

Frequency and Voltage Control by Decentralized Controllable Loads with Fuzzy Control

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Abstract—In recent years, amount of renewable energy facilities using wind turbine generator and photovoltaic power system have been increased due to natural environment and resource depletion. Moreover, all electrification apartment houses or residences and electric vehicles have been increased. However, due to the fluctuating power from renewable energy sources and loads, fluctuations of grid frequency and voltage become problematic. This paper presents a methodology of control system frequency and voltage by distributed controllable loads such as heat pump and electric vehicles. By applying power consumption controller using distributed fuzzy control for HP and H_∞ control for battery, fluctuations of grid frequency and voltage are suppressed around a desired value. In order to verify the effectiveness of the proposed system, MATLAB/Simulink is used for computed simulations.

keywords—frequency and voltage fluctuation, autonomous control, heat pump, distributed control, battery, H_∞ control.

I. INTRODUCTION

The amount of power generation utilizing renewable energy has shown an upward trend due to depletion of energy sources and consideration about environment [1, 2]. But, there are important issues of electric power quality due to change conditions of the weather. Additionally, the relation between power supply and demand becomes more complex by installing photovoltaic equipment in house and transition to all electric equipments. In small power system such as island, diesel generator is used as major source of electricity but it has high environmental issue and high unit price of power energy. Diesel generators have their limits with respect to maintaining the balance of supply and demand because diesel generators with governors have mechanical constraint. Moreover, due to the fluctuating power generation from renewable energy sources, frequency and voltage fluctuation are problematic in island power systems. Therefore provision is needed to control the system frequency and voltage.

As provision in supply side, installation of storage equipment and pitch angle control for wind generator have been proposed to control dispersed power system [3, 4]. However the installation of storage equipment that needs large storage capacity, and the cost of maintenance with quality degradation is expensive. In addition, wind generator is an obstacle for

output power leveling due to mechanical constraint of control mechanism and irregularity of energy. Hence, in case of large amount of renewable energy is connected to the power system, the electricity quality degrades by measuring only supply side.

In recent years, smart grid technology with power consumption control at the power demand side becomes an active area of new research. This technology allows bidirectional information transmission between supply side and demand side [5~7]. On the demand side, the transition to all-electrification in consideration of economy, safety, and use of heat pump water heater (HP) and electric vehicle (EV) that is suitable for the environment. Thus, power conditioning ability is increasing by these large capacity load connected to power system in the demand side [8, 9]. In addition, increase of equipment capacity for frequency and voltage control are not used for the electric power supplier.

This paper presents a method for system frequency control and voltage control using decentralized loads in a small power system based on smart grid. Decentralized controllable loads (HP, battery) are controlled to maintain the supply-demand balance, thereby suppressing frequency deviation. Also, terminal voltage control becomes possible by reactive power control of inverter connected to controllable loads that is introduced on the demand side. Since HP is limited by heating medium stabilization, it is necessary for each HP to start and stop separately at different timing. As the control method, HP is controlled with the probability distribution of storage water temperature and system frequency that are local information. By applying H_∞ control theory which makes controller design possible by considering a response characteristic of frequency domain of battery operate in super high-frequency domain. On frequency domain, diesel generator operates in low-frequency domain because of mechanical constraint. Within the low-frequency domain, HP operates separately at different timing, and suppressing frequency fluctuations. That helps to diesel generator is operated with rated output power, and it can operate with high efficiency. In addition, controllable load is operated with system frequency, terminal voltage and storage water temperature. Thus the control method are achieved without any communications. The effectiveness of the pro-

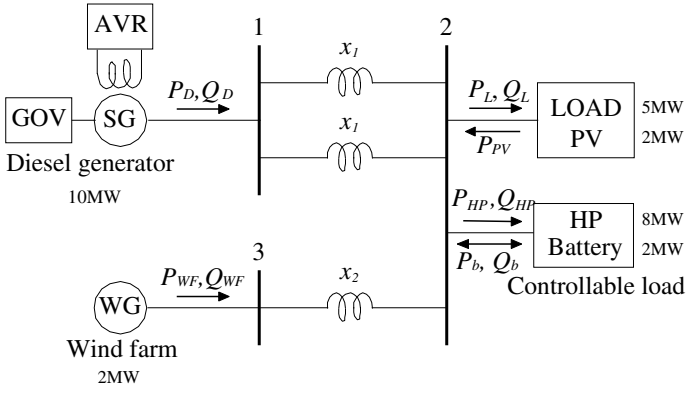


Fig. 1. Power system model.

Table 1. System constants.	
Diesel generator	
$H = 1.07$ s,	$x_d = 1.5$ pu, $x'_d = 0.30$ pu
$x_q = 1.06$ pu, $x'_q = 0.3$ pu,	$T'_{d0} = 3.7$ s,
$T'_{q0} = 0.21$ s, $T_G = 0.22$ s, $T_A = 0.329$ s	
Transmission lines	
$x_1 = 0.8$ pu, $x_2 = 0.3$ pu	
HP and Battery	
$K_{HP} = 0.00012$ pu, $T_B = 0.2$ s	

posed control system is validated by simulation results in MATLABTM.

II. MODELING

Fig. 1 illustrates a small power system. There are diesel generator, wind farm and photovoltaic in power system which supply electricity for load demand. They operate independently without communication large-scale power system. The system capacity is 10MW which is the base rule in Per Unit method. The system frequency is maintained constant at 60Hz by a diesel generator with governor. The diesel generator is modeled as a synchronous generator. The electrical and mechanical characteristics of the synchronous generator can be described by the following differential equations:

$$2H \frac{d\Delta\omega}{dt} = P_m - P_e \quad (1)$$

$$\frac{d\delta}{dt} = \Delta\omega \quad (2)$$

$$\frac{de'_q}{dt} = \frac{1}{T'_{do}} [e_{fd} - (x_d - x'_d)i_d - e'_q] \quad (3)$$

$$\frac{de'_d}{dt} = \frac{1}{T'_{q0}} [e'_d - (x_q - x'_q)i_q] \quad (4)$$

where H is the inertia constant, T_m is the mechanical input into generator, P_e is the generator output, δ is the angular phase difference, $\Delta\omega$ is the angular speed deviation, e'_d, e'_q are the transient voltage for the direct and quadrature-axis

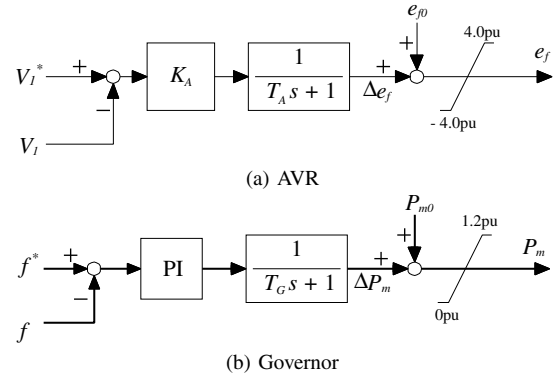


Fig. 2. Control block diagram of diesel generator.

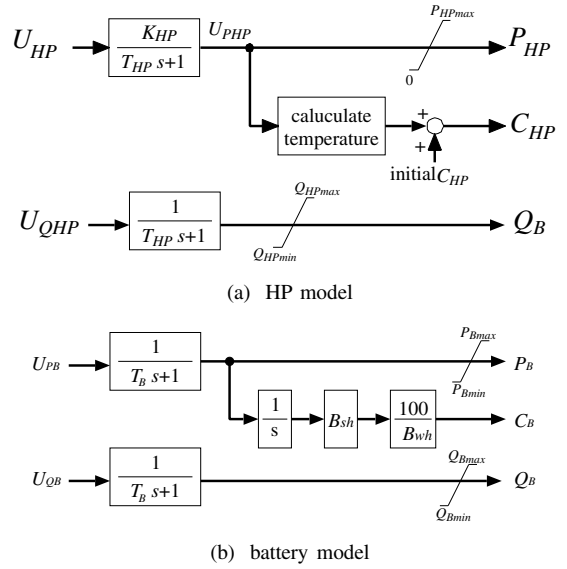


Fig. 3. Controllable load model.

of synchronous generator, e_{fd} is the excitation voltage converted to the q -axis, x_d, x_q are the d - and q -axis synchronous reactances, x'_d, x'_q are the d - and q -axis transient reactances, i_d, i_q are the generator terminal currents for the d - q axes, T'_{do}, T'_{q0} are the d - and q -axis open circuit transient time constant, respectively. The parameter values for each element are shown in Table 1. Fig. 2 illustrates control block diagram of diesel generator. Excitation using automatic voltage regulator (AVR) is modeled by first-order lag element shown in Fig. 2(a). Control composition of governor of diesel generator is shown in Fig. 2(b). System frequency control is achieved by mechanical input T_m of generator. The wind turbine generator and photovoltaic are modeled as fluctuation source because of output power is fluctuated by weather conditions. On supply side, wind farm (2MW) is introduced, and 800 photovoltaic panels (2MW) are introduced on demand side. As controllable load, heat pump (HP) group (8MW) and battery group (2MW) are introduced in power system, and its control system is explained in the next chapters.

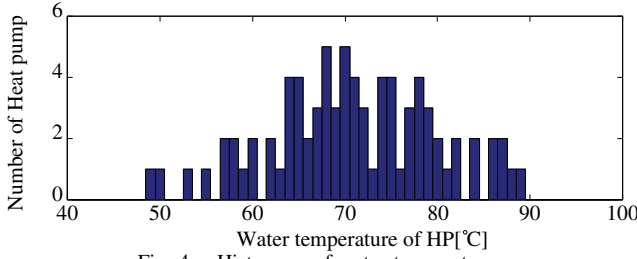


Fig. 4. Histogram of water temperature.

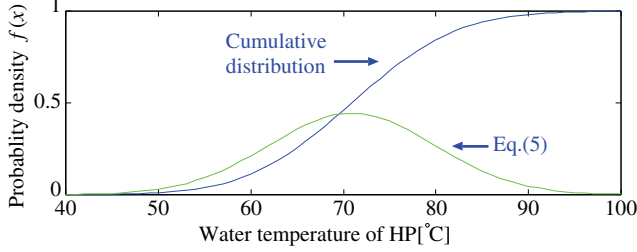


Fig. 5. Normal probability density distribution and cumulative distribution of water temperature.

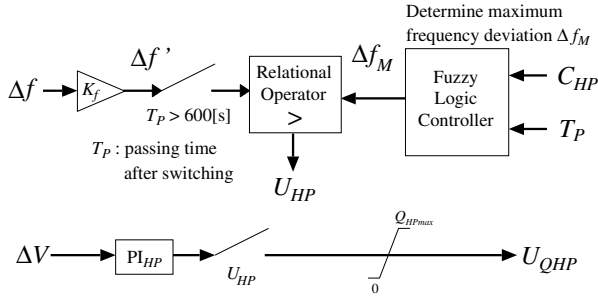


Fig. 6. Control block diagram of HP.

Table 2. Fuzzy rules

		C_{HP}			
		LR	L	H	HR
T_P	SR	LT	LR	L	ML
	S	LR	L	ML	MS
	L	ML	MS	S	SR
	LR	MS	S	SR	ST

LR=Lower ST=Smallest SR=Shorter LR=Longer
 LT=Largest SR=Smaller MS=Middle Small ML=Middle Large

III. CONTROLLABLE LOAD

The system frequency and terminal voltage fluctuations are suppressed by active and reactive power control with controllable loads. HPs and batterie are used as controllable load in this research. These electric appliances can be used as controllable load because their power consumption are adjustable and expend only during a given period of time. The decentralized HP model for houses is illustrated in Fig. 3(a). The water temperature of HP is controlled by feedback control with integral of power consumption under COP (coefficient of performance) is 4.0. The control block diagram is explained in the next section. The decentralized battery model is illustrated in Fig. 3(b). The discharge and charge operation are modeled as a first-order lag system, and charging rate is calculated by feedback control with integral of discharge and charge power consumption.

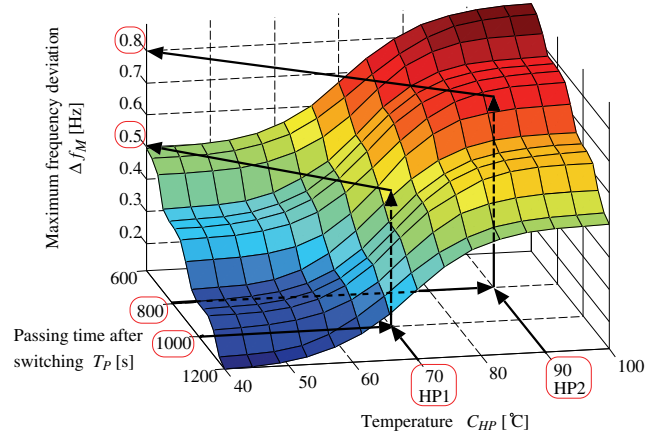
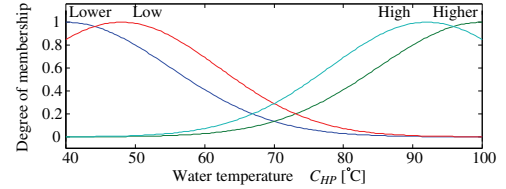
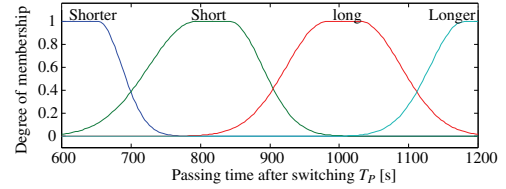


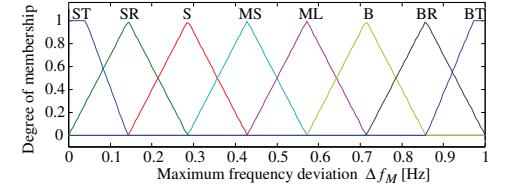
Fig. 7. maximum frequency deviation by fuzzy output response.



(a) Input variable of water temperature



(b) Input variable of passing time after switching



(c) Output variable of maximum frequency deviation

Fig. 8. Membership functions.

IV. DECENTRALIZED AUTONOMOUS CONTROL OF HP

A. Cumulative Distribution of Water Temperature

Each decentralized HP hold a unique water temperature, respectively, in power system. Those water temperature are produced by normal distribution random numbers shown in Fig. 4 as an average of 70 degrees °C. It can express the distribution of water temperature as a normal probability density distribution. The normal probability density distribution of water temperature is described by the following equation, and the normal probability density and its cumulative distribution are shown in Fig. 5.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{x - \mu}{\sigma} \right)^2 \right] \quad (5)$$

where σ is the standard deviation ($\sigma > 0$), x (C_{HP}) is sample, and μ is the mean value.

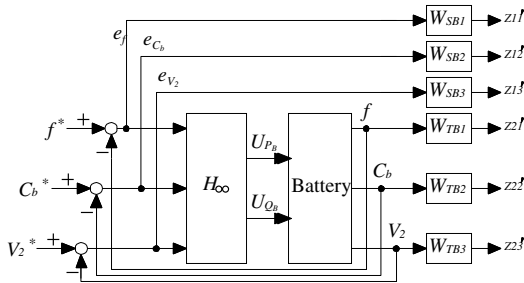
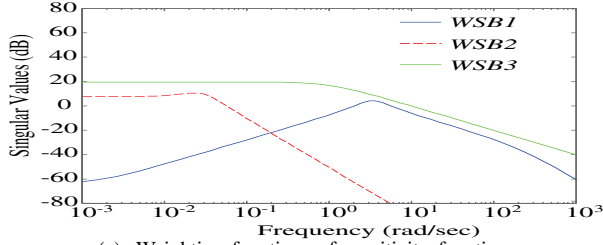
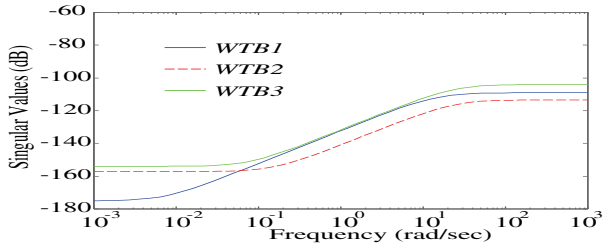


Fig. 9. Controller design of battery.



(a) Weighting functions of sensitivity function



(b) Weighting functions of complementary sensitivity function

Fig. 10. Weighting function for control of battery.

B. Control System of HP

First, it is necessary to show property of HP before saying about control method. HP provides heat to the storage water with compressing and inflating heating medium. Because of this process, HP needs a time that heating medium stabilize. In fact, it cannot be turn off for 10 minutes if it turns on once. For above-mentioned constrained behavior, each HP is switched on/off separately at different timing, and control frequency. In this study, decentralized autonomous control of HP is entertained by Fuzzy Logic ToolboxTM. By two input function of water temperature C_{HP} and passing time after switching T_P , each HP decides a maximum frequency deviation Δf_M shown in Fig. 6. Each HP switch to frequency fluctuation based on these maximum frequency deviations, and control frequency. And these passing time are produced by uniformly distributed pseudorandom numbers from 0 s to 1,200 s. Fuzzy output response is shown in Fig. 7. It is seen that switching priority is so high that water temperature is low, and passing time is long. Maximum frequency deviations respectively are decided as above, and when a signal $\Delta f'$ from Δf is approached to the maximum frequency deviation, HP control system of Fig.6 commands HP to switch. With this system, each HP is switched separately at different timing, and suppress frequency fluctuation. Fig. 8 illustrate fuzzy membership functions. Fig. 8(a) is designed to analogizing

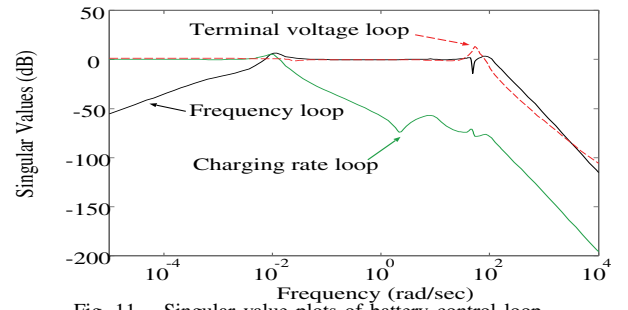


Fig. 11. Singular value plots of battery control loop.

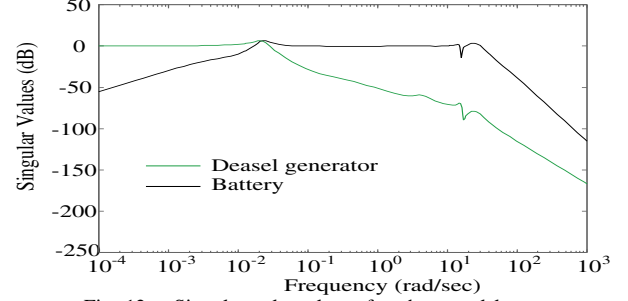


Fig. 12. Singular value plots of each control loop.

to cumulative distribution curve of water temperature, and it corresponds to distribution of water temperature. And Fig. 8(b) is designed that a maximum frequency deviation becomes smaller with increasing passing time.

V. BATTERY CONTROL METHOD

H_∞ control block diagram of battery is shown in Fig. 9. The weighting function W_{SB1} , W_{SB2} and W_{SB3} for frequency deviation e_f , the charging rate deviation e_{C_b} and terminal voltage deviation V_2 in battery are shown in Fig. 10(a). To suppress only high frequency component of frequency deviation, W_{SE1} for battery discharge and charge behavior is designed to have high gain in high frequency domain and is designed low in low frequency domain. W_{SB2} for charging rate control of battery is designed to have low gain against W_{SB1} . W_{SB3} is designed to suppress the terminal voltage. Where charging rate reference and terminal voltage reference are 50% and 1.0 pu, respectively. Weighting functions of complementary sensitivity function is decided the robustness against the disturbance as illustrated in Fig. 10(b). The linear matrix inequality (LMI) approach is applied to the design of the H_∞ controller [10~12]. The singular value plots of diesel generator and battery are illustrated in Fig. 11. It is seen that battery operates in high-frequency domain. Frequency loop of each controller are shown in Fig. 12. It is seen that diesel generator and battery operate in low-frequency and high-frequency domain, respectively.

VI. SIMULATION RESULTS

The simulation results show the effectiveness of system frequency control and voltage control by the power consumption control of decentralized controllable loads in demand side. Because of a simulation time, 160 HP operate in simulation, and all output of HP are adjusted to the realistic value

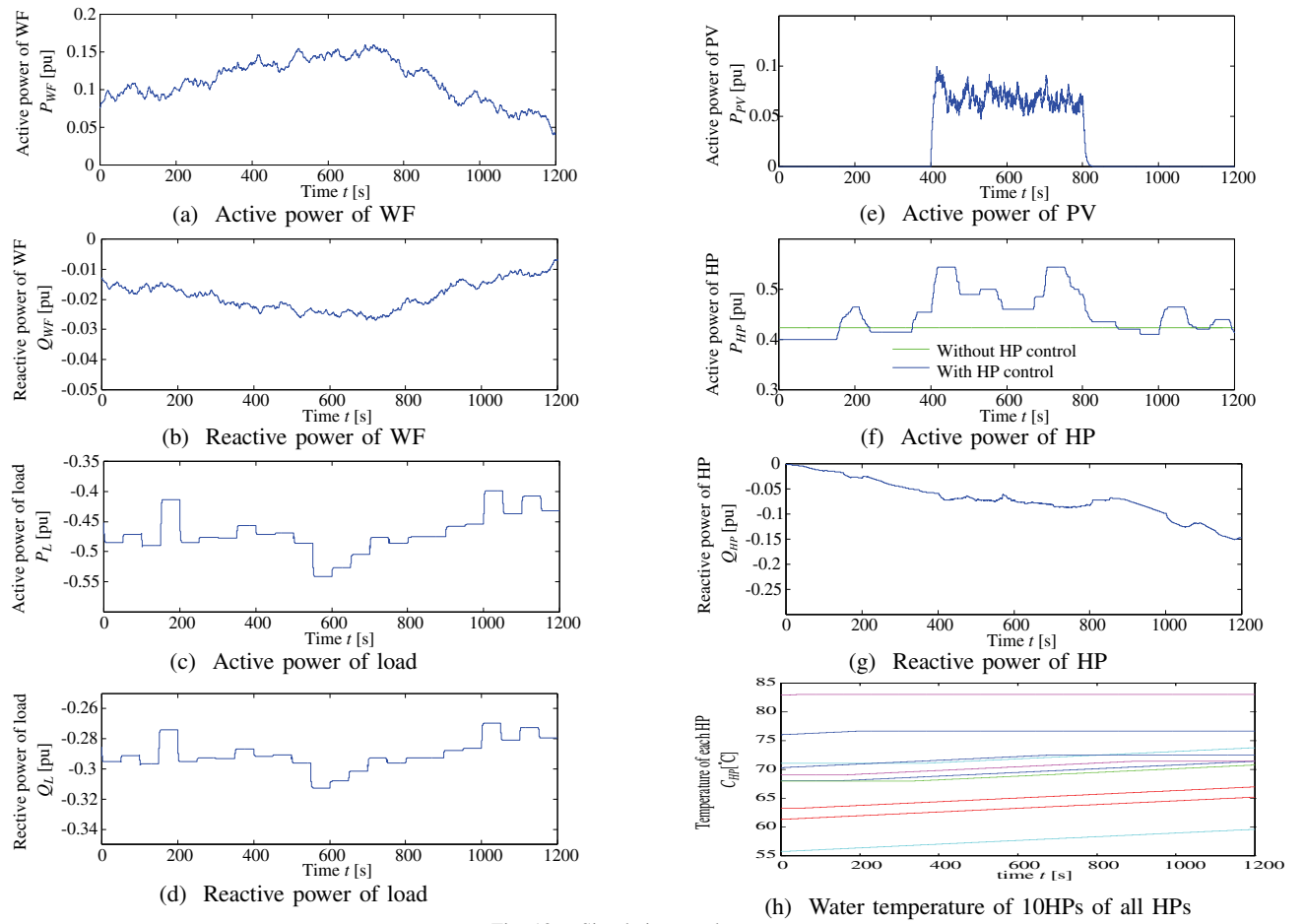


Fig. 13. Simulation results.

with gain multiple. The variation of wind farm output, non-controllable loads and photovoltaic outputs are assumed in this paper are shown in Fig. 13 (a)~(e), respectively. The wind farm output is assumed by long-period fluctuation in 40-minute and short-period fluctuation in seconds as shown in Fig. 13(a), (b). The non-controllable load power consumptions P_L , Q_L are changed to assume the on/off operation of electric appliance as shown in Fig. 13(c), (d). The white noise is used to represent drastic change of photovoltaic output P_{pv} as shown in Fig. 13(e). The power consumption P_{HP} of HP is changed to suppress low-frequency component of frequency fluctuation in power system as seen in control results of Fig. 13(f). The reactive power Q_{HP} of HP is changed to suppress voltage fluctuation at bus 2 as shown in Fig. 13(g). Also the water temperature C_{HP} of 10 HPs are raised up respectively as seen in control result of Fig. 13(h). Fig. 14(a) show number of HP on each states that waiting states to stabilized and controllable states. The discharge and charge power P_b of battery are changed to suppress high-frequency component of frequency fluctuation in power system as seen in control results of Fig. 14(b). It can be seen that charged rate of battery stays constant as shown in Fig. 14(c). The reactive power Q_b of battery is changing to suppress voltage fluctuation at bus 2 as shown in Fig. 14(d). In case of without control, the active

power P_d and reactive power Q_d of diesel generator fluctuate due to wind farm, photovoltaic and load variation are shown in Figs. 14(e), (f). Alternatively, when controllable loads are controlled, the diesel generator output P_d becomes smooth. The reactive power Q_d (Fig. 14(f)) also becomes smooth as well as active power. Therefore, it is seen that HP suppresses frequency fluctuation from low-frequency domain of diesel generator to low-frequency component in battery operating domain. Terminal voltage V2 of bus 2 is illustrated in Fig. 14(g). Although the terminal voltage fluctuates for the case where controllable load without control and with control, the voltage becomes smooth and are kept in rated range as seen in same figure. It can be seen that the system frequency deviation df stays constant in Fig. 14(h). Therefore, the effectiveness of system frequency control and voltage control by power consumption control of decentralized controllable load in demand side is confirmed.

VII. CONCLUSION

This paper presents a control system to achieve suppression of frequency deviation and voltage fluctuation by using controllable load that may steadily increase in demand side in future. The power fluctuation occurred due to disperse power system is suppressed by active and reactive power control of controllable loads. Therefore, controllable loads are

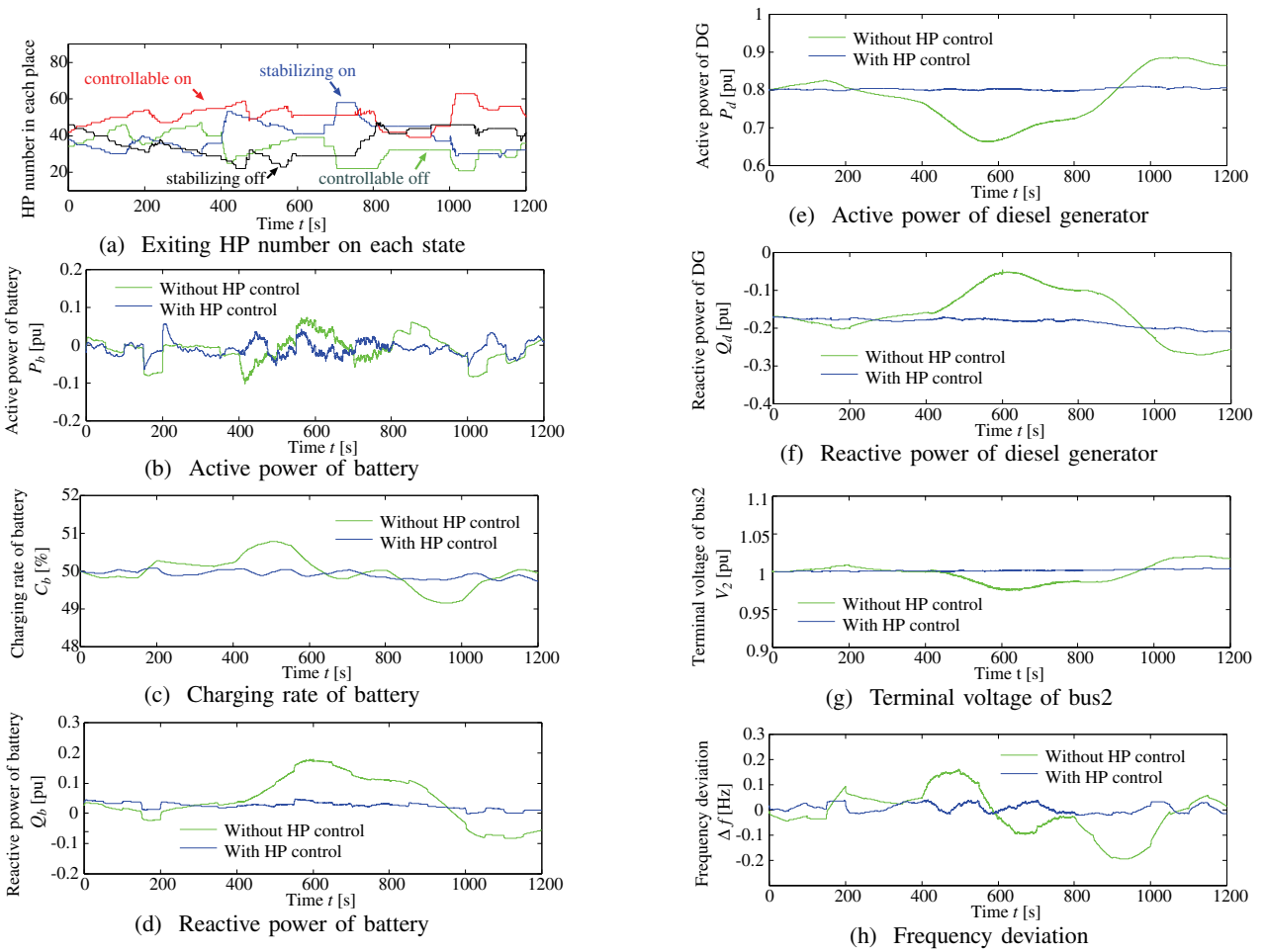


Fig. 14. Simulation results.

operated to suppress the power fluctuation, and the following are achieved without any communication: balancing of the supply-demand, generating power leveling of output power of diesel generator, and suppressing frequency fluctuation. There are advantages that wind turbine generator and photovoltaic generation enable to operate in maximum power point, equipment cost of battery is reduced and the ability to control the frequency is ensured. Consequently, electricity companies can expect to supply the high quality power and to reduce the capital cost.

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