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Application of FESS Controller for Load Frequency Control

Jeong-Phil Lee *, and Han-Guen Kim**

Abstract – This paper presents the effect on application of the flywheel energy storage system (FESS) for load frequency control (LFC) of an interconnected 2 area power system. To do this, the control characteristics with the FESS were compared with that of the conventional governor controller. The controller for the FESS control and the governor control used a PID type controller. Both the FESS PID controller and the governor PID controller using genetic algorithm (GA) were designed to optimize the PID parameters. The frequency and generation output characteristics with the only FESS controller and with the only conventional governor controller were compared. To verify robust performance of the FESS controller, the computer simulations were performed under various disturbances. The simulation results showed that the FESS controller provided better dynamic responses in comparison with the conventional governor controller.

Keywords: Flywheel energy storage system, Genetic algorithm, Load frequency control, Power system

1. Introduction

In recent, interconnection of the new and renewable energy source such as a wind power and solar power, and the distributed generation in the power system is increased and various loads are complicatedly connected. Irregular output of the new and renewable energy source and continuous load change cause mismatch between the generated and demanded power. This causes change of the frequency and the tie line power flow. The load frequency control (LFC) problem of the power system is one of very important subjects. To do this, the controller for a governor system have been designed and applied [1]-[5]. However, in case of sudden large loads change, the frequency of a power system may be considerably oscillated from a normal operating value. In this case, the LFC using the conventional governor control is limited due to physical constraints of the governor system which has slow response. Because the active power output of a flywheel energy storage system (FESS) is very fast, it is possible to control frequency quickly in spite of the sudden large load change. Therefore this paper presents an effect on application of the FESS controller for LFC. The dynamic simulations were performed under various disturbances of the power system. The simulation model for the interconnected 2 area power system included a reheat turbine, governor and nonlinearity such as the governor deadband and the generation rate constraint (GRC) [7]-[11]. The generation output characteristics and the control performance for the FESS controller and the conventional governor controller were compared. Both the FESS controller and the governor controller used the PID controller. A genetic algorithm (GA) [6] was used for optimizing parameters of the PID controller. The used performance index for selecting PID parameters both the controllers was identical one.

The robust performance and output characteristics of the proposed FESS PID controller was compared to those of the conventional governor PID controllers. The results showed that the proposed FESS PID controller using GA was more robust than the governor PID controller using GA. Because it is possible to directly control power input/output of the FESS, the sudden generation change of governor turbine system can be prevented and the efficient operating of power plant facilities is expected

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2. Power System Model

2.1 Interconnected 2 area power system

Fig. 1 shows the block diagram for the interconnected 2 area power system [7]-[10] including the FESS and controller. The output power of the generator in the area 1 and 2 are equal and both areas have the FESS.

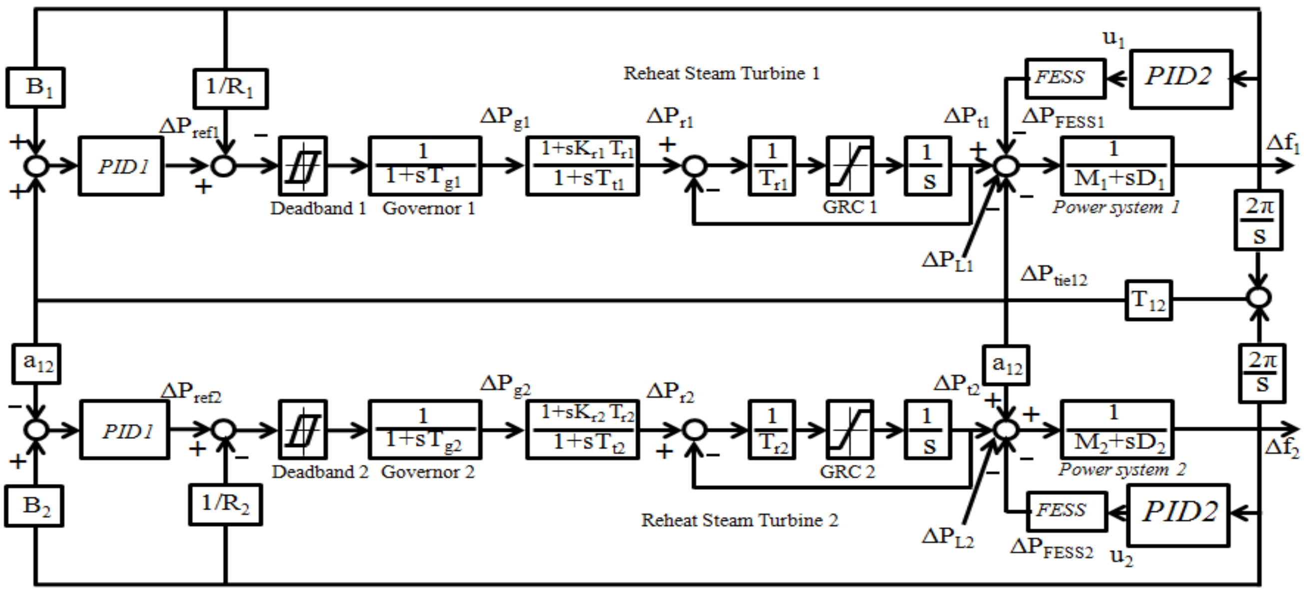


Fig. 1. Block diagram of interconnected 2 area power system

The purpose of this paper in Fig. 1 is to design separately both the governor controller PID1 and the FESS controller PID2 controlling the output ΔP_{FESS} of the FESS in order to control the load frequency of the interconnected 2 area power system.

The linearized equation [1], [8], [11] of the power system in Fig. 1 is as follows.

$$\Delta\dot{x} = A\Delta x + B\Delta u + \Gamma\Delta p \qquad (1)$$

where, Δx , Δu and Δp are the state, control and disturbance vector respectively. A, B and Γ are constant matrices which depend on system parameters and the operating point.

The state, control and disturbance variables without controller are as following,

$$\Delta x = [\Delta f_1, \Delta P_{t1}, \Delta P_{r1}, \Delta P_{g1}, \Delta P_{tie12}, \Delta f_2, \Delta P_{t2}, \Delta P_{r2}, \Delta P_{g2}]$$

$$\Delta u = [u_1, u_2], \quad \Delta p = [\Delta P_{L1}, \Delta P_{L2}]$$

The state, control and disturbance matrices (A, B and Γ) of 2 area interconnected thermal reheat power system are as following, where, M_i is an inertia constant of an area i, D_i is a damping constant of an area i, a_{12} is an area capacity ratio between the area 1 and 2, T_{12} is a synchronizing power constant of a tie line between the area 1 and 2, K_{ri} is the reheat gain of the turbine in an area i, T_{ri} is the reheat time constant of the turbine in an area i, T_{gi} is the time constant of the governor in an area i, T_{ti} is the time constant of the turbine in an area i, R_i is the regulation ratio in an area i, B_i is the bias coefficient in area i. ΔP_{tie12} is the tie line power flow deviation between the area 1 and 2.

$$A = \begin{bmatrix} -\frac{D_1}{M_1} & \frac{1}{M_1} & 0 & 0 & -\frac{1}{M_1} & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{t1}} & \left(\frac{1}{T_{r1}} - \frac{K_{r1}}{T_{t1}}\right) & \frac{K_{r1}}{T_{t1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{T_{g1}R_1} & 0 & 0 & \frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 \\ 2\pi T_{12} & 0 & 0 & 0 & 0 & -2\pi T_{12} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{a_{12}}{M_2} & -\frac{D_2}{M_2} & \frac{1}{M_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{r2}} & \left(\frac{1}{T_{r2}} - \frac{K_{r2}}{T_{t2}}\right) & \frac{K_{r2}}{T_{t2}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{t2}} & \frac{1}{T_{t2}} \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{g2}R_2} & 0 & 0 & \frac{1}{T_{g2}} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{g2}} \end{bmatrix}^T \quad \Gamma = \begin{bmatrix} -\frac{1}{M_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{M_1} & 0 & 0 & 0 \end{bmatrix}^T$$

2.2 Flywheel energy storage system

Fig. 2 shows the FESS with a power conditioning system (PCS). The FESS is an electric power storage system in which an electrical energy is stored by converting into a mechanical rotationary energy. The FESS is composed of a flywheel, a bearing, a motor/generator and a power conditioning system (PCS). The bearing can use a mechanical ball bearing, a magnetic bearing and a superconductor magnetic bearing.

The kinetic energy stored in a flywheel is proportional to the mass and to the square of its rotational speed as following

$$E = \frac{1}{2} I \omega^2 \tag{2}$$

where E is a stored energy in the flywheel, I is moment of inertia and ω is the angular velocity of the flywheel. In (2), the stored power amount in the FESS can be measured easily through measurement of the flywheel rotational speed.

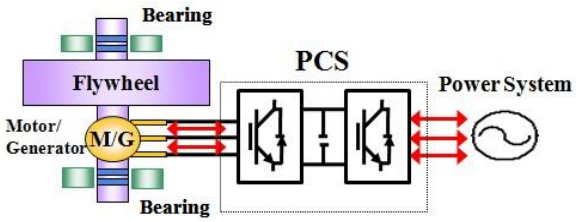


Fig. 2. Flywheel energy storage system with PCS

The significant progress of the power electronics and the control technology make it possible for the FESS to control the power input/output very rapidly within few cycle after the load change. The FESS can control both an active and reactive power independently. But to evaluate the effect of the frequency control of the FESS, only the active power control for the FESS is considered in this paper. The FESS can handle high power level and charge/discharge speed of the FESS is very fast. Therefore the FESS can be treated as following a block diagram as Fig. 3

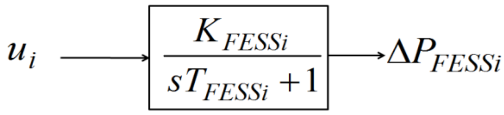


Fig. 3. Block diagram of FESS

The output power of the FESS can be written as following equation.

$$\Delta \dot{P}_{FESSi} = (-\Delta P_{FESSi} + u_i) / T_{FESSi} \tag{3}$$

where ΔP_{FESSi} is an output power of the FESS in the area i, T_{FESSi} is a time constant of the FESS in the area 1.

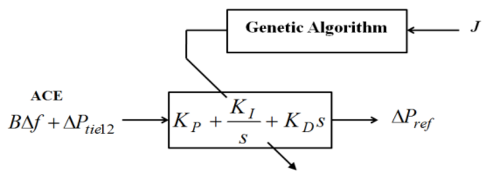
3. Design of Controller using GA

Fig. 1 shows the block diagram of the interconnected 2 areas power system model including the governor controller and the FESS controller. The governor controller is the PID1 and the FESS controller is the PID2. The parameters of both PID1 and PID2 were selected separately using GA.

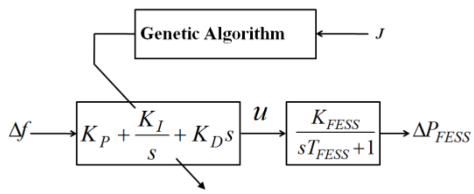
Fig.4 shows the block diagram for selecting PID parameters for the governor and FESS controller using GA. The input of governor controller PID1 is an area control error (ACE) as Fig. 4 (a) but the input of FESS controller PID2 is frequency deviation as Fig. 4 (b). The performance index J used to select parameters of each PID controller using the GA is as follows

$$J = \int_{t=0}^{t=te} t \cdot \Delta f_1 + t \cdot \Delta f_2 + t \cdot \Delta P_{tie12} dt \tag{4}$$

where, t is time, te is simulation time. The generation rate constraint (GRC) of 0.0017 (puMW/s) is considered in dynamic simulation. The FESS output power limit of $-0.01 \leq \Delta P_{FESS} \leq 0.01$ (puMW) is considered. The system parameters are shown in Table. 1 [7][9][10].



(a) PID1 parameters selection for governor controller



(b) PID2 parameters selection for FESS controller

Fig. 4. Block diagram for selecting PID parameters

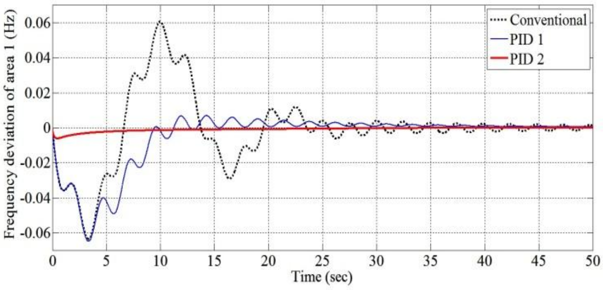
Table 1. System Parameters

$M_1 = M_2 = 0.1667$, $D_1 = D_2 = 0.00833$, $K_{r1} = K_{r2} = 0.333$
$T_{r1} = T_{r2} = 10$, $T_{g1} = T_{g2} = 0.2$, $T_{t1} = T_{t2} = 0.25$
$R_1 = R_2 = 2.4$, $B_1 = B_2 = 0.425$, $K_{I1} = K_{I2} = 0.4$
$T_{12} = 0.0707$, $a_{12} = 1$, $T_{FESS1} = T_{FESS2} = 0.1$

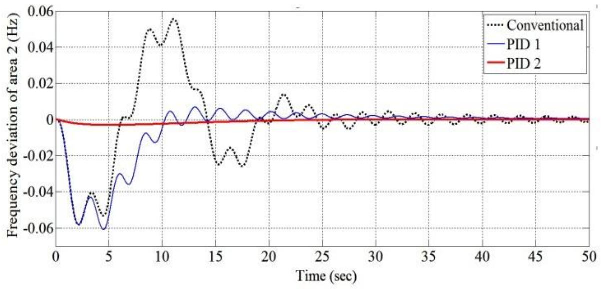
4. Simulation Results

To assess characteristic and performance of the FESS controller, the dynamic simulations were performed. For comparison, the applied controllers were the conventional [7] integral (I) type governor controller, the governor controller PID1 and the FESS controller PID2. The control input of the conventional I type controller and PID1 used an area control error (ACE) and the control input of FESS controller PID2 used a frequency deviation.

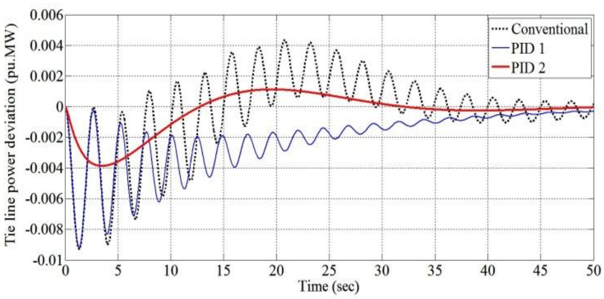
Fig. 5 shows the simulation results for the frequency variation, tie line power variation, the generation output characteristics and the FESS output characteristics with the conventional, PID1 and PID2 respectively for a step load change of 0.01 (puMW) in area 1. The frequency oscillations with the FESS controller PID2 in Fig. 5 (a), (b) are significantly suppressed and settling time of the frequency response is very fast. The oscillation and settling time for tie line power in Fig. 5 (c) are reduced considerably. Fig. 5 (d) shows the rate of generation of area 1. Rate of generation using the governor controller such as conventional and PID1 has the limited value of 0.0017 (pu.MW/s) from initial time to about 10 s ~ 20 s. However, rate of generation using the FESS controller PID2 has the small value less than 0.0017 (pu.MW/s).



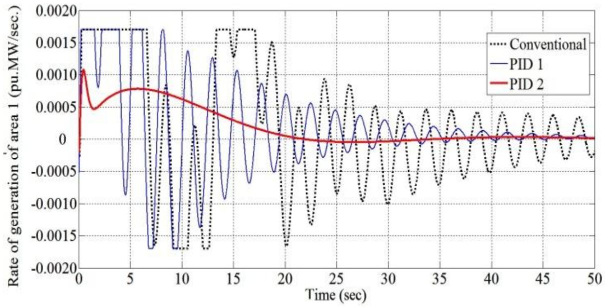
(a) Δf_1



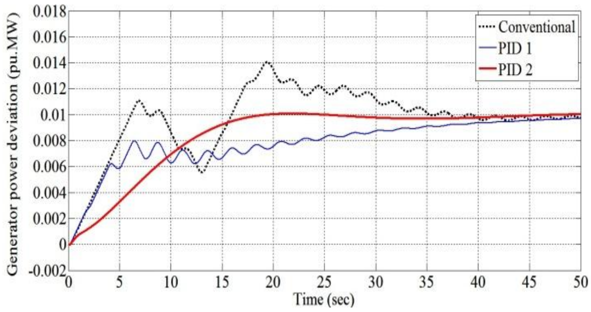
(b) Δf_2



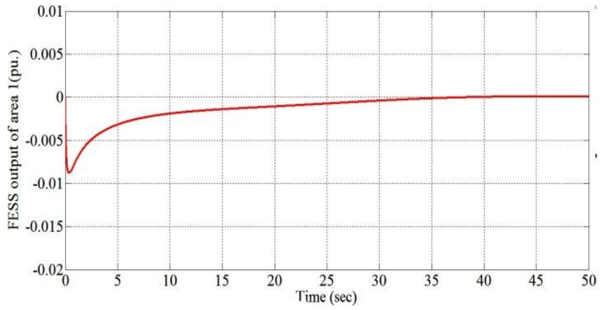
(c) ΔP_{tie12}



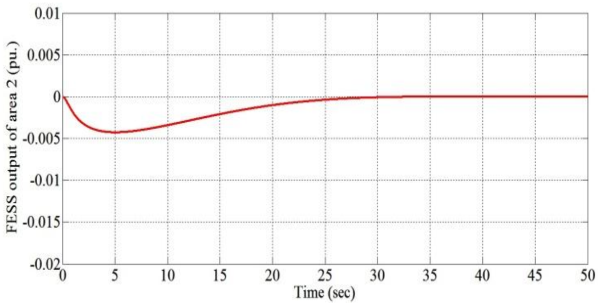
(d) Rate of generation of area 1



(e) ΔP_{t1}



(f) ΔP_{FESS1}



(g) ΔP_{FESS2}

Fig. 5. Simulation results in case of $\Delta P_{L1} = 0.01\,[p.u.]$

Fig. 5 (e) shows the generation power of area 1. Because the active power output of the turbine is limited by GRC, the frequency control by the conventional and PID1 is very slow. In case of the FESS controller PID2, although the active power output of the turbine is small, it is possible to control the frequency quickly in spite of the sudden load change due to fast active power output of the FESS.

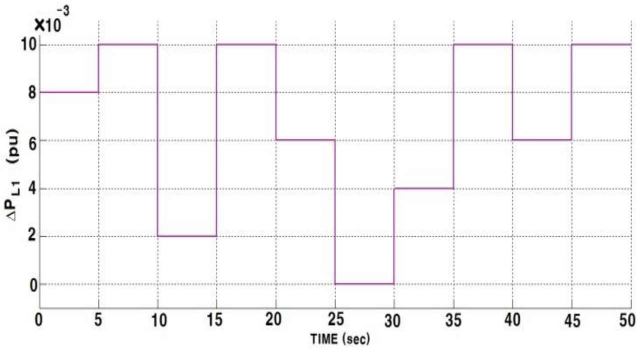
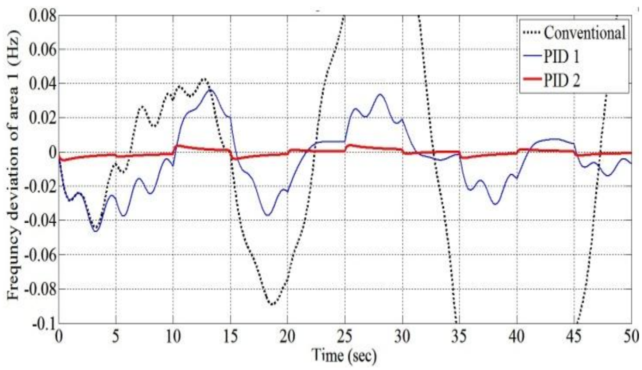
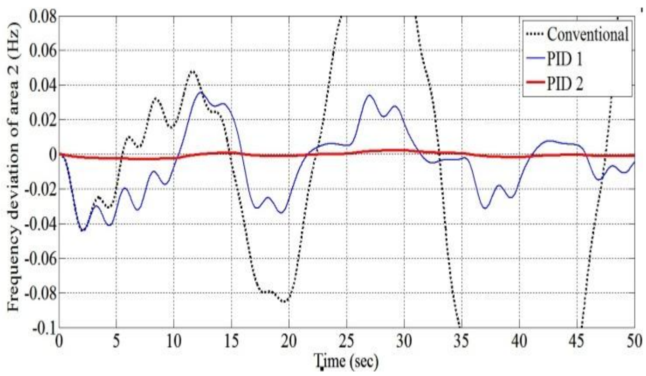


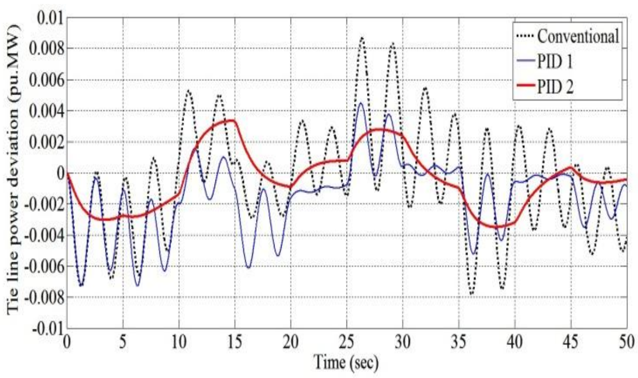
Fig. 6. Random load change of area 1



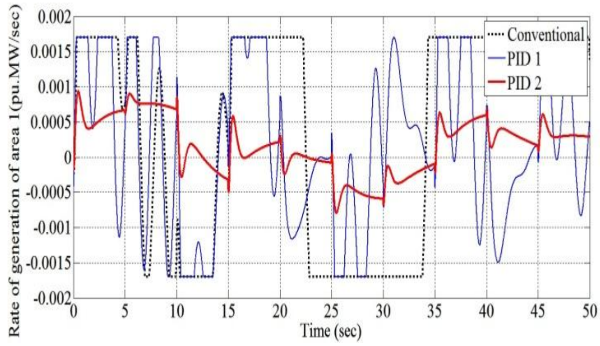
(a) Δf_1



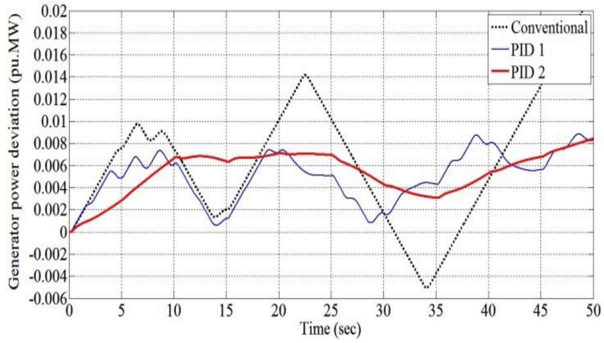
(b) Δf_2



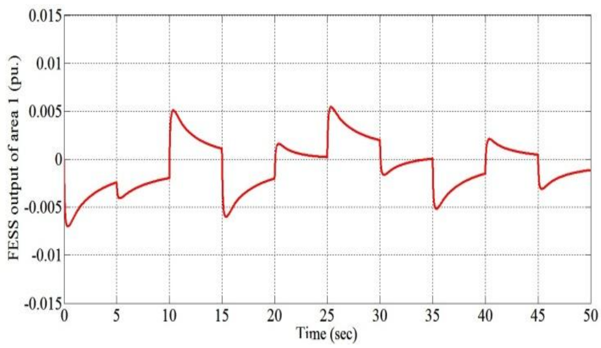
(c) ΔP_{tie12}



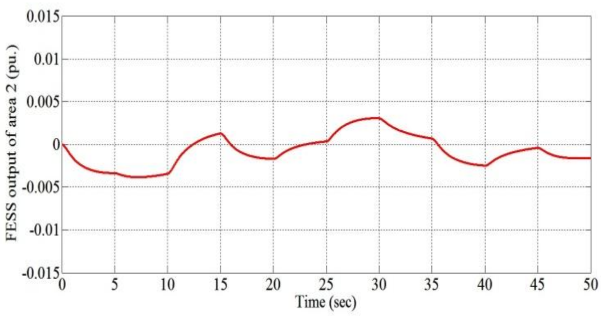
(d) Rate of generation of area 1



(e) ΔP_{t1}



(f) ΔP_{FESS1}



(g) ΔP_{FESS2}

Fig. 7. Simulation results according to random load change in area 1

Fig. 5 (f) and (g) show the SFES output power of area 1 and area 2. To compensate mismatch between the generated and demanded power by a step load change, the active power of the FESS flows into the power system. It can be seen that the oscillation of the frequency and the tie line power are damped rapidly and the settling time is very fast through the rapid active power output of FESS.

Fig. 6 shows random load changes in area 1. Fig. 7 shows a comparison of the dynamic simulation results for frequency variation, tie line power variation, rate of generation, generation power and the FESS output when the random load changes as Fig. 6 are applied to area 1.

The frequency oscillations with the FESS controller PID2 in Fig. 7 are significantly suppressed and settling time of the frequency response is very fast. The oscillation and settling time for tie line power are reduced considerablyIt can be seen that the oscillation of the frequency and the tie line power are damped rapidly and the settling time is very fast through the rapid active power output of FESS. The results showed that the FESS controller PID2 was more robust than that using the conventional and PID1.

5. Conclusion

In this paper, the flywheel energy storage system was used for the load frequency control of the interconnected 2 areas power system. A genetic algorithm was used to design the FESS PID controller and governor PID controller. The performance index of both PID controllers is equal. The dynamic simulation results showed that the proposed FESS PID controller using GA was more robust than the governor PID controller. Because it is possible to control directly the power input/output of the FESS, the sudden generation change of the governor turbine system can be prevented and the efficient operating of the power plant facilities is expected.

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