Torsional Torque Suppression of Decentralized Generators Based on H_∞ Control Theory

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***Abstract*— The renewable energy power plants such as wind turbine generator and photovoltaic system have been introduced in isolated island power system recently. The output power fluctuations of wind turbine generator and load deviations result in frequency deviation and terminal voltage fluctuation. Furthermore, these power fluctuations also affect the turbine shafting of diesel generators and gas-turbine generators, which are the main components of power generation systems in isolated islands. For stable operation of gas-turbine generator, the torsional torque suppression should be considered as well as power system stabilization. In this paper, the control strategy that achieves torsional torque suppression and power system stabilization is presented based on H_∞ control theory. The effectiveness of the proposed control system is validated by numerical simulation results.**

***Index Terms*— Decentralized generator, torsional torque suppression, voltage control, frequency control, H_∞ control, microgrid**

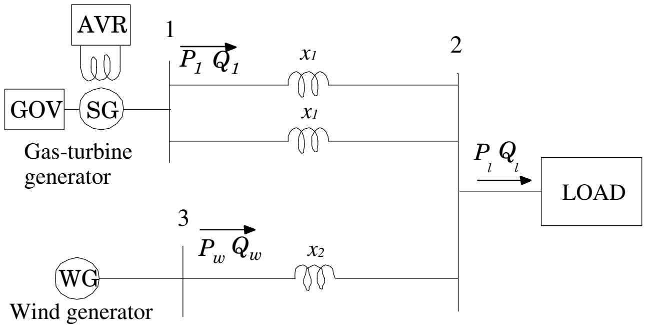

Fig. 1. Isolated power system model.

I. INTRODUCTION

Energy demand in remote small islands is steadily increasing. At present, power generation in remote islands mostly depends on diesel generators and gas-turbine generators. The gas-turbine generator have been introduced in isolated islands because of its superiority to diesel generator in reducing emissions of NOx and Co_2 and also its compact sizing. Due to fossil fuel combustion of the gas-turbine generator, there are many problems with gas-turbine generators such as lack of fossil fuel, environmental pollution, transportation cost of fuel and so on.

One of the solutions for these issues is to introduce renewable energy power plants such as photovoltaic systems and wind turbine generators, which use clean energy that is abundantly available in nature. However, output power of wind turbines is not constant but varies proportional to the cube of the wind speed that significantly affects the stability of isolated power systems resulting in frequency deviations and voltage fluctuations. Since the isolated island power system is weak, these disturbances become serious problems. In order to compensate the load deviations and output power fluctuations of wind turbine generator, the battery energy storage system is conventionally used. Although it is effective in suppressing frequency deviations and terminal voltage fluctuations, it needs large inverter and storage capacity which results in increase of equipment cost. Therefore the use of existing facilities is preferred, improving load following capability of gas-turbine generator. However, excessive power deviations of load and wind turbine generator affect the turbine shafting, that is, torsional torque oscillations [1]. Torsional torque oscillations cause excessive fatigue on the turbine shaft that may lead to shaft damage. The gas-turbine generator has a shear-pin that breaks when excessive torque is applied to turbine shaft. However, once the shear-pin breaks to protect turbine shaft, it requires a lot of time to repair and restart the generator. Therefore there has been a great demand for control schemes to suppress the torsional torque oscillations.

Some research on torsional torque suppression have been reported that uses Static Var Compensator(SVC) to regulate the reactive power [2]. Since these FACTS devices are expensive, it leads to increase of equipment cost. The other way to suppress torsional torque oscillations is to use generator power flow control. However, by controlling power flow depending on the torsional torque oscillation, the system frequency and terminal voltage may deviate significantly. Given these factors, applying an excitation control system to torsional torque suppression is preferred. Although there are some researches on torsional torque suppression by using excitation control [3], there is no research which considers power system stabilization control simultaneously. This paper presents the control strategy for achieving both stabilization control of remote power system and torsional torque suppression by means of excitation system and governor system. The proposed control system incorporates H_∞ control theory which improves load-

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TABLE I
SYSTEM CONSTANTS.

Gas-turbine generator
$H = 1.07\ \mathrm{s},\ x_d = 1.5\ \mathrm{pu},\ x'_d = 0.30\ \mathrm{pu},\ x_q = 1.06\ \mathrm{pu}$
$x'_q = 0.3\ \mathrm{pu},\ T'_{d0} = 3.7\ \mathrm{s},\ T'_{q0} = 0.21\ \mathrm{s}$
$K_A = 50,\ K_G = 100,\ T_G = 4\ \mathrm{s},\ T_A = 0.06\ \mathrm{s}$
Transmission lines
$x_1 = 0.8\ \mathrm{pu},\ x_2 = 0.3\ \mathrm{pu}$

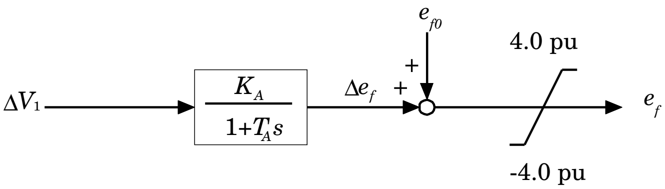


Fig. 2. Automatic voltage regulator.

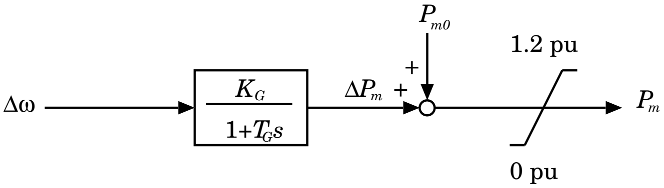


Fig. 3. Governor.

following capability and robustness of the controller. The effectiveness of the proposed control system is validated by numerical simulation results on MATLAB.

II. MODELING

Fig. 1 shows the isolated power system model consisting of the gas-turbine generator, wind turbine generator, and load. The reference capacity for per unit system is selected as 20 MVA and the wind turbine generator is rated at 5 MVA. Each model is described in the following subsections.

A. Gas-turbine Generator and Wind Turbine Generator

The gas-turbine generator is modeled as a synchronous generator. The electrical and mechanical characteristics of the synchronous generator can be described by the following differential equations [4]:

$$2H\frac{d\Delta\omega}{dt} = T_{23} - T_e \tag{1}$$

$$\frac{d\delta}{dt} = \Delta\omega \tag{2}$$

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

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

where H is the inertia constant, T_{23} is the mechanical input into generator, T_e is the electromagnetic torque of generator, 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 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 and i_q are the generator terminal currents for the d-q axes, T'_{do}, T'_{qo} are the d and q-axis open circuit transient time constants, respectively. The parametervalues for each element are shown in TABLE I.

The gas-turbine generator has automatic voltage regulator (AVR) and governor (GOV). The excitation and governor system can be generally described as the first-order lag system shown in Figs. 2 and 3. In this paper, these excitation and governor systems are defined as the conventional control system. Output power of wind turbine generator fluctuates with the wind speed. Since this paper does not consider control of the wind turbine generator, the wind turbine generator is modeled as a fluctuating power source.

B. Shaft Torsional System

The turbine shaft model of gas-turbine generator can be described as a 7 mass model as shown in Fig. 4, which is composed of high-pressure turbine, generator, exciter and some joints [5]. For a detailed analysis, this paper adopts the 7 mass torsional system. The parameters for each mass

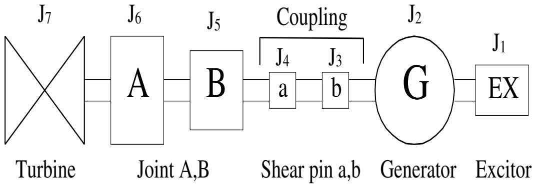


Fig. 4. Turbine shaft model.

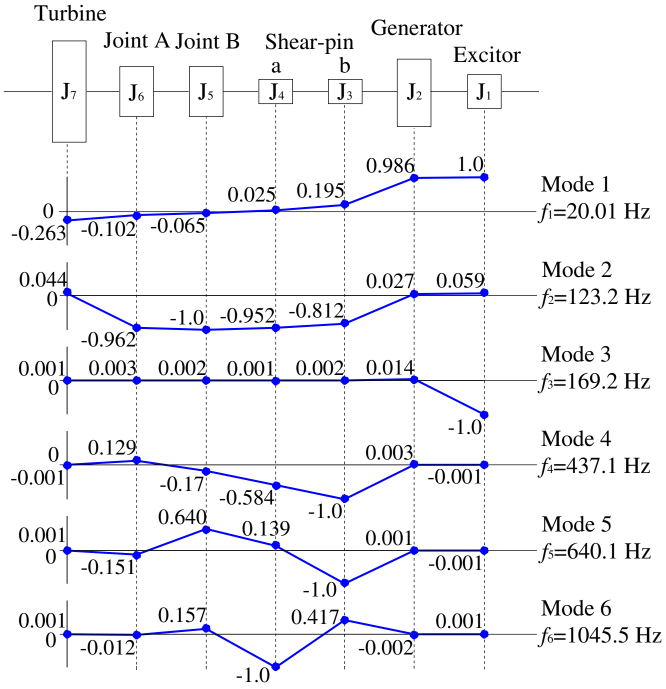


Fig. 5. Rotor natural frequency and mode shapes.

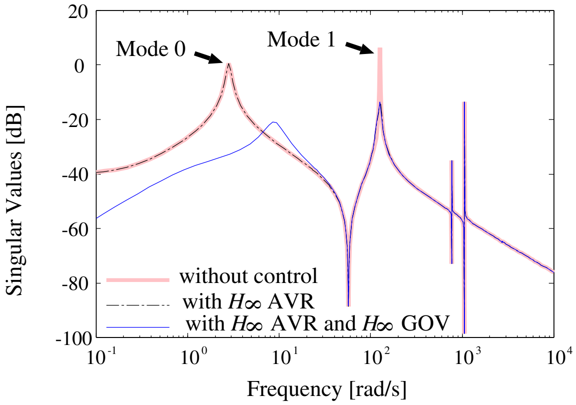


Fig. 6. Frequency response of 7 mass model ($T_e \rightarrow \omega_2$).

TABLE II

MECHANICAL SYSTEM CONSTANTS.

Mass	Inertia constant H [s]	Spring constant K [pu/rad]
Turbine	1.19	164.5228
Joint A	0.0454	712.153
Joint B	0.013	300.3748
shearpin a	0.0025	158.5285
shearpin b	0.0025	34.0054
Generator	0.3185	26.0130
Exciter	0.0044	

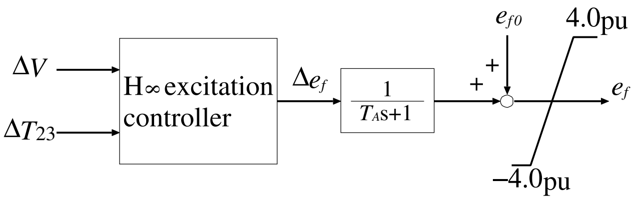
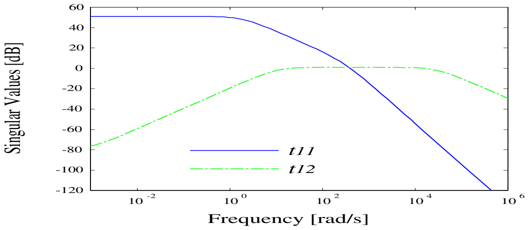
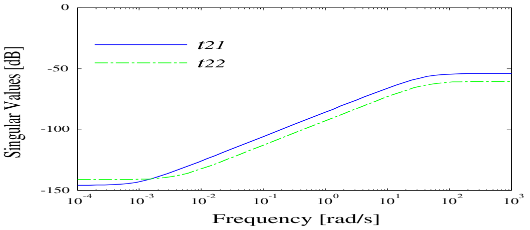


Fig. 7. Configuration of H_∞ excitation controller



(a) Weighting functions of sensitivity functions



(b) Weighting functions of complementary sensitivity functions

Fig. 8. Singular value plot of weighting functions.

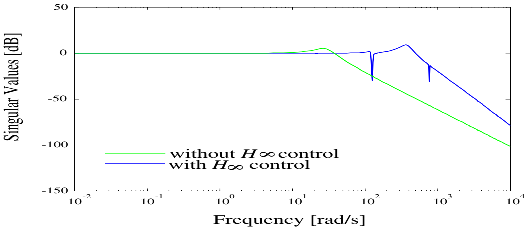


Fig. 9. Singular value plots (voltage loop).

are shown in TABLE II. Since a rotor with seven masses is considered, there are six torsional oscillation modes. The natural frequencies, as given by the imaginary components of the eigenvalues of torsional system, are $f_1 = 20.01$ Hz, $f_2 = 123.2$ Hz, $f_3 = 169.2$ Hz, $f_4 = 437.1$ Hz, $f_5 = 640.1$ Hz, and $f_6 = 1045.5$ Hz. Since the gas-turbine generator, which is kind of decentralized generator, has small inertia compared with large machinery, its torsional oscillation frequency is relatively high. The relative rotational displacements of the individual masses for each mode of oscillation are given by the right eigenvector of the corresponding eigenvalue.

Fig. 5 shows the analysis results of rotor natural frequencies and mode shapes. Damping coefficients are assumed to be negligible since this has no effect on the calculation of the natural frequencies or the mode shape. In the torsional modes 2, 4, 5, and 6 that have higher natural frequency, the rotors of generator and turbine sections have very low relative amplitudes of rotational displacement. This means that this mode cannot be easily excited by applying torques to the generator and turbine rotors. In mode 3, there is high amplitude of rotational displacement between generator and exciter rotors. Since the inertia constant of exciter rotor is relatively low, this oscillation mode scarcely affects the turbine shafting. On the other hand, the mode 1 representing a natural frequency of 20.01 Hz has one polarity reversal in the mode shape. The polarities of eigenvector elements associated with the rotors of the exciter, generator and shear-pin $a \cdot b$ are opposite to those associated with the rotors of the Joint $A \cdot B$ and turbine section. This indicates that the exciter, generator and shear-pin $a \cdot b$ rotors oscillate against the other three rotors when this mode is excited.

Since the generator and turbine rotor have high inertia constant and their relative rotational displacement is significantly large, the oscillation mode 1 has dominant effect on the whole turbine shafting. Therefore, eliminating the oscillation mode 1 is important in order to achieve torsional torque suppression. The natural frequency of mode 1 (20.01Hz) is reasonable because the general torsional oscillation frequency in real system ranges from 5 Hz to 40 Hz. The frequency response of the 7 mass torsional system is depicted as dotted line in Fig. 6. From Fig. 6, there are resonance points at the oscillation mode of power system (Mode 0) and torsional oscillation mode (Mode 1). In designing the controller that achieves damping of power system oscillation and torsional torque suppression, it is necessary to eliminate these resonance points.

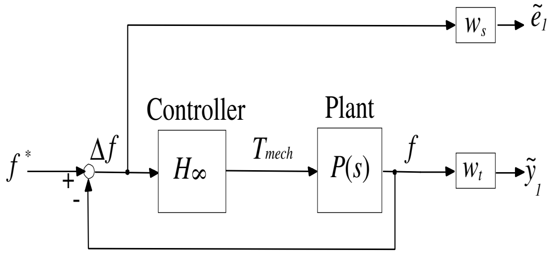


Fig. 10. Configuration of H_∞ controller

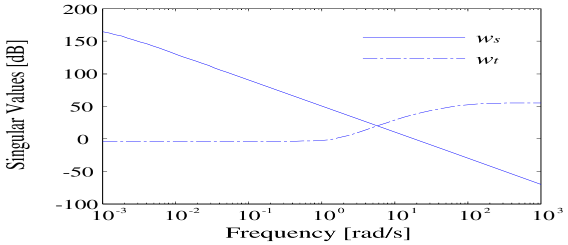


Fig. 11. Singular value plot of weighting functions (GOV).

III. Controller Design

This section presents the principle of designing the proposed control system which achieves torsional torque suppression and power system stabilization. The proposed control system operates as decentralized control system since the H_∞ controllers are designed at exciter and governor system individually. Subsections III A and B present the design of excitation controller and governor system respectively.

A. Design of Excitation Controller

This subsection describes the design of H_∞ excitation controller that achieves terminal voltage control and torsional torque suppression. The H_∞ controller is designed based on LMI approach [6]-[10]. Fig. 7 shows the configuration of the H_∞ excitation controller. The controller inputs are terminal voltage deviation ΔV and fluctuation component of torsional torque ΔT_{23}. The weighting functions of H_∞ controller are shown in Fig. 8. The weighting function of voltage control loop t_{11} is selected to have gain high in low frequency domain so that the steady state error can be removed. The weighting function of torsional torque loop t_{12} is selected to hold the gain in high frequency domain so that the elimination of resonance point of torsional oscillation mode can be achieved.

The closed loop characteristic of voltage loop in case of H_∞ excitation controller is shown as solid line in Fig. 9, showing that the controller bandwidth is improved. The frequency response of the 7 mass torsional system after applying H_∞ excitation controller is shown as dashed line in Fig. 6. From Fig. 6 it is seen that the elimination of torsional oscillation mode is achieved by applying H_∞ excitation controller.

B. Design of Governor System

This subsection presents the design of the governor system. In the past subsection, the elimination of torsional oscillation mode can be achieved by applying the H_∞ excitation controller, however, there still exist the resonance of power system oscillation mode (Mode 0) as shown in Fig. 6. Therefore, the governor system should be designed to eliminate the resonance of power system oscillation to achieve stabilization control of power system. The control system that achieves damping of power system oscillation is shown in Fig. 10. The controller adjusts the mechanical input to the gas-turbine generator according to frequency deviation Δf in order to achieve load frequency control and power system stabilization.

The weighting functions of H_∞ controller are shown in Fig. 11. The weighting function of frequency control loop, w_s, is selected to hold the gain high in low frequency domain so that the steady state error can be removed and resonance point of power system oscillation can be eliminated. The frequency response of torsional system in case of applying H_∞ governor system is shown as solid line in Fig. 6. Since the weighting function of H_∞ controller of governor system is selected to hold the gain high in low frequency domain, the power system oscillation mode, which is low frequency component, is successfully damped.

IV. Simulation Results

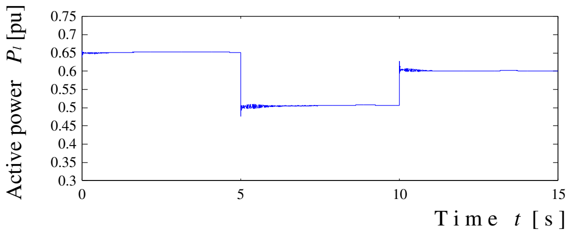
In order to verify the effectiveness of the proposed control system, computer simulations are conducted in two cases. Subsection IV A shows the simulation results in case of load deviations and generating power fluctuations of wind turbine. The simulation results assuming instantaneous voltage drop are presented in subsection IV B.

A. Simulation Results (case 1)

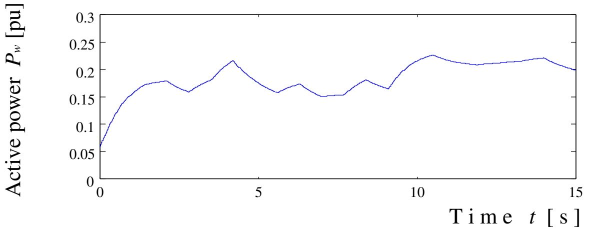
This subsection presents the simulation results assuming load deviations and output power fluctuations of wind turbine generator. The simulation results are shown in Fig. 12. From Fig. 12(a), it is observed that load demand is rapidly changed at $t = 5$ s and $t = 10$ s. Fig. 12(b) shows the generating power of the wind turbine generator. These power fluctuations cause frequency deviation and affect the turbine shafting of gas-turbine generator. From Fig. 12(c), it is seen that the torsional torque oscillation due to the excessive load deviations is well damped by applying the H_∞ excitation controller. Fig. 12(d) shows terminal voltage of gas-turbine generator. Although the terminal voltage fluctuates to suppress the torsional torque oscillation, the voltage deviation is controlled to be within the acceptable range of $\pm 5\%$. Fig. 12(e) shows the mechanical input to gas-turbine generator. From Fig. 12(e), it can be noted that the load-following capability is improved and the torque oscillation is damped by applying H_∞ control to governor system. From Fig. 12(f), load frequency control and damping of power system oscillation are achieved by applying the proposed control system.

B. Simulation Results (case 2)

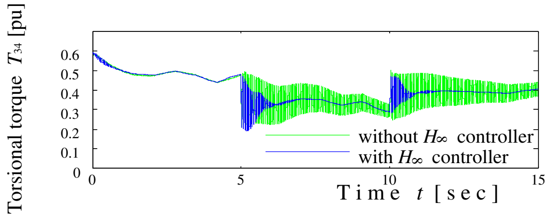
This subsection presents the simulation results assuming instantaneous voltage drop. The instantaneous voltage drop significantly affects the turbine shafting of generator [1]. To



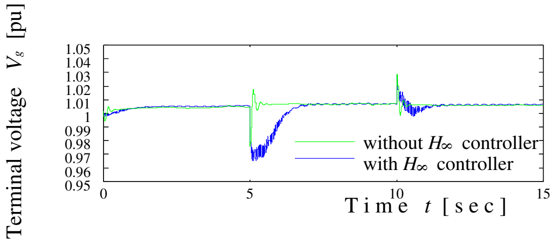
(a) Active power demand, P_l



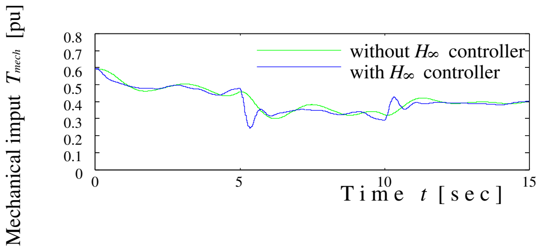
(b) Generating power of wind turbine generator, P_w



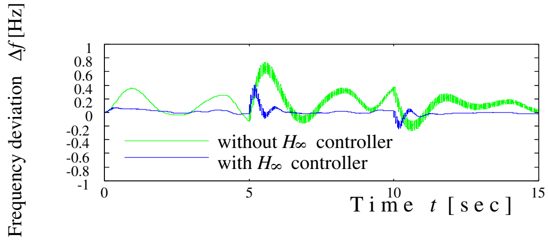
(c) Torsional torque, T_{34}



(d) Terminal voltage of bus 1, V_1

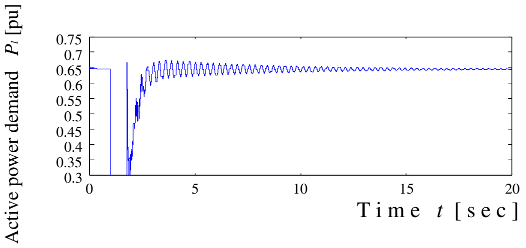


(e) Mechanical input to gas-turbine generator, T_{mech}

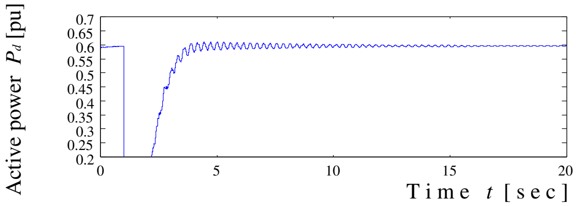


(f) Frequency deviation, Δf

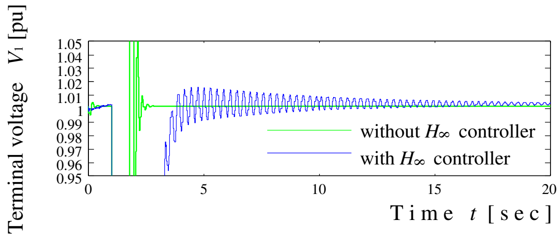
Fig. 12. Simulation results (case 1).



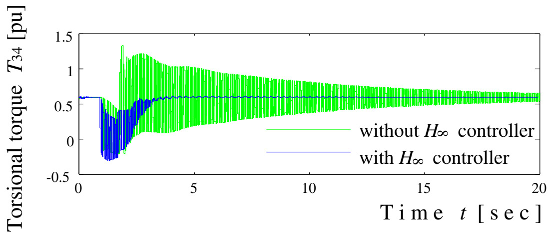
(a) Active power demand, P_l



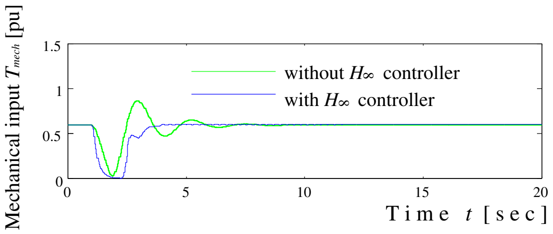
(b) Active power of gas-turbine generator, P_1



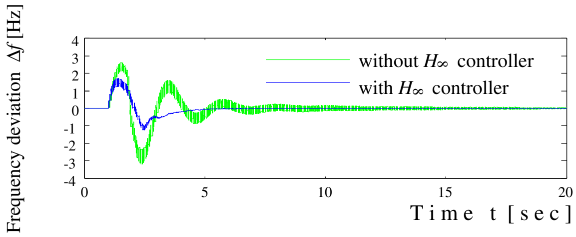
(c) Terminal voltage of bus 1, V_1



(d) Torsional torque, T_{34}



(e) Mechanical input to diesel generator, T_{mech}



(f) Frequency deviation, Δf

Fig. 13. Simulation results (case 2).

validate the effectiveness of the proposed control system, numerical simulation is conducted assuming one-line three phase grounding fault at the transmission line between generator bus 1 and load bus 2. Simulation results are shown in Fig. 13. In this case, the grounding fault has occurred at $t = 1$ s, the circuit interruption at $t = 1.3$ s, and reclosure at $t = 1.78$ s. From the simulation results, without applying H_∞ controller, the torsional torque oscillation caused by instantaneous voltage drop leads to instability.

On the other hand, by applying H_∞ control that is designed to remove resonance of torsional mode and power system oscillation mode, the torsional torque suppression and power system stabilization are simultaneously achieved.

V. CONCLUSION

This paper proposes a control system that achieves torsional torque suppression and damping of power system oscillation by means of excitation and governor system. The proposed control system incorporates H_∞ control theory that enables intuitive controller design in frequency domain and improves load-following capability of the controller. In designing the H_∞ controller, the weighting functions are selected to eliminate the resonances of torsional mode and power system oscillation mode. By using the proposed control system, stabilization control of remote power system and stable generator operation can be achieved. However, the proposed control system needs to measure the torsional torque. The measurement of torsional torque is difficult technically. Although there is equipment for measuring the torsional torque by means of laser measurement system, this equipment is expensive. Past research proposed the observer system for torsional torque by measuring generator rotating speed [3]. The control system proposed in this paper can be applied in real system by using such an observer system. However, the observer system proposed in past research does not consider the system uncertainty such as modeling error and parameter variations. Hence, designing the observer system that achieves robust observation in case of parameter variation is greatly needed, and will form the basis of our future work.

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