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Frequency Control by Decentralized Controllable Heating Loads with H_∞ controller

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Abstrak

Banyak sistem daya kecil terisolasi yang dicatu oleh generator diesel, yang menghasilkan biaya operasi lebih besar daripada yang saling berhubungan ke grid yang besar. Oleh karena itu diinginkan untuk mengintegrasikan sumber energi terbarukan seperti tenaga angin ke dalam grid kecil. Namun, karena pembangkit listrik berfluktuasi dari sumber energi terbarukan, penyimpangan frekuensi sistem tenaga menjadi bermasalah. Kendali beban terdistribusi cerdas dapat digunakan untuk meningkatkan penetrasi energi terbarukan secara signifikan dan mengurangi konsumsi bahan bakar solar. Makalah ini menyajikan suatu metodologi untuk kendali frekuensi grid dengan pemanas air listrik sebagai beban terkendali. Sistem ini terdiri dari generator diesel, wind farm, dan beban. Dengan menerapkan sebuah pengendali konsumsi daya yang diadopsi dari teori kendali H∞, deviasi frekuensi grid dipertahankan di sekitar nilai kapasitas. Verifikasi efektivitas dari sistem yang diusulkan digunakan MATLAB / Simulink untuk simulasinya.

Kata kunci: *beban terkendali, deviasi frekuensi, kendali H_∞, catudaya seimbang, galat catudaya*

Abstract

Many isolated small power systems are powered by diesel generators, which results in greater operating costs than interconnected large grids. It is therefore desirable to integrate renewable energy sources such as wind power into these small grids. However, due to the fluctuating power generation from renewable energy sources, frequency deviations of power systems become problematic. Distributed intelligent load control can be used to significantly increase renewable energy penetration and cut diesel fuel consumption. This paper presents a methodology for grid frequency control by electric water heaters as controllable loads. This system consists of diesel generator, wind farm, and loads. By applying a power consumption controller adopted from H_∞ control theory, grid frequency deviation is maintained around rated value. In order to verify the effectiveness of the proposed system, MATLAB/Simulink is used for simulations.

Keywords: *controllable load, frequency deviation, H_∞ control, supply balance, supply error*

1. Introduction

Behind the steady increase in demand for energy that is envisaged in the future are reasons for electric power development for various utilities, including buildings and electric vehicles. These, however, increase the chances for rapid fluctuations of power loads. Demand for energy has shown an upward trend in most of the islands, which are supplied by diesel generators.

But, heavy fuel oil which is used on diesel electric power generation is expensive for unit price of generated output due to cost of transportation and hoarding. Additionally, such power generation exerts a bad influence on the environment due to use of heavy fuel oil to generate electricity. Wind generation and photovoltaic generation using natural energy have attracted attention from depletion issue of energy resource and foresight to environment. In the future wind power facilities connected to small grid on islands can get good wind because of wind power generation and photovoltaic generation with the aim of each being respectively

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3,000,000kW and 820,000kW, in Japan by 2010. However, due to the fluctuating power generation from renewable energy sources, voltage and frequency deviation of the power system become problematic.

In cases where above-mentioned electric power fluctuation occur in small power systems as on islands, diesel generators are used to control the frequency to maintain the balance of supply and demand by governor free operation [1]. But diesel generators have their limits with respect to maintaining the balance of supply and demand because diesel generators with governors have automatic constraint. On the other hand, pitch angle control on wind generator has been proposed for control of dispersed power system [2], but sometimes interfere with output power leveling by automatic constraint of control mechanism and irregularity of wind energy. There is power consumption control of decentralized controllable loads on the load side as another method for frequency deviation control to maintain the balance of supply and demand [3]. In fact, there is a specific example that power consumption control of home electric appliances for each customer on some island in Britain [4]. In addition, it is effective that control to suppress the frequency deviation using electric vehicle with storage battery not mere load which may steadily increase as controllable load in the load side in the future.

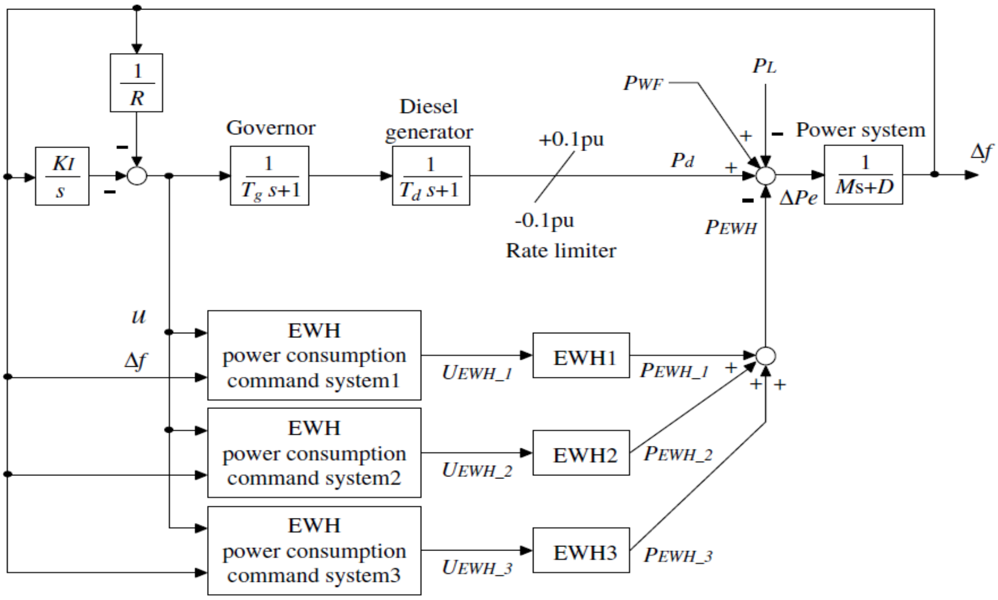


Figure 1. Power System Model

This paper presents a method for system frequencycontrol using decentralized loads in a small power system. Decentralized controllable loads are controlled to maintain the balance of supply and demand, thereby suppressing frequency deviation. To control, H_∞ control theory is used in this paper which possible controller design about consider a response characteristic of frequency domain. Controllable loads which have a short time constant expend energy in load side to suppress the high-frequency component of supply error. Diesel generator which has long-time constant is controlled to suppress the slowly varying component of supply error. Electric water heater is used as controllable load in this paper, and the effectiveness of the proposed control system is validated by simulation results in MATLAB.

2. Power System Model

Figure 1 illustrates the small power system proposed in [5]. There are diesel generator and wind farm in small power system which supplies electricity for power demand. They operate independently without connection with large-scale power system as the general electric power supplier; the system capacity is 20MW which is the fundamental base in Per Unit method. There are 600electric water heaters in the proposed system whose total capacity is 3.24MW represents 16.2% of system capacity. Flat frequency control method is used for frequency control of the power system. This method controls the output of diesel generator to control frequency deviation Δf of system frequency toward zero. P_d, P_{WF}, P_L, P_{EWH} in Figure 1 represent the output power of diesel generator, output power of wind farm, all power consumption except electric water heater, and power consumption of electric water heater, respectively:

$$P_d + P_{dis} - P_{EWH} = \Delta P_e \quad (1)$$

$$P_{dis} = P_{WF} - P_L \quad (2)$$

where P_{dis} and ΔP_e represent the difference between output power of wind farm and power consumption, and supply error. Frequency deviation Δf is computed using the transfer function in Figure 1.with supply error generated in the power system.

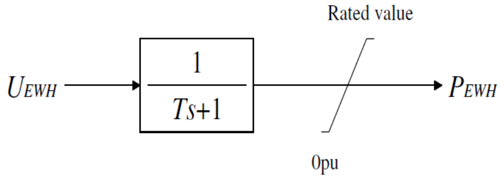


Figure 2. EWH Model

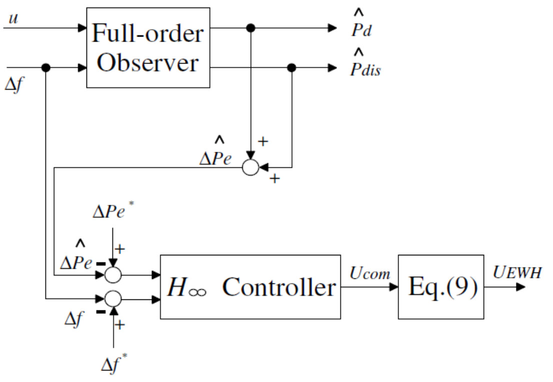


Figure 3. EWH power consumption command system

3. Electric Water Heater EWH

Electric water heater is used for hot water supply of the home. The standard is a 370l type with 4.4kW heater, to heat the water until between 55°C (summer) and 85°C(winter) using midnight power. The electric water heater model is illustrated in Figure 2. The electric water heater is modeled as a first order lag system, and time constant T is0.1s. There are 600 electric water heaters are decentralized in system, with rated power consumption of, respectively,4.4kW (EWH1), 5.4kW (EWH2), and 6.4kW (EWH3).

4. EWH Power Consumption Command System

EWH power consumption command system is to control the power consumption of EWH and its configuration is described in this section. Imbalance of supply and demand occurs at the small power system from fluctuation for output power of wind farm and power consumption of load, when it is resolved, then frequency deviation is suppressed. EWH power consumption command system is illustrated in Figure 3. The supply error ΔP_e and frequency deviation Δf are desired to be zero. First the supply error is estimated by estimated result from full-order observer as explained in the next section. Next, controller is designed to control the EWH power consumption using estimated supply error $\Delta\hat{P}_e$ and frequency deviation Δf. H_∞ controller using H_∞ control theory is designed in order to decide the quantitative evaluation of control performance on the frequency domain. The proposed method is examined by comparing with use of PI controller and H_∞ controller in the simulation outcome.

4.1.Design of Full-order observer

The full-order observer is configured to estimate the supply error ΔP_e in the power system by constructing the state equation for power system model as illustrated in Figure 1. Output power of diesel generator and disturbance of power system, P_{dis}, are estimated using frequency deviation Δf and input signal of governor u which can compute from frequency deviation Δf. The state equation has the form:

$$\left.\begin{aligned}\dot{\boldsymbol{x}} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}u\\ y &= \boldsymbol{C}\boldsymbol{x}\end{aligned}\right\} \tag{3}$$

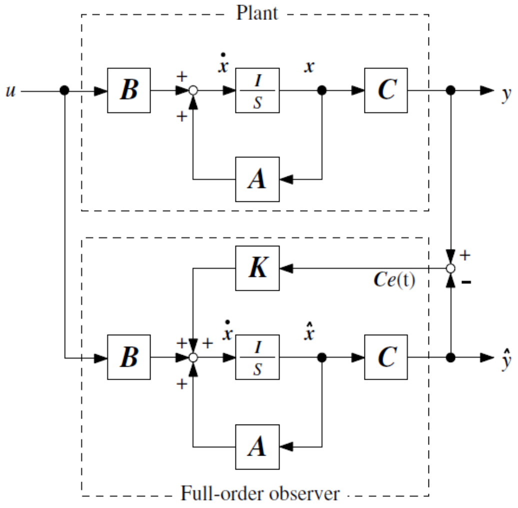


Figure 4. EWH Model

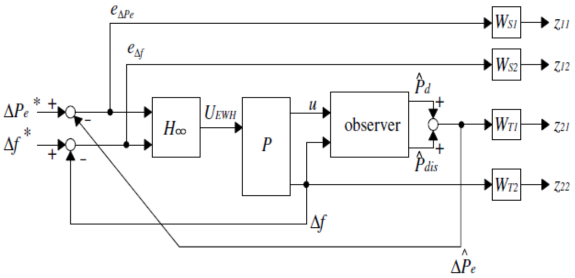


Figure 5. EWH power consumption command system

$$\boldsymbol{A} = \begin{bmatrix} -D/M & 1/M & 0 & 1/M \\ 0 & -1/Td & 1/Td & 0 \\ 0 & 0 & -1/Td & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

$$\boldsymbol{B} = \begin{bmatrix} 0 \\ 0 \\ 1/Tg \\ 0 \end{bmatrix} \tag{5}$$

$$\boldsymbol{C} = [1 \quad 0 \quad 0 \quad 0] \tag{6}$$

where **x** is the state variable vector, x_1, x_2, x_3, x_4 represent frequency deviation Δf, output of diesel generator P_d, output of governor, disturbance of power system $P_{dis}=P_{WF}-P_L$, respectively. Full-order observer is configured by the followingequation and block diagram is illustrated in Figure 4.

$$\dot{\hat{\boldsymbol{x}}} = \boldsymbol{A}\hat{\boldsymbol{x}}(t) + \boldsymbol{B}u(t) - K\boldsymbol{C}e(t) \tag{7}$$

Where the poles of the observer (γ_1=-80, γ_2=-0.2, γ_3=-10, γ_4=-60) are decided by a good estimate. Supply error $\Delta\hat{P}_e$ is estimated by estimated value of output power of diesel generator $\hat{P}_d$ and estimated value of disturbance of power system $\hat{P}_{dis}$ using the following equation

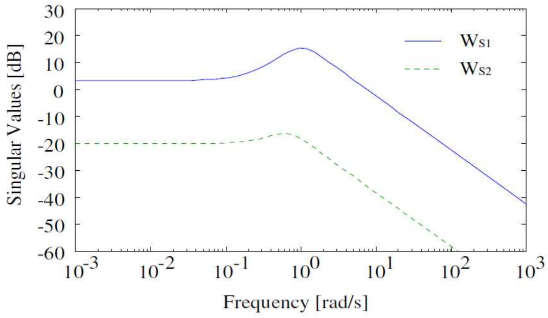
$$\Delta\hat{P}_e = \hat{P}_d - \hat{P}_{dis} \tag{8}$$

It is used the decision of input signal for controller which is explained in the next section.

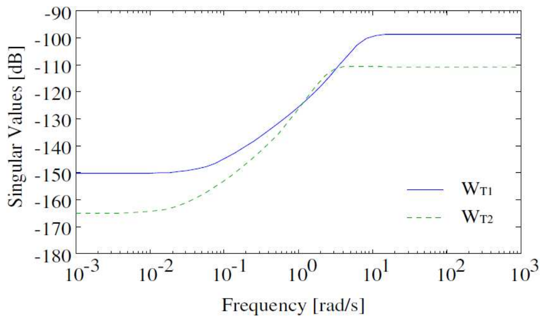
4.2 Design of H∞ controller

Two-input one-output H∞ controller is designed in this section. Input of H∞ controller is $e_{\Delta Pe}$ and $e_{\Delta f}$, where $e_{\Delta Pe}$ is difference between supply error $\Delta\hat{P}_e$ and command value of supply error ΔP* e which is always 0,$e_{\Delta f}$ is difference between frequency deviation Δf and command value of supply error Δf*which is always0. Linear matrix inequality (LMI) approach [6]-[10] is applied to the design of the H_∞ controller. Controller configuration is illustrated in Figure 5. The following are the design goals:

- On the load side, EWH expend energy to reduce the high-frequency component of supply error. Weighting functions of sensitivity function W_{S1}, $W_{S2}$are selected so as to high sensitivity at the high frequency component.
- On the generator side, diesel generator generates power to reduce the low-frequency component of supply error. Weighting function of sensitivity functionW_{S1}, $W_{S2}$is selected so as to low sensitivity at the low-frequency component of supply error.



(a) Weighting functions of sensitivity function



(b) Weighting functions of complementary sensitivity function

Figure 6.Singular value plots of weighting functions

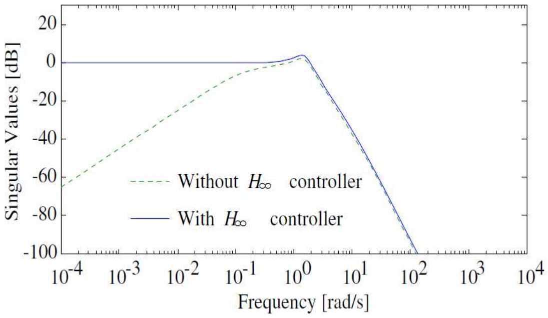


Fig. 7 Singular values plot of diesel generator

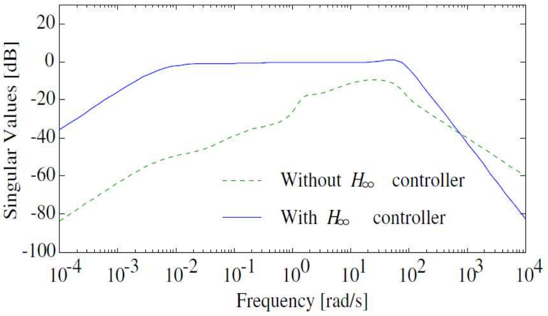


Figure 8.Singular values plot of EWH

Weighting functions W_{S1}, W_{S2}, W_{T1}, and WT2are selected by design goals in Figure 5 as illustrated in Figure 6(a),(b). Weighting functions of sensitivity function W_{S1},W_{S2}determine the command value following capability as illustrated in Figure 6(a). Weighting functions of complementary sensitivity function W_{T1}, W_{T2}decide the robustness against the disturbance as illustrated in Figure 6(b). Robustness for parameter variation is examined in the next section. Singular value plots of diesel generator and EWH for before-after the additional controller are illustrated in Figure 7, and 8, respectively. From singular value plots of diesel generator after controller addition as shown in Figure 7, the diesel generator generates to reduce the low-frequency component of supply error by gain of diesel generator that is maintained constant at zero at the low-frequency component. From singular value plots of EWH after controller addition as shown in Figure 8, EWH can operate to reduce the high-frequency component of supply error by singular value plots of EWH as configured at the high-frequency domain compared to singular value plots of diesel generator. Electricity consumption of EWH has low sensitivity at the low-frequency component of supply error by gain of EWH declining at the low frequency domain.

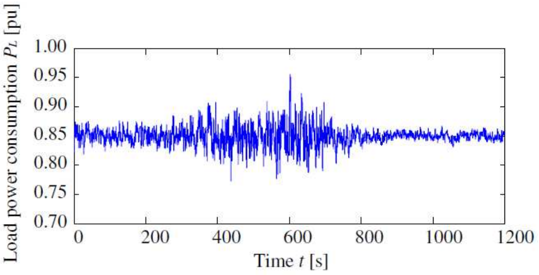


Figure 9. All power consumption except EWH

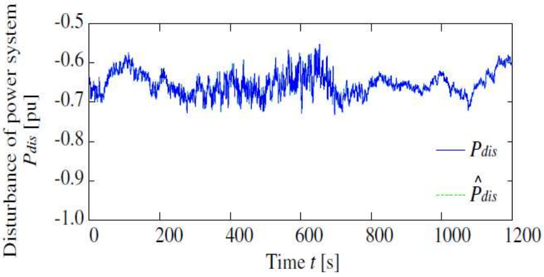


Figure 11. Disturbance of power system and estimated value

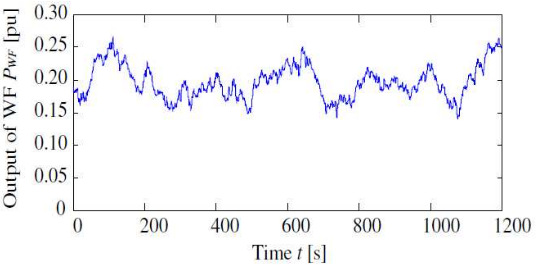


Figure 10. WF output power

Table 1.Simulation Parameters

inertia constant M	0.1 puMW·s/Hz
damping constant D	0.12 puMW·s/Hz
governor time constant Tg	0.1 s
diesel generator time constant Tg	5.0 s
EWH time constant T	0.1 s

4.3 Distributed control

EWH group power consumption is controlled by decentralized controller that depends on each capacity. In other words, command value for determining the power consumption of EWH is chosen according to capacity of EWH. The following equation decides the power consumption command value of EWH from the foregoing concept:

$$U_{EWH\_N} = P_{EWH\_maxN} \times \eta + \left(\frac{P_{EWH\_maxN}}{2}\right) \tag{9}$$

$$\eta = \frac{U_{com}}{\sum_{N=1}^{N} P_{EWH\_maxN}} \tag{10}$$

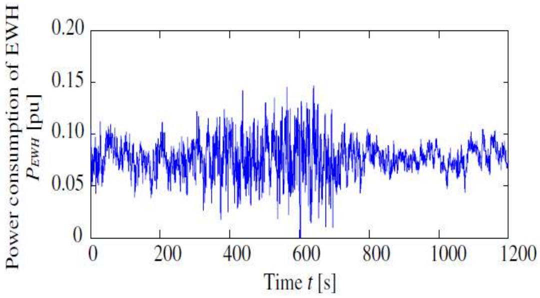
where P_{EWH_maxN} and η represent rated power consumption of EWH and proportion to P_{EWH_maxN}.

5. Simulation Result and Discussion

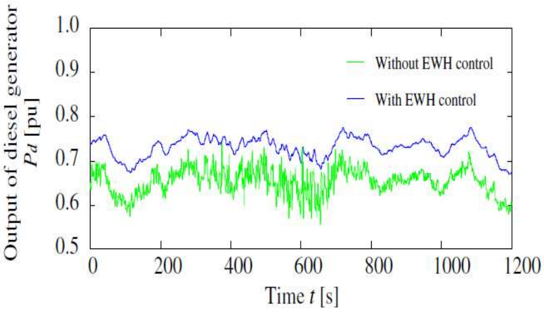
The simulation results show the effectiveness of system frequency control by power consumption control of decentralized controllable load in load side. In EWH power consumption command system, H_∞ controller is compared with using PI controller for simulation. Table 1 shows the parameter of the power system used in the simulations.

Variations of all power consumption except EWH and output power of wind farm are assumed in this paper as shown in Figure 9 and 10. Power consumption of load as shown in Figure 9 has sharp fluctuation between about 400sand 800s. Moreover, wind farm is assumed to operate at peak power and simulated with random fluctuation. The full-order observer running for good estimate as seen in Figure 11 illustrates disturbance P_{dis} and the estimated value $\hat{P}_d$.

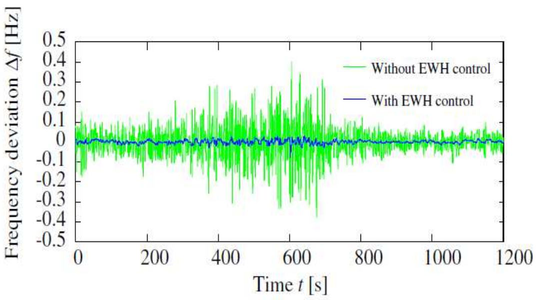
Simulation results are shown in Figure 12 for the case where the system frequency is controlled by a PI controller. Power consumption of all EWH in the power system is illustrated in Figure 12(a), and EWH expend electric power so as to reduce the high-frequency component of supply error ΔP_e as seen in this figure. Output power of diesel generator, in case of not using EWH and with using EWH on control, is illustrated in Figure 12(b), and high frequency component is reduced by power consumption control of EWH. Frequency deviation is illustrated in Figure 12(c). Frequency deviation is suppressed in about ±0.04Hz due to power consumption that is done so as to reduce the high-frequency component of supply error on the load side.



(a) Power consumption of all EWH in power system

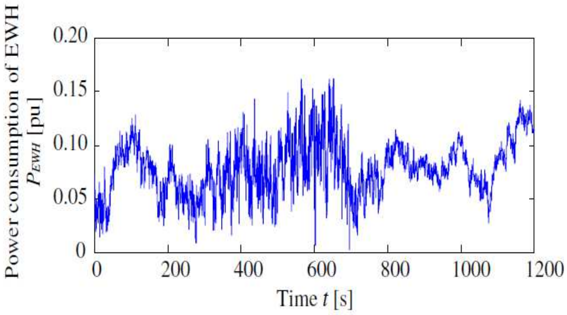


(b) Output of diesel generator

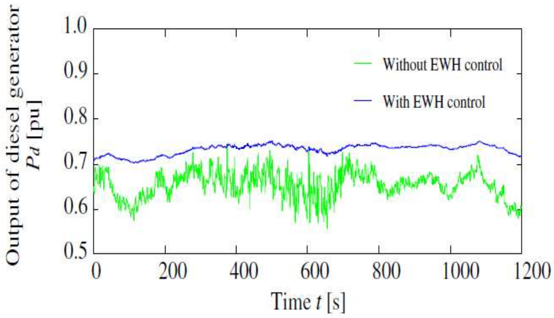


(c) Frequency deviation

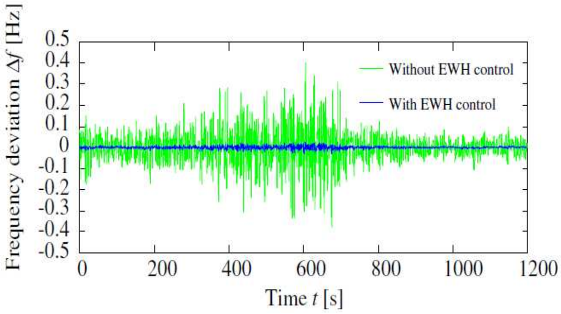
Figure 12. Simulation results (PI control).



(a) Power consumption of all EWH in power system



(b) Output of diesel generator



(c) Frequency deviation

Figure 13. Simulation results (H_∞ control).

On the other hand, simulation outcome in case of using H_∞ control on control system is illustrated in Figure13. Power consumption of all EWH in power system is illustrated in Figure 13(a), and EWH expend electric power so as to reduce the high-frequency component of supply error ΔP_e and keep pace under the high-frequency component. Then output power of diesel generator P_d becomes smooth and constant. It is seen that the case of using H_∞ control is better than the case of using PI control for frequency deviation Δf, as seen in control result of Figure 13(c). Next, frequency deviation Δf is statistically evaluated to show the validity of the proposed method for parameter variation. The following equation is used to show the probability density of frequency deviation Δf. However, it is assumed as form of normal distribution

$$f = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \qquad (11)$$

where σ(>0), x and μ represent standard deviation, sample Δf, and mean value, respectively. Variable parameters are assumed which are diesel generator's parameters T_d and inertia for equivalent generator's parameter M.

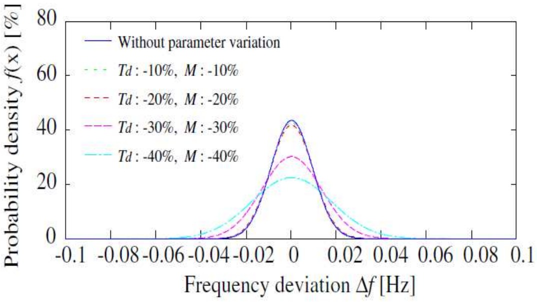


Figure 14. Probability density of frequency deviation (PI control).

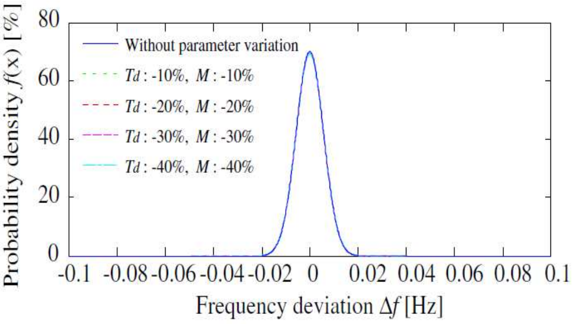


Figure 15. Probability density of frequency deviation (H_∞ control).

Scope of parameter variation is between −10% and −40%,probability density of frequency deviation in case of using each control method is illustrated in Figure 14, and 15.Statistical results for PI control of Figure 14 confirm that rate of distribution for frequency deviation to be lower at 0 Hz, while the frequency deviation band widens with increase in parameter variation. Statistical results for H_∞ control of Figure 15 confirms that rate of distribution for frequency deviation is maintained at a high level at 0 Hz even though parameter variations increases. Therefore, it can be observed that the proposed control system shows robustness to parameter variations.

6. Conclusion

This paper presents a control system to achieve suppression of frequency deviation by using controllable load that may steadily increase in the load side in the future. Controllable load expend electric power to reduce the high-frequency component of supply error in load side and diesel generator generate to reduce the low-frequency component of supply error in generator side from estimated supply error of power system by full-order observer using H_∞ controller which can decide the control performance on frequency domain. It is found that the following are achieved: demand side supply balance is maintained, generating-power leveling of output power of diesel generator, as well as suppressing frequency deviation for parameter variations by the H_∞ controller that has robustness.

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