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Study on Frequency Fluctuations in Power System with a Large Penetration of Wind Power Generation

M.R.I. Sheikh*[1], R. Takahashi #, and J. Tamura#

Abstract – *As wind turbine output is proportional to the cube of wind speed, the wind turbine generator output fluctuates due to wind speed variations. Hence, if the power capacity of wind power generators becomes large, wind power generator output can have an influence on the power system frequency. Therefore, this study investigates the influence of the ratio of the wind generator capacity to the power system capacity, on the power system frequency. Thus, the impacts of different governor control system models are investigated with different operating modes of synchronous generators (SGs), when a total capacity of SGs are considered as 100 MVA. It is seen that though thermal governor control system perform better frequency control, but it cannot be maintained to the acceptable level when wind power capacity become 10% of total capacity. Finally, it is seen that when several interconnected SGs are operated with different control modes, system frequency become more severe for 10% capacity of wind power.*

Keywords – Governor control system model, power system frequency, SGs operating mode, and wind generator capacity.

1. INTRODUCTION

Recently, exhaustion of the fossil fuel and environmental problem such as global warming has become serious problems. Therefore, it is necessary to introduce clean energy more in place of the fossil fuel. Wind power is one of the prospective clean energy resources and thus a large number of wind farms are being in service in the world. However, wind generator output power fluctuates greatly due to the wind speed variations. Hence, if the power capacity of wind generators becomes large, the wind generator output can have an influence on the power system frequency [1]-[4]. In the conventional operation of wind power generators, when the wind speed is between the rated speed and the cut out speed, the wind power generator output is controlled at the rated value by a pitch control system. On the other hand, when the wind speed is between the cut in speed and the rated speed, the blade pitch angle is maintained constant (= 0 deg), in general, for the wind turbine to capture the maximum power from the wind turbine. Therefore, the wind power generator output fluctuates due to wind speed variations in the latter condition, because the wind power is proportional to the cube of wind speed. Therefore, it is necessary to investigate the influence of the ratio of the wind generator capacity to the power system capacity, on power system frequency. The governor control system models have a great influence to maintain frequency to the desired level with the increased wind power penetration. So impacts of different governor control system models have been investigated. Also performances of governor system model for maintaining frequency fluctuations are investigated both considering single SG or combination of several SGs operating in different control mode. Finally, it is seen that when single SG or several SGs with same total capacity are connected to the network, only governor control system model and pitch controller cannot maintain power system frequency to the desired level and severe situation occur when wind power penetration become 10% of the total capacity. For this, as the wind power penetration increases day by day, this study will be helpful for taking preventive measures for the power grid companies to improve the stability and quality of electric power. Considering these view points, the study plays a vital role for power system application.

2. MODEL SYSTEM ANALYSES

The model system used in the simulation analyses is shown in Figure 1. Two switches S1 and S2 are used to connect the synchronous generator (SG) with the network. When only one generator (SG, 100 MVA) is need to work with the network, it is done by turning S1 switch ON and disconnecting other generators by turning S2 switch OFF. Similarly, when needed S2 switch is turn ON to connect several generators with the network (total capacity 100 MVA) and S1 switch is turn OFF. The model system consists of a wind generator, IG [1], a hydropower generator, HG (a salient pole synchronous generator, SG1), two thermal power generators, TG (cylindrical type synchronous generators, SG2 and SG3), a nuclear power generator NG (a cylindrical type synchronous generator, SG4), and two loads. SG1 and SG3 are operated under load frequency control (LFC), SG2 is under governor-free (GF) control and SG4 is under load limit (LL) operation [5].

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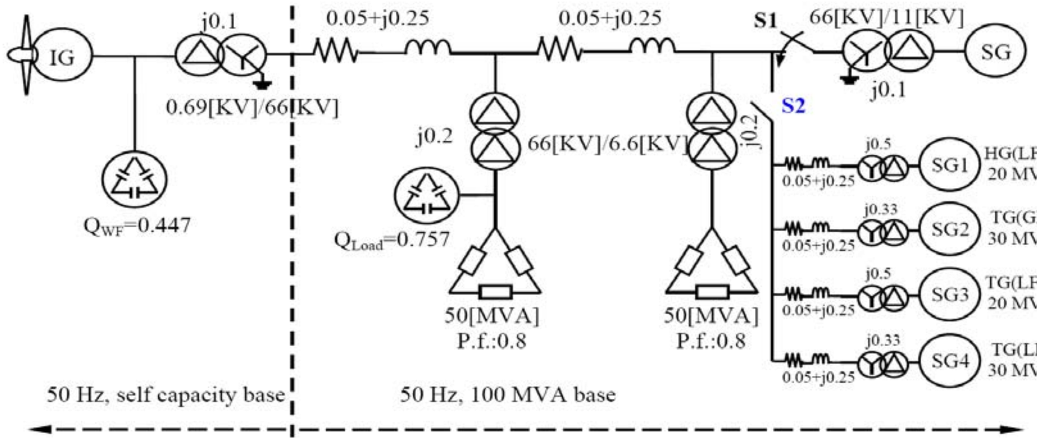


Fig.1. Model system.

In general, LFC is used to control frequency fluctuations with a long period more than a few minutes, and GF is used to control fluctuations with a short period less than a minute. LL is used to output constant power. Q_{WF} and Q_{Load} are capacitor banks. Q_{WF} is used at the terminal of IG to compensate the reactive power demand of wind generator at steady state. The value of the capacitor is chosen so that the p.f. becomes unity, when the wind generator operated in the rated condition [6]. Q_{Load} is used at the terminal of load to compensate the voltage drop by the impedance of transmission lines. Core saturations of induction generator and synchronous generators are not considered for simplicity. Parameters of IGs and SGs are shown in Table 1. The initial power flow and initial conditions are shown in Table 2.

Table 1. Parameters of generator.

	Induction Generator		
	Squirrel cage type (IGn,n=1,2,3)		
MVA	3	5	10
R_1 (pu)		0.01	
X_1 (pu)		0.18	
X_m (pu)		10	
R_2 (pu)		0.015	
X_2 (pu)		0.12	
2H (s)		1.5	
	Synchronous Generator		
	Salient pole type (HG)	Cylindrical type (TG)	
MVA	100	100	
Xd (pu)	1.2	2.11	
Xq (pu)	0.7	2.02	
Xd’(pu)	0.3	0.28	
Xd” (pu)	0.22	0.215	
Xq” (pu)	0.25	0.25	
Tdo’ (s)	5.0	4.2	
Tdo” (s)	0.05	0.032	
Tqo”(s)	0.14	0.062	
H (s)	2.5	2.32	

Table 2. Initial conditions.

	IG	SG1	SG2
P	0.03/0.05/0.1	1.00	1.00
V	1.00	1.05	1.05
Q	0.00		
s(Slip)	-1.733%		

3. SYNCHRONOUS GENERATOR MODEL

Governor

The governor is a device that automatically adjusts the rotational speed of the turbine and the generator output. When the generator load is constant, the turbine is operated at a constant rotational speed. However, when the load changes, balance between the generator output and the load is not maintained, and the rotational speed changes. When the load is removed, the governor detects the increase of the rotational speed, and then, the valve is closed rapidly so that an abnormal speed increase of the generator is prevented.

Governor for hydro and thermal generators [5]

The governor models used in the simulation analyses are shown in Figures 2 and 3, in which the values of 65M and 77M for hydrogenerator and thermal generator are shown in Table 3 and Table 4, respectively. When several SGs are connected together their values of 65M and 77M are shown in Table 5. Where, Sg: the revolution speed deviation (pu); 65M: the initial output (pu); 77M: the load limit (65M + rated MW output × PLM (%)); PLM: the spare governor operation (%); Pm: the turbine output (pu). PLM for SG2 is set 5%, and for SG4 PLM is set -20% because the nuclear generator output (SG4) is controlled constant (LL, load limit operation).

For governor-free (GF) operation:

When PLM > 0
65M = the initial output (pu)
77M = 65M + rated MW output × PLM (%)

For load limit (LL) operation:

When PLM < 0
65M = 77M + rated MW output × PLM (%)
77M = the initial output (pu)

Sg is set zero for SG1 and SG3 because these generators are operated under LFC to control frequency fluctuations with a relatively long period.

Table 3. Values of 65M and 77M for hydrogenerator.

	IG: 3 MVA	IG: 5 MVA	IG: 10 MVA
65M (pu)	0.72	0.703	0.653
77M (pu)	0.756	0.7733	0.751
PLM (%)	5	10	15

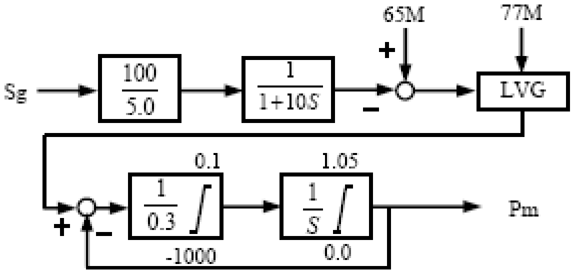


Fig. 2. Hydro governor.

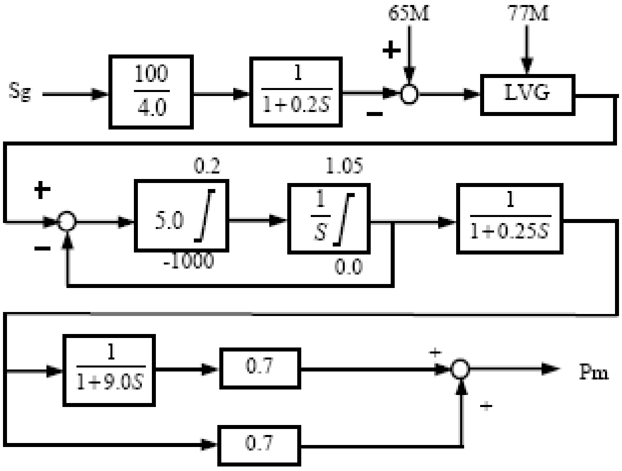


Fig. 3. Thermal governor.

Table 4. Values of 65M and 77M for thermal generator.

	IG: 3 MVA	IG: 5 MVA	IG: 10 MVA
65M (pu)	0.72	0.7	0.65
77M (pu)	0.828	0.805	0.767
PLM (%)	15	15	18

Table 5. Values of 65M and 77M for using multiple generator.

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

Automatic voltage regulator (AVR)

To keep the voltage of the synchronous generators constant, AVR is needed. In the simulation analyses, the AVR is expressed by a first order time delay system. AVR model is shown in Figure 4. Parameters of AVR are shown in Table 6.

Load Frequency Control Model

In the Load Frequency Control (LFC) model, the output power signal is sent to each power plant when the frequency deviation is detected in the power system. Then, governor output value (65M) of each power plant is changed by LFC signals, and then the power plant output is changed. The frequency deviation is input into Low Pass Filter (LPF) to remove fluctuations within short period, because the LFC is used to control frequency fluctuations with a long period. The LFC model is shown in Figure 5, where, Tc: the LFC period = 200 s; ωc: the LFC frequency = 1 / Tc = 0.005 Hz; ζ: the damping ratio = 1.

4. WIND TURBINE MODELLING

In this paper, the MOD-2 model [7] is considered for the Cp-λ characteristics, which is represented by the following equations and shown in Figure 6 for different values ofβ. The captured power from the wind can be obtained from Equation 1. Tip speed ratio, λ and power coefficient, C_P, can be expressed as Equations 2 and 3. Since C_P is expressed in feet and mile, Γ is corrected as Equation 4.

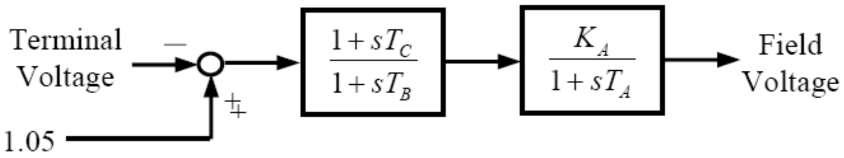
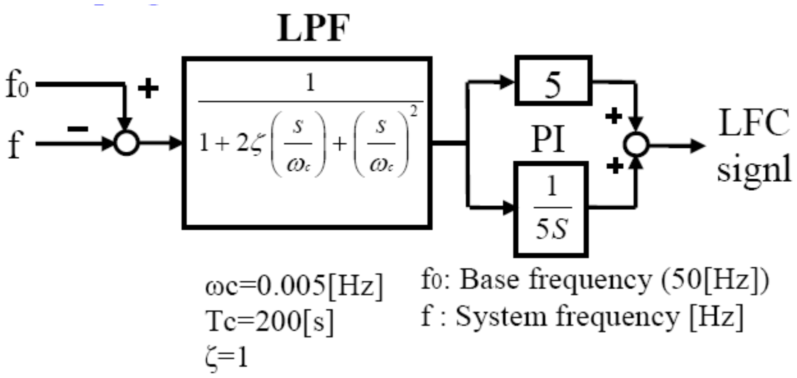


Fig.4. AVR model.

Table 6. Parameters of AVR.

Gain K_A (pu)	400
Time Constant T_A (s)	0.02
Time Constant T_B=T_C (s)	0.00



ωc=0.005[Hz]
Tc=200[s]
ζ=1

f0: Base frequency (50[Hz])
f : System frequency [Hz]

Fig. 5. LFC model.

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

$$\lambda = \frac{\omega_{wtb} R}{V_w} \qquad (2)$$

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

$$\Gamma = \frac{R}{\lambda}\cdot\frac{3600}{1609} \qquad (4)$$

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

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

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

Where, P_{wtb} is the wind turbine output (W), R is the radius of the blade (m), ω_{wtb} is the wind turbine 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).

5. PITCH CONTROLLER

In the simulation analysis, conventional pitch controller as shown in Figure 7 is used. The purpose of using the pitch controller is to maintain the output power of the wind generator at rated level by controlling the blade pitch angle of turbine blade when the wind speed is over the rated speed. Generally, the blade pitch operation system is complicated, but this paper simulates the pitch operation system by using a first order time delay system with time constant T_w=5 seconds. In addition, the pitch angle cannot be changed instantly due to the rotational inertia of blade and mechanical limitations. Therefore, the rate of change of pitch angle is limited to 10 degrees per second in the simulations.

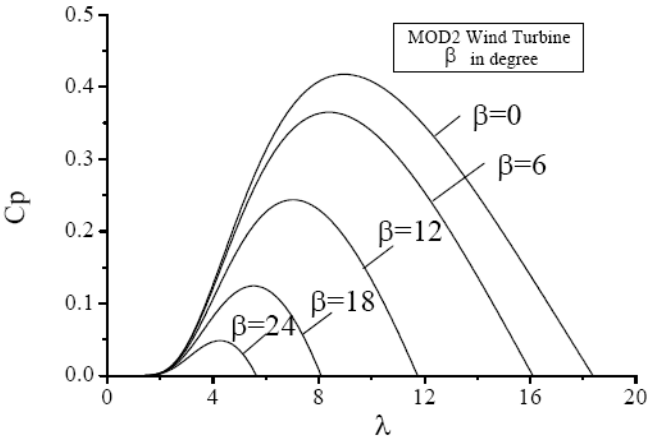


Fig. 6. C_P- λ curves for different values of pitch angle.

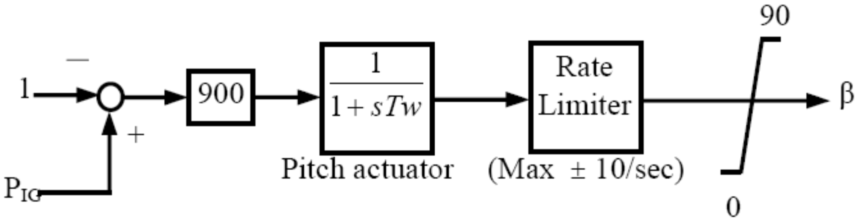


Fig. 7. Conventional pitch control system.

6. SIMULATION RESULTS

Simulations have been carried out to investigate the performance of the power system frequency with the increased wind power penetration using real wind speed data. The wind speed data is the real data, which was obtained in Hokkaido Island, Japan. The wind speed data applied to the wind generator is shown in Figure 8. Simulation analyses have been carried out for seven patterns shown in Table 7 in order to investigate the influence of the ratio of the wind generator capacity to the power system capacity, on the power system frequency. The simulation analyses have been performed using PSCAD/EMTDC [8].

Figures 9 and 10 show the output performances of IG and SG respectively for the cases 1-2. It is seen that SG output decreases as IG output increases. This is because the governors maintain the constant load with the variation of IG output variation according to the wind speed variations. Figures 11 and 12 show the output performances of IG and SG respectively for the cases 3-4. Similarly, Figures 13 and 14 show the output performances of IG and SG respectively for the cases 5-6. It is clear from Figures 9, 11, and 13 that though the wind generator output shapes are seem to be similar; however their output magnitudes (Figures 9, 11, and 13) are different as the capacities are different. Similarly through the SG output in Figures 10, 12 and 14 are seem to be similar pattern; however their magnitudes must be different. It is also seen that the output of SG in cases 1 to 6 is fluctuating in nature, because this generator is operated in governor free mode to control the frequency within a short period. Figure 15 shows the simulation results of hydro generator (SG1) and thermal generator (SG3). These outputs are comparatively smooth, because these generators are operated in load frequency control mode to control frequency for a long period.

Table 7. Simulation patterns.

Cases	IG	SG	Condition of switches	
			S1	S2
Case – 1	3 MVA	100 HG	ON	OFF
Case – 2	3 MVA	100 HG	ON	OFF
Case – 3	5 MVA	100 HG	ON	OFF
Case – 4	5 MVA	100 HG	ON	OFF
Case – 5	10 MVA	100 HG	ON	OFF
Case – 6	10 MVA	100 HG	ON	OFF
Case – 7	10 MVA	Multiple SGs, total capacity of 100 MVA	OFF	ON

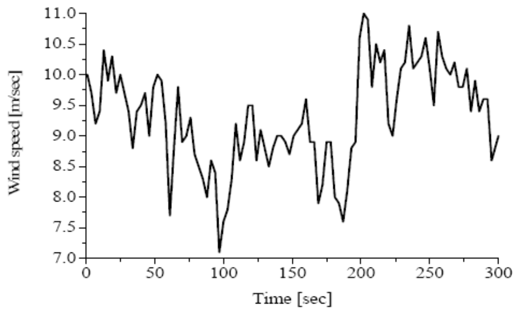


Fig. 8. Wind speed data.

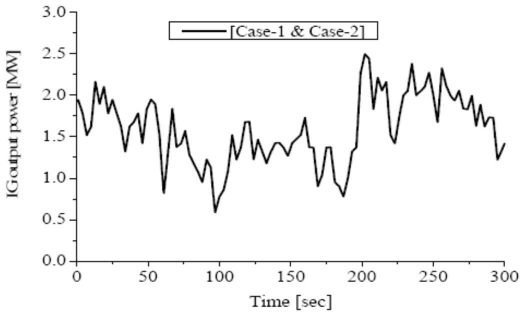


Fig. 9. Responses of wind generator output power.

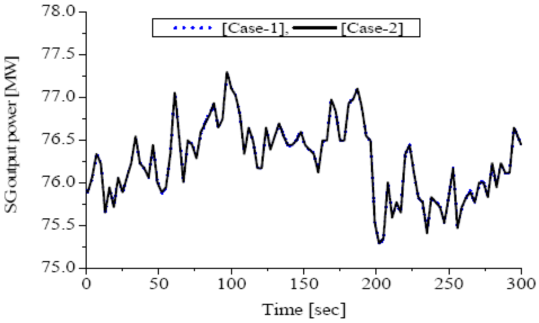


Fig. 10. Responses of SG output power.

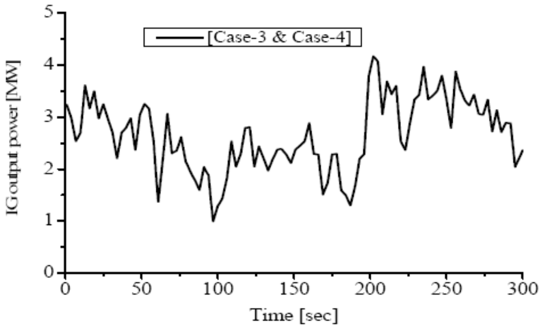


Fig. 11. Responses of wind generator output power.

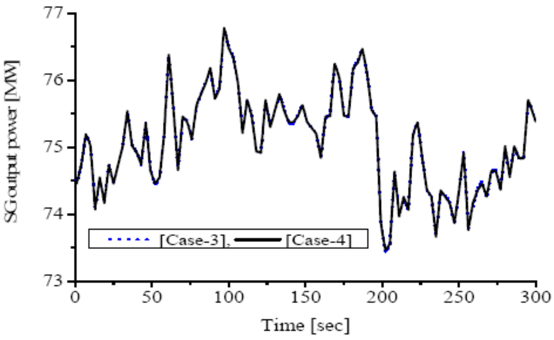


Fig. 12. Responses of SG output power.

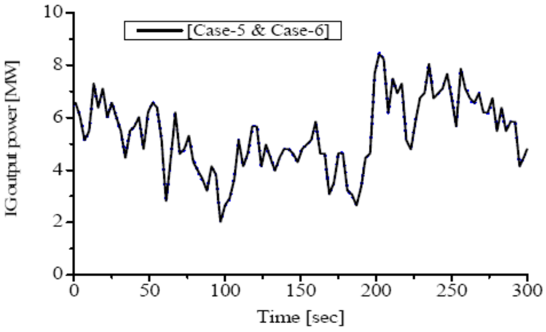


Fig. 13. Responses of wind generator output power.

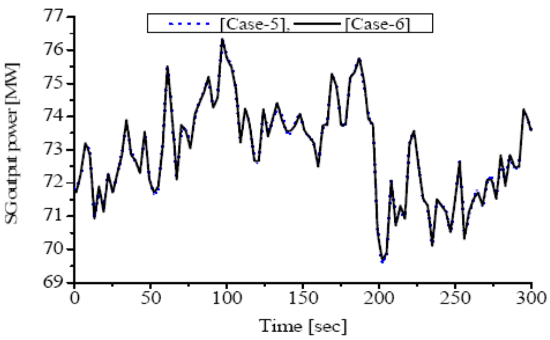


Fig. 14. Responses of SG output power.

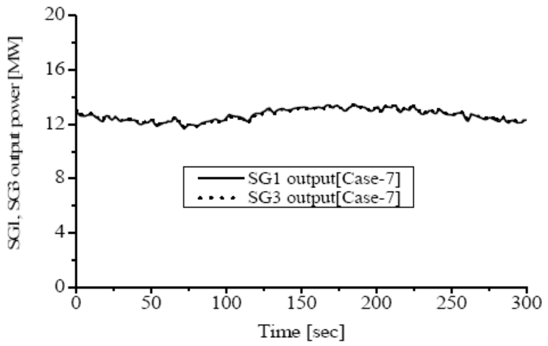


Fig. 15. Responses of hydro (SG1) and thermal (SG3) generators output power.

Figure 16 shows the simulation results of thermal generator (SG2) and nuclear generator (SG4). The output of SG2 is fluctuating so much, because this generator is operated in governor free control mode. Whereas the output of SG4 is maintained constant. Because, this generator is operated in load limit mode. Figure 17 to Figure 19 show the performances of the active power load for different cases. Figure 20 shows the responses of power system frequency for cases 1-2. It is seen that though the frequency fluctuation in case 1 is comparatively bigger than case 2 for 3% capacity of IG, but frequency fluctuation remains in the acceptable range.

Figure 21 shows the responses of power system frequency for cases 3 and 4, in which for the 5% IG capacity, SG cannot maintain the frequency to the acceptable range (50±0.2 Hz) for case 3. Figure 22 shows the responses of power system frequency for case 5 and 6. It is seen that for the 10% capacity of IG, SG cannot maintain the frequency to the acceptable range for both case 5 and 6, and system become severe. Actually, in a region power system is connected with different types of generators and they are operated in different control modes.

Figure 23 shows the responses of power system frequency for case 7, when generator SG1 (20 MVA) is operated in load frequency control mode, generator SG2 (30 MVA) is operated in governor free mode, generator SG3 (20 MVA) is operated in load frequency control mode and generator SG4 (30 MVA) is operated in load limit mode. It is seen from Figure 23 (case-7) that power system frequency becomes more severe than case 5 and 6. Finally, evaluation of results for power system frequency is shown in Table 8.

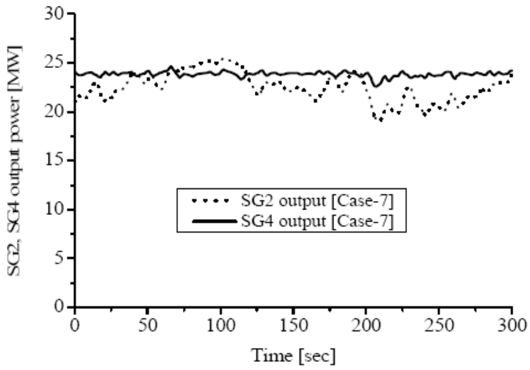


Fig. 16. Responses of thermal (SG2) and nuclear (SG4) generators output power.

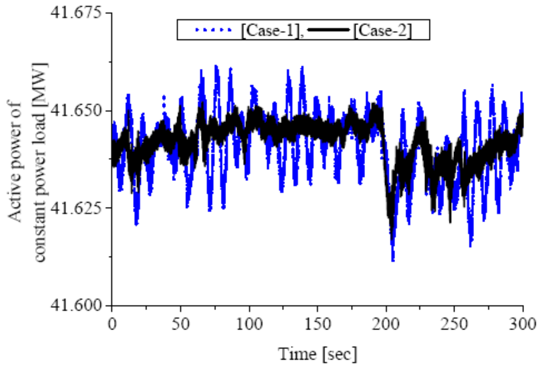


Fig. 17. Responses of constant power load.

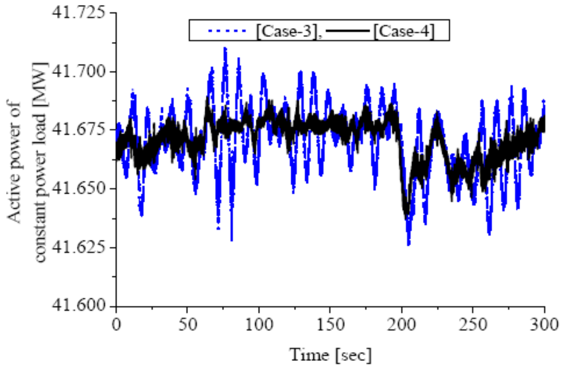


Fig. 18. Responses of constant power load.

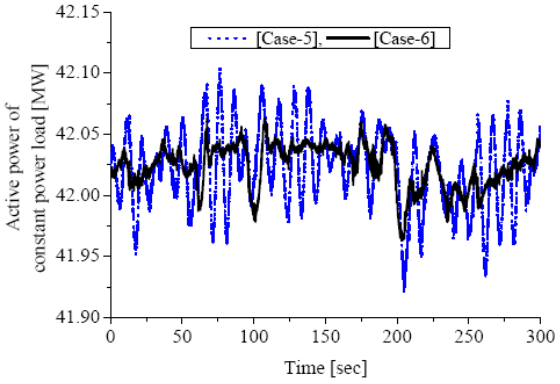


Fig. 19. Responses of constant power load.

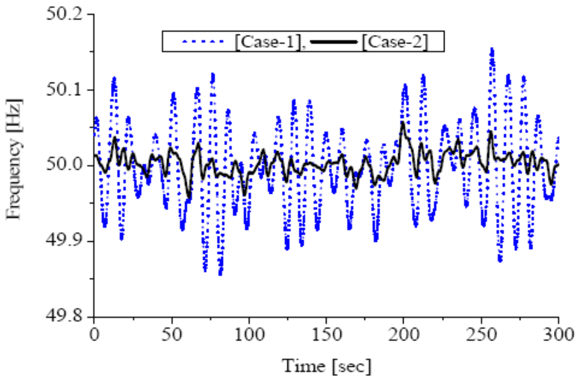


Fig. 20. Responses of power system frequency

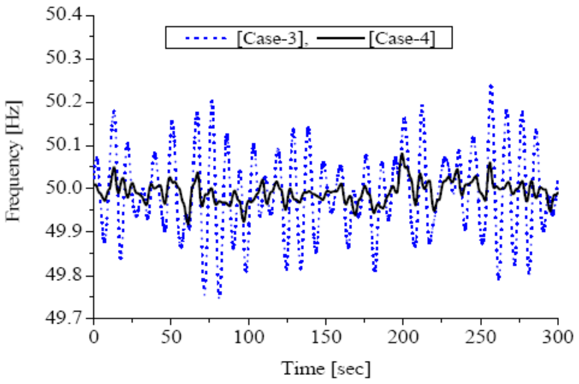


Fig. 21. Responses of power system frequency

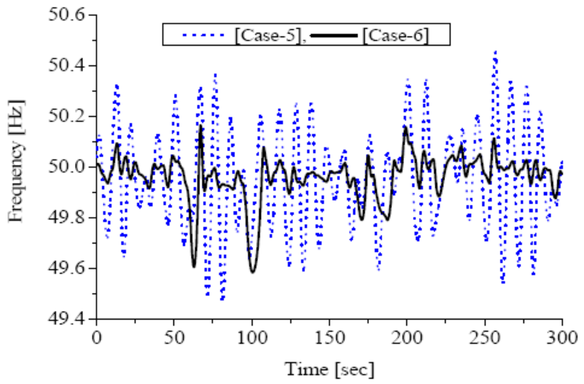


Fig. 22. Responses of power system frequency

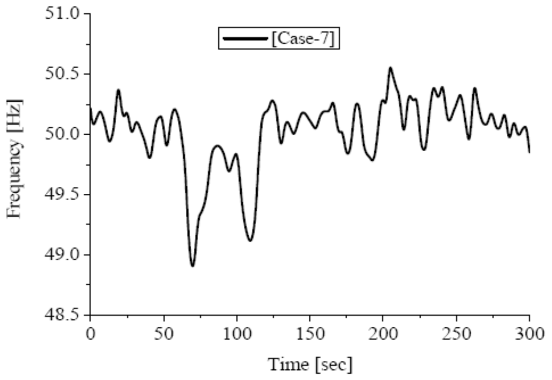


Fig. 23. Responses of power system frequency

Table 8. Evaluation of simulation results

Cases	’o’ and ’×’ of frequency fluctuations
Case-1	o
Case-2	o
Case-3	×
Case-4	o
Case-5	×
Case-6	×
Case-7	×

’o’ means within ± 0.2 Hz and ’×’ means beyond ± 0.2 Hz

7. DISCUSSION

A permissible range of the power system frequency deviation provided by the general electric utility industry law in Japan is within ±0.2 Hz. Evaluating the frequency responses (shown in Figures 20 to 23) based on this law, the results are shown in Table 8. In the case with the wind generator of 3 MVA and 5 MVA capacity, the frequency deviation can be controlled within ±0.2 Hz by the conventional pitch controller. But when hydro generator is used, frequency deviation cannot be maintained within the permissible range for 5 MVA capacity of wind generator. In the case (cases 5 and 6) with the wind generator of 10 MVA, the frequency deviation cannot be controlled within ±0.2 Hz by the conventional pitch controller, with either hydro generator (HG) or synchronous generator (SG). Also system frequency becomes more severe (as seen from Figure 23) when multiple generators with different governor control modes are used.

8. CONCLUSIONS

Since frequency is one of the measures to determine the quality of electric power, this paper focuses a very good study on power system frequency fluctuations with wind power penetration. Effects of the governor control system models of SG on system frequency fluctuations are also presented. It is seen that thermal governor can provide better performance than that of hydro governor; however, system frequency (case-7) of wind farm integrated power system seems to be severe when wind generator capacity about 10% of the total capacity. Therefore, it is confirmed that the wind power gives rise to fluctuations of system frequency more as the power capacity of wind power becomes large.

9. RECOMMENDATIONS

As the wind power penetration influences on power system frequency, some measures must need to be considered in near future by the power grid companies, to improve the reliability and quality of electric power. In these cases (i) new pitch control system can be used to improve the performance, up to a certain percentage of wind power, but the problem is that some energy need to be lost to maintain frequency, (ii) energy storage devices like battery energy storage system (BESS) [9], electric capacitor system (ECS) consisting of electric double layer capacitor (EDLC) [10] or superconducting magnetic energy storage (SMES) [11] system can reduce the fluctuation of output power without any loss of energy, but these devices are expensive. So, governor control with a combination of energy storage device and new pitch control system may be the good tool for reducing frequency fluctuations with large wind power penetration.

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