Co-ordinated Frequency Control of Power System with High Wind Power Penetration

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Abstract—**The inherent characteristics of randomness and uncertainty of wind energy would have a drastic effect on power system frequency along with the development of wind power. In order to share the burden with the frequency-regulating power plants, and to improve the power system stability, it is essential for wind farm to control the frequency. Therefore, the influences of different governor control system models have been investigated with different operating modes of synchronous generators (SGs), when a total capacity of SGs is considered as 100 MVA, to control frequency fluctuation. It is seen that output frequency fluctuation can also be maintained in the acceptable range by using several number of wind generators connecting in parallel instead of using a comparatively smaller capacity single wind generator. Real wind speed data have been considered for this study. PSCAD/EMTDC software is used for simulation analysis.**

Keywords—wind farm; single wind generator; power system frequency; governor control system model;

I. Introduction

From the very beginning it is noted that wind power saves money as well as energy and comes to a greater use of mankind. In regard to the development of human civilization, global energy consumption has increased by leaps and bounds to improve our living standards, particularly in the industrialized nations of the world. But it is a matter of great regret that, the world has limited amounts of fossil fuel and nuclear power resources. As a result, it is mandatory to introduce clean energy more and more in place of the fossil fuel. In this case 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 [1].

As wind turbine output is proportional to the cube of wind speed, the wind turbine generator output fluctuates due to wind speed variations. Further if the power capacity of wind generators becomes huge, the wind generator output can have an influence on the power system frequency [1-4]. In the conventional operation of wind power generator, the output of wind power generator is controlled at the rated value by a pitch control system when the wind speed is between the rated speed and the cut off speed. On the contrary, 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. Because of the proportionality of wind power to the cube of wind speed, the wind power generator output fluctuates due to wind speed variations in the latter condition. Thus, it is necessary to investigate the influence of the ratio of the wind generator capacity to the power system capacity, on power system frequency. Different studies have been considered in this regard in [1, 5]. 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 becomes 10% of total capacity. Therefore, a new pitch control system has been proposed in [2], however it causes energy losses. In [1, 6-9] different energy storage systems have been proposed, but these are not economical.

Therefore, this study investigates the effect of governor control model of SGs in minimizing frequency fluctuation. Again, as output power of wind generator can be smoothed by using multiple small size wind generators connecting in parallel instead of using single big size wind generator, the frequency fluctuation can also be maintained in this case. It is observed that, wind penetration can be increased more than 10% of the total capacity by maintaining frequency to the acceptable range while multiple wind generators can be considered instead of lower number of large generators.

II. Model System For Simulation Analysis

A. Model System

The model system used in the simulation analysis is shown in Fig 1. The model system consists of 5 wind generators IG [5], two switches, a hydropower generator, HG, a thermal power generator, TG and two loads.

Two switches S1 and S2 are used to connect the synchronous generator (SG) with the network. Here S1 is connected with the thermal governor generator and S2 is connected with the hydro governor generator. When only hydro governor generator (SG2, 100 MVA) is needed with the network, it is done by turning S2 switch ON and disconnecting other generator by turning S1 switch OFF. Similarly when thermal governor generator (SG1, 100 MVA) is needed S1 switch is turned ON and S2 is turned OFF.

When both generators are needed, S1 and S2 become turned ON. In this case the rated value of two generators is reduced from 100MVA to 50MVA to make a total capacity of 100MVA.

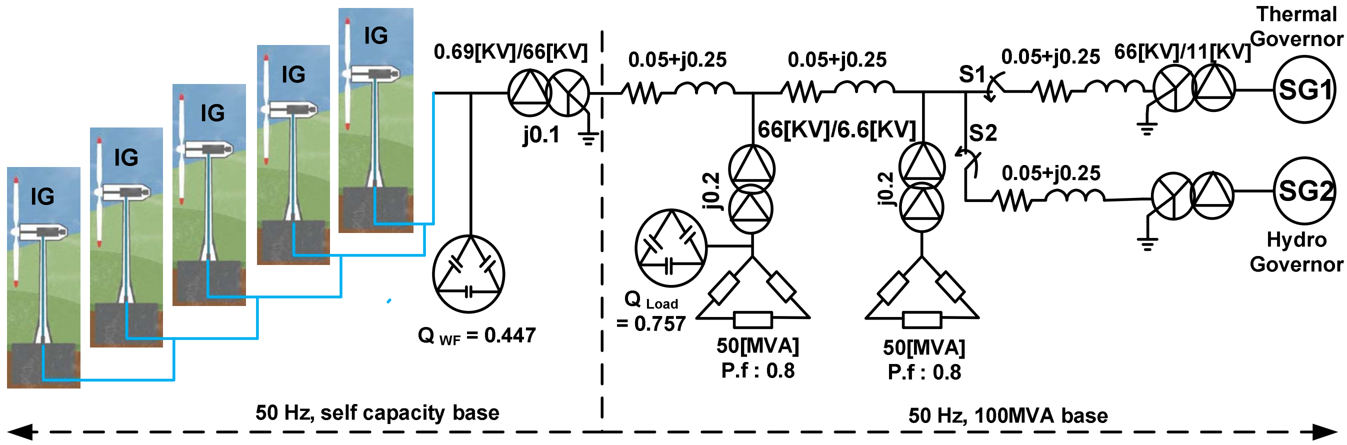

Fig. 1. Model system.

In the Fig. 1 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 generators at steady state. The value of the capacitors is chosen so that the p.f. becomes unity, when the wind generators are operated in the rated condition [5]. Q_{Load} is used at the terminal of load to compensate the voltage drop by the impedance of transmission lines. Core saturations of induction generators and synchronous generators are not considered for simplicity.

III. Synchronous Generator Model

A. Governor [5,10]

The governor is such a device which automatically adjusts the rotational speed of the turbine and the generator output. The turbine is operated at a constant rotational speed, when the generator load remains constant. 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 generators is prevented.

B. Governor for Hydro and Thermal Generators [5,10]

The governor models used in the simulation analyses are shown in Fig. 2 and Fig. 3, in which the values of 65M and 77M for hydro generator and thermal generator are shown in Table I and Table II respectively.

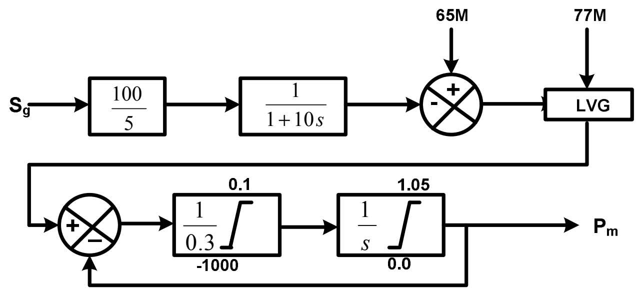

Fig. 2. Hydro governor.

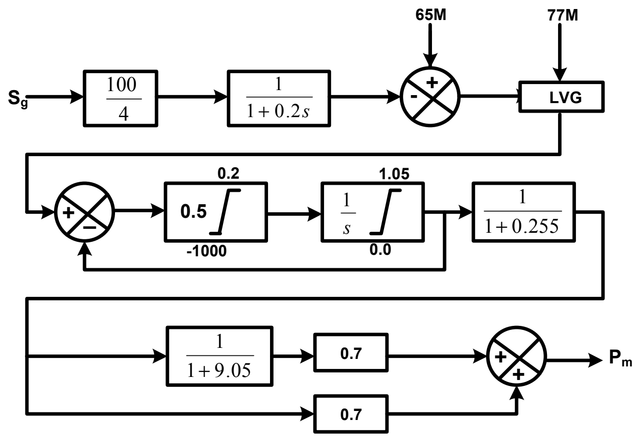

Fig. 3. Thermal governor.

TABLE I. Values of 65M and 77M for hydro generator

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

TABLE II. Values of 65M and 77M for thermal generator

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

C. Automatic voltage regulator (AVR) [5]

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

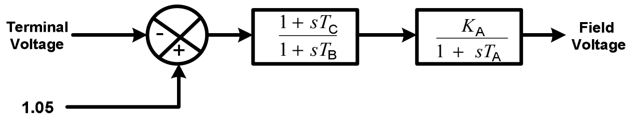

Fig. 4. AVR model.

TABLE III. PARAMETERS OF AVR

Gain, K_A [pu]	400
Time Constant, T_A [sec]	0.02
Time Constant T_B=T_C [sec]	0.00

IV. WIND TURBINE MODELING

In this paper, the MOD-2 model [11] is considered for the Cp-λ characteristics, which is represented by the following equations and shown in Fig. 5 for different values of β. 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 eq.(2) and eq.(3). Since C_P is expressed in feet and mile, Γ is corrected as eq.(4).

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

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

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

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

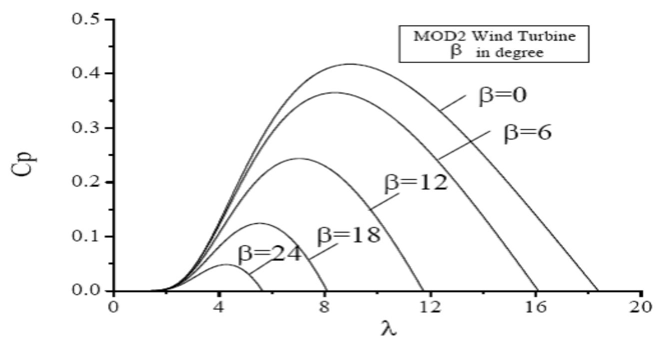

Fig. 5. C_P- λ curves for different values of pitch angle.

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

$$\tau_M = \frac{1}{2} \rho C_1(\lambda) \pi R^3 V_w^{\ 2} \tag{6}$$

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 Γ_M is the wind turbine output torque [Nm].

V. PITCH CONTROLLER

Conventional pitch controller as shown in Fig. 6 is used in the simulation analysis. 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 sec. In addition, the pitch angle can not 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.

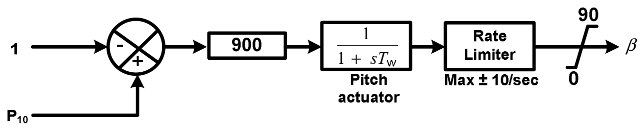

Fig. 6. Conventional pitch control system.

VI. SIMULATION ANALYSIS

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 are the real data, which were obtained in Hokkaido Island, Japan. The wind speed data applied to the wind generator are shown in Fig. 7. The conventional pitch controller as shown in Fig. 6 is used to maintain the output power as describe in section V.

In this study, simulation analyses have been carried out for nine different cases as shown in Table IV in order to investigate the effect of the power system frequency with the increased wind power penetration. The simulation analyses have been performed by using PSCAD/EMTDC [12].

TABLE IV. SIMULATION PATTERN

Governor	Cases	No of IGs	Rating of IGs [MVA]	Total Capacity
Hydro Governor	Case-1	1	15	15
	Case-2	3	5	
	Case-3	5	3	
Thermal Governor	Case-4	1	15	
	Case-5	3	5	
	Case-6	5	3	
Hydro + Thermal Governor	Case-7	1	15	
	Case-8	3	5	
	Case-9	5	3	

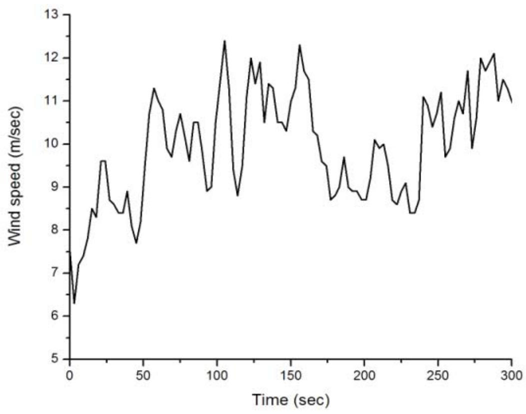

Fig. 7. Wind speed data.

Figures from 8 to 18 show the simulation results. Figures 8 & 9 show the output power variation for different cases (1-6) when hydro and thermal governor control systems are connected to the SG. It is noticed from both Figs. (8 and 9) that output fluctuations are comparatively smooth when multiple wind generators are connected to the system. Thus frequency fluctuation also reduced as seen from Figs. 10 and 11. It is also noticed from Figs.10-11 that frequency fluctuation can be more reduced by using more wind generators instead of using same total capacity single generator or less number of generators. Figures from 12 to 14 show the comparative (for similar cases) results for frequency fluctuation when hydro or thermal governor is connected with SG. It is observed from Figs. 12 to 14 that thermal governor is more effective to control frequency fluctuation compared to hydro governor. Thus frequency fluctuation can be reduced more by using thermal governor system.

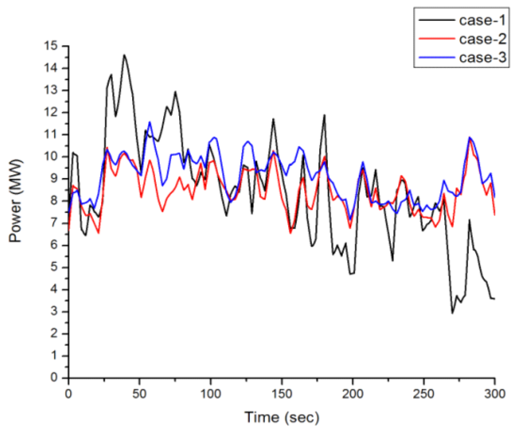

Fig. 8. Responses of active power for hydro governor system.

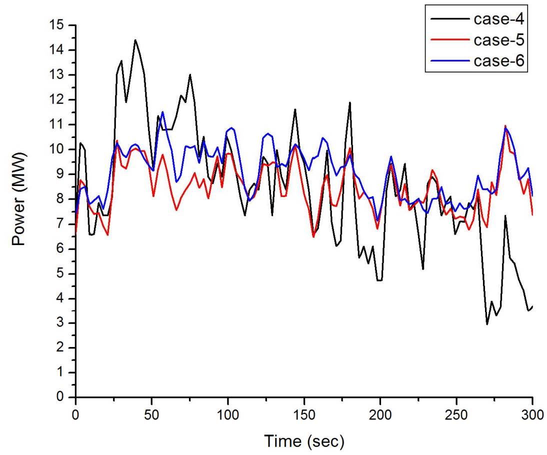

Fig. 9. Responses of active power for thermal governor system.

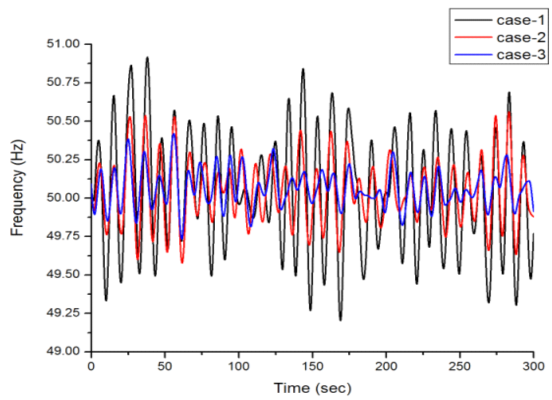

Fig. 10. Frequency fluctuation for hydro governor connected system.

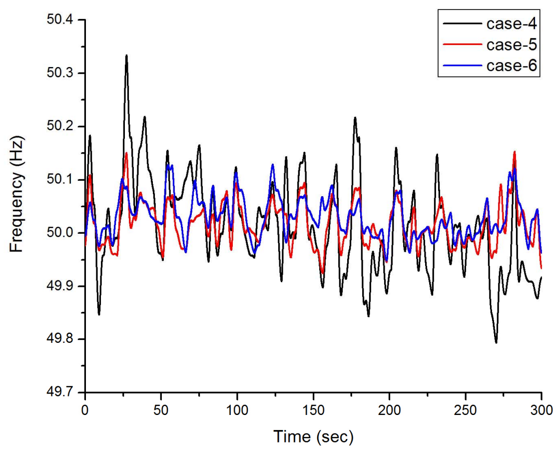

Fig. 11. Frequency fluctuation for thermal governor connected system.

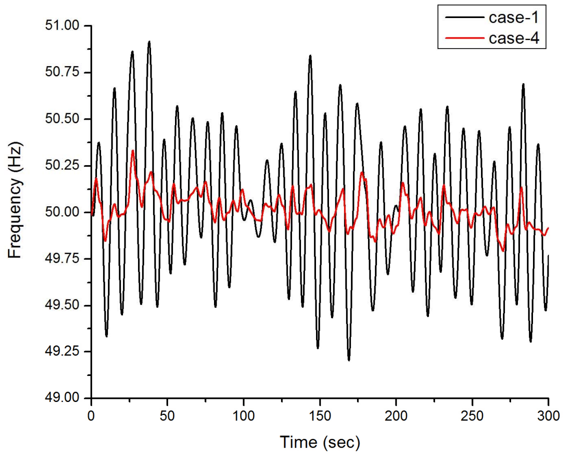

Fig. 12. Comparison of frequency fluctuation for hydro & thermal system.

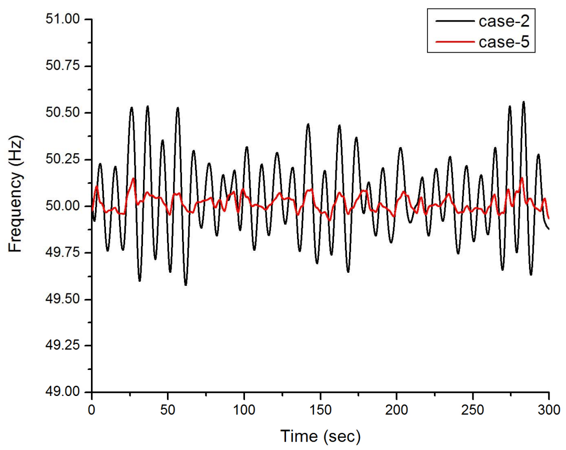

Fig. 13. Comparison of frequency fluctuation for hydro & thermal system.

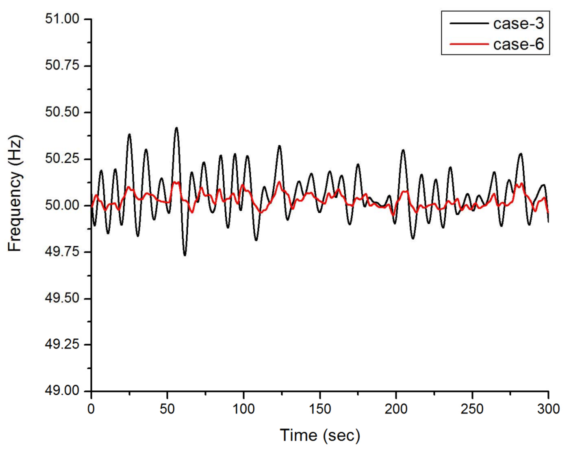

Fig. 14. Comparison of frequency fluctuation for hydro & thermal system.

Figure 15 shows the responses of active power for hydro-thermal system for different cases (7-9). Figure 16 shows the comparative results for frequency fluctuation. It is also seen that frequency fluctuation remains less when a multiple number of generators (case 9) are connected parallel with each other. A comparison is also made among thermal, hydro & hydro-thermal governor system, as seen from Fig. 17. It is clear from Fig. 17 that best result can be obtained when thermal governor with multiple generators are connected. Thus wind farm capacity can be increased more than 10% of the total capacity (about 15%) with maintaining frequency to the acceptable range (±0.2 Hz) as seen from Fig. 18.

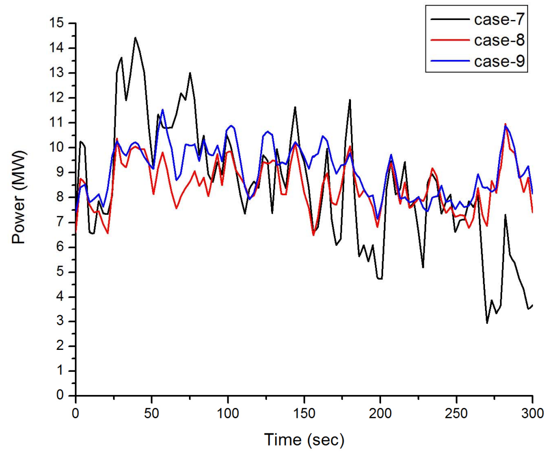

Fig. 15. Responses of active power for hydro-thermal system.

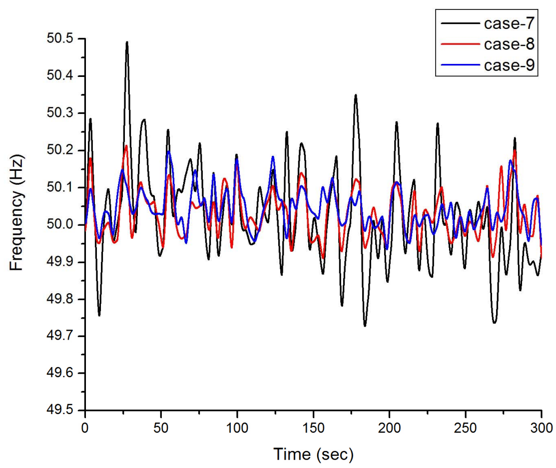

Fig. 16. Comparision of frequency fluctuation for hydro-thermal system.

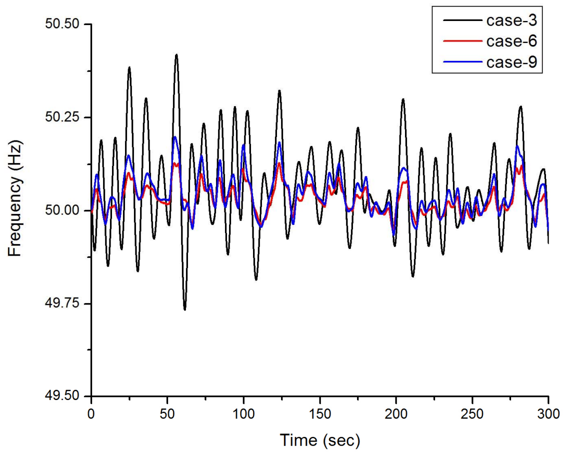

Fig. 17. Comparision of frequency fluctuation for hydro-thermal system.

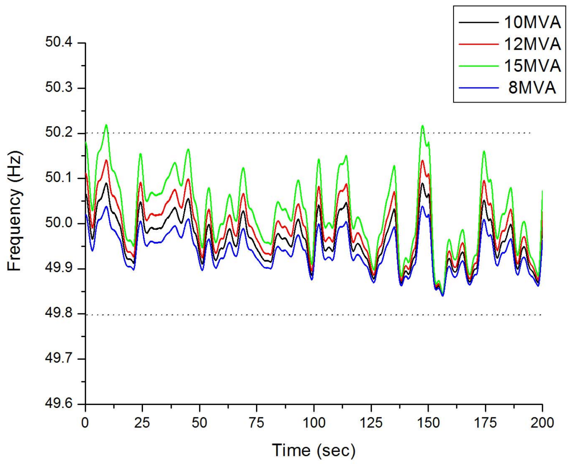

Fig. 18. Frequency fluctuation for different capacities with thermal governor.

VII. Conclusion

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 fluctuation with high wind power penetration. As a large number of wind farms are going to be connected with the utility network every year, wind power as well as frequency fluctuation caused by randomly varying wind speed is still a serious problem for power grid companies or transmission system operators. According to the research, it is seen that instantaneous frequency variation can considerably be reduced by coordinated control of governor with connecting multiple generators in parallel, which are easy to install and comparatively cost effective. It also can minimize the output fluctuations effectively during random wind speed variations. It is a matter of fact that for the case of thermal governor connected system frequency fluctuation is smaller than other governor.

VIII. References

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