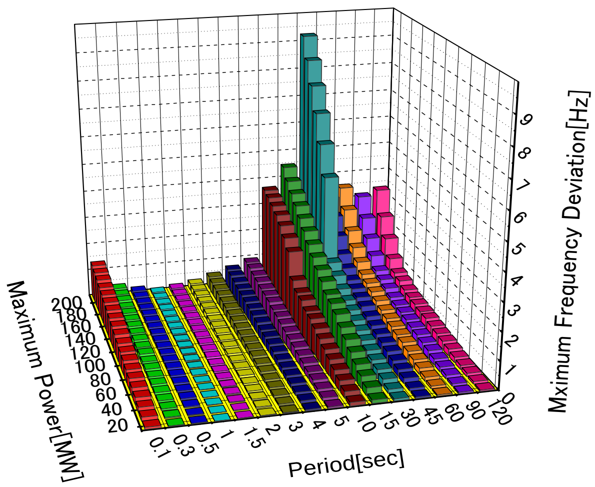

Fig. 7. Maximum Frequency Deviation.

3. Control Method of Battery System

In traditional control method of battery system, output from a wind farm is smoothed by charge/discharge control into/from the battery system. Reference power P_{ref} for the output from the wind farm to the grid system is, in general, calculated as output from a low pass filter (LPF) whose input is actual wind farm output, P_{WG}. Therefore, reference value for the battery input P_{bat_ref} is determined by (8).

$$P_{bat\_ref} = P_{WG} - P_{ref} \quad (8)$$

The control system for the chopper of the battery system based on the above traditional method is shown in Fig. 8, where P_{SYS} is actual power supplied from the wind farm to the grid. Time constant of LPF is set 120[sec] in this study.

The new control system using a band pass filter (BPF) proposed in this paper is shown in Fig. 9. Based on the frequency response analysis results in the previous chapter, the value of the BPF is determined as follows: Gain G = 4.6, Characteristic Frequency ωc = 0.03333[Hz], Characteristic Period Tc = 1/fc = 30[sec], and Damping ratio ζ = 2.3. Bandwidth of the BPF is 0.2635[Hz].

4. Simulation Condition

Simulation analyses have been carried out to investigate the performance of the proposed control system with BPF based on the frequency response analysis. Comparative analysis on the model system of Fig. 1 between the traditional control system using LPF and the proposed control system using BPF is performed. Initial charge level of the battery unit is set at 75%. Simulation time is 600 seconds. The validity of the proposed method is evaluated considering the responses of output of wind farm, charge level and output of the battery unit, output of each synchronous generator (SG1, SG2, SG3, SG4), and the frequency of the power system.

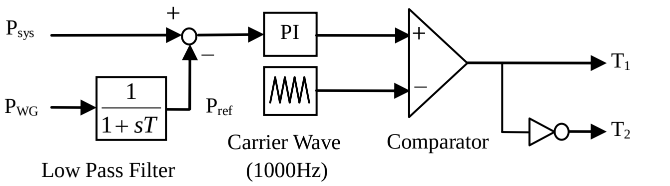

Fig. 8. Traditional Control method

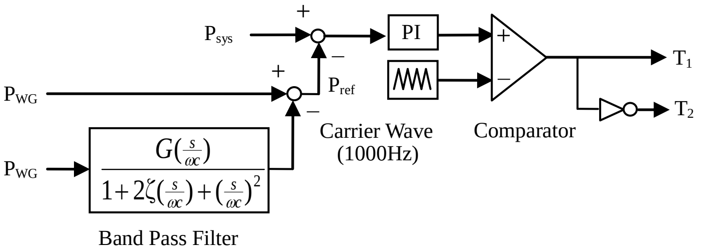

Fig. 9. Control Method Using BPF

5. Simulation Results

Simulation results are shown in Fig. 10 to Fig. 18. Wind speed data is shown in Fig, 10, output of wind generator is shown in Fig, 11. From these results, it is seen that the wind generator is operating in accordance with the wind data.

The output of battery system is shown in Fig. 12. It is seen that there is not so large difference between the two responses of the new method using BPF and the conventional method based on LPF. Response of P_{SYS} is shown in Fig. 13. Charge level of the battery system is shown in Fig. 14. Comparing two responses of the new method using BPF and the conventional method, charge level of the conventional method has decreased by 1.3% at maximum from the initial value, but that of the new method has decreased by 0.5% at maximum. Considering the performance in charged energy in MJ, the conventional control method requires charged capacity of at least 5237 [MJ], however the new control method requires only 1913 [MJ]. From this point of view, energy capacity of the battery system can be decreased by using the proposed control method.

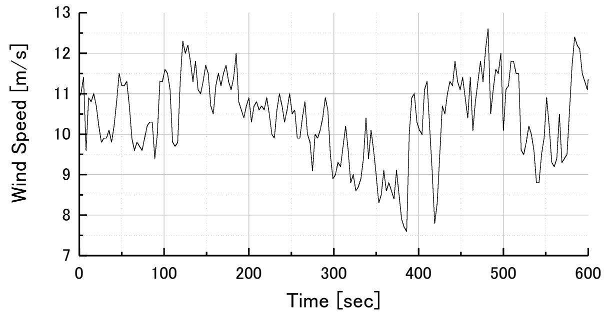

Fig. 10. Wind Speed

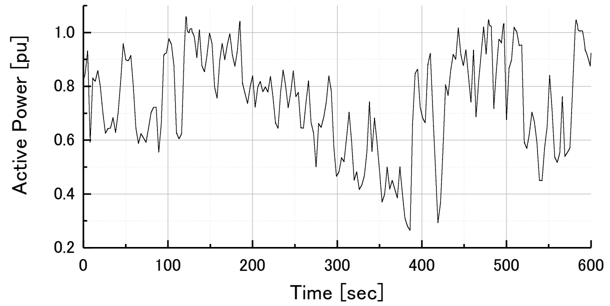

Fig. 11. Wind Generator Output

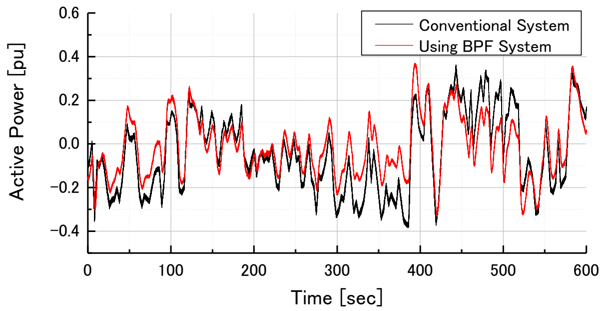

Fig. 12. Battery System Output

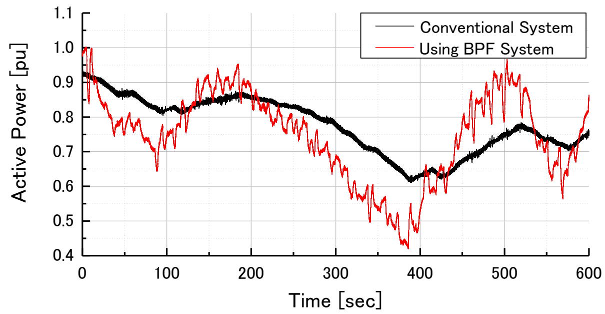

Fig. 13. Response of P_{SYS}

Frequency response of the power system is shown in Fig. 15. When there is no battery system, frequency variation of the power system is more than ±0.2Hz, the maximum permissible limit in Japan. It is seen from the figure that frequency variation of the power system can be suppressed within ±0.2Hz in both cases with the new method and the conventional method.

Response of each generator output is shown in Fig. 16 to Fig. 18. Output power in the case without the battery system is shown in Fig.16, and responses in the cases with the conventional control method and the new control method are shown in Figs. 17 and 18, respectively. It is seen from the figures that, the cooperative control between the battery and synchronous generators can be achieved in both cases, but GF and LFC generators are working more in the case with the new method.

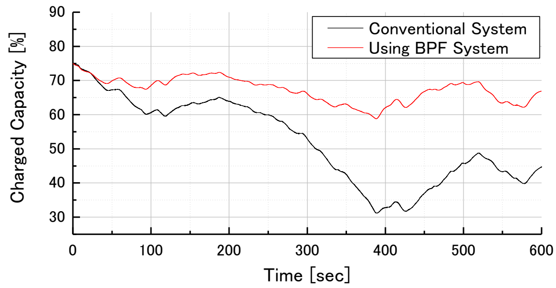

Fig. 14. Charge Level

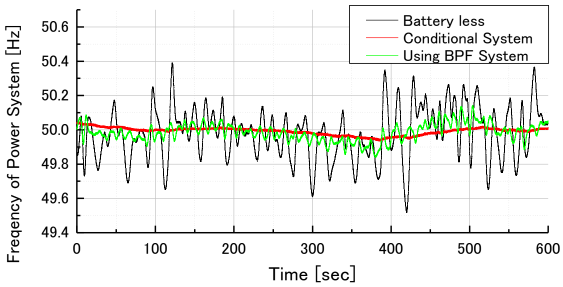

Fig. 15. Frequency Variation of Power System

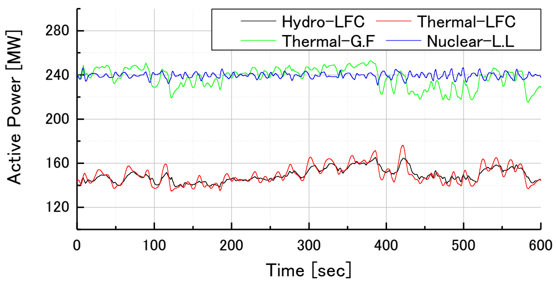

Fig. 16. Power Output without Battery

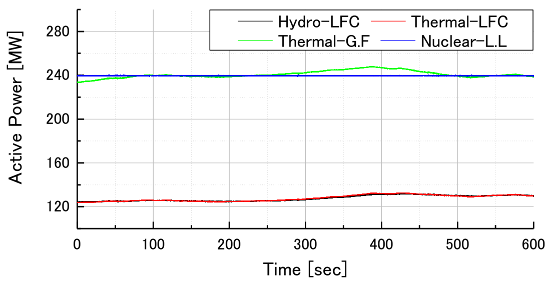

Fig. 17. Power Output of Conventional System

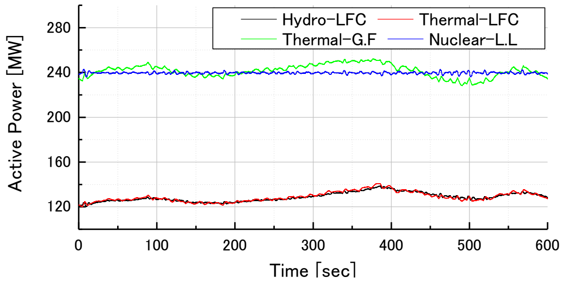

Fig. 18. Power Output of New System

6. Conclusion

In this paper, new control method of battery system for suppressing the frequency variations in power system with wind farm connected is proposed. The new control method is based on the frequency response analysis of power system. The battery system responds only to power fluctuations within a limited frequency range obtained through a band pass filter (BPF) that cannot be compensated by conventional synchronous generators. The band pass filter can be designed based on the frequency response analysis.

Validity of the proposed method is evaluated by a comparative analysis between the conventional battery system and the proposed system, in which the conventional system compensate for the power supplied from wind farm to the grid system to follow the reference value determined by using a low pass filter. As a result, it is concluded that energy capacity of the battery system can be decreased by using the proposed control method compared to the conventional one.

Acknowledgements

This study was supported by a Grant-in-Aid for scientific Research (B) from The Ministry of Education, Science, Sports and Culture of Japan. The authors wish to thank Mr. Akira Kuwayama and Mr. Kazuki Yoshioka of Hokkaido Electric Power Co., Inc., for their valuable advice and encouragement.

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