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Improved Dynamic Performance in Interconnected Power System Using Secondary Frequency Control

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Abstract

Load changes affect the frequency of electrical networks. Frequency stabilization is very important due to the increasing penetration of renewable energy sources in power systems. The main task of load frequency control is to keep the system frequency according to the specified nominal value and to maintain the correct amount of exchange power between the control areas. In this paper, load frequency control in two-area power system is studied and simulated. Each area has a steam generating unit with a reheat steam turbine. The system equations are expressed in the state space and the system model is determined based on the transfer function. The simulation results have been obtained using MATLAB software. The simulation results show the effect of Richter's parameters on the transient dynamic behavior of the system.

Keywords: load frequency control, two-area power system, state space, reheater
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1. Introduction

Power systems are a complex system, which to control them in steady state, different control loops are needed [1-3]. All production units that have speed governors, regardless of the position and location of the load change, they contribute to the overall change in production [4-6]. Frequency plays an essential role in the power system which must be well and properly controlled [7-9]. Sudden load changes in any control area in the power system cause the frequency and power of the transmission line connected to other areas of the power system to change. Therefore, primary and secondary frequency control loops are used in the power system [10,11]. Due to the change of active and reactive power and their almost independent from each other, two automatic load-frequency control systems and automatic voltage regulator are always needed to control transient and permanent responses of the system in power plants. The function of the secondary frequency control, or load frequency control (LFC), is to keep the frequency at the desired level after the disturbance [12-15]. This system corrects the area control error based on the initial frequency and returns the frequency to the nominal value [16-18]. Fig. 1 shows a typical frequency tuning scenario under a contingency event, where the rate of change of frequency is specified. The system frequency starts to deviate to a minimum set as a rare point [19]. LFC or automatic generation control (AGC) is one of the main operations that is performed every day according to the performance in a modern power system [20,21]. Load frequency control is necessary to create better control in order to achieve a lower effect on the frequency and power deviations of the connection line after load perturbation [22,23]. One of the important actions for reliability and quality assurance in power system operation is LFC. A number of subsystems that are connected to each other through transmission lines make up the power system. Each subsystem must meet requirements such as supplying the load of the area and regulating the frequency.

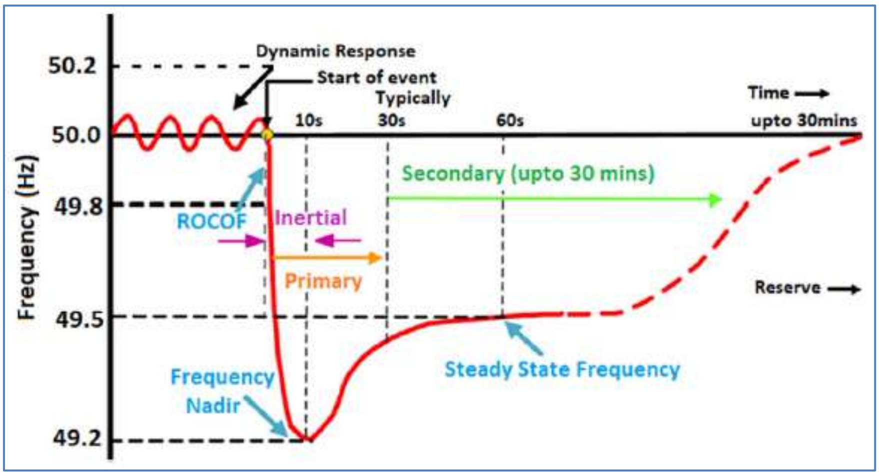

Fig. 1. Regulation services during frequency variation

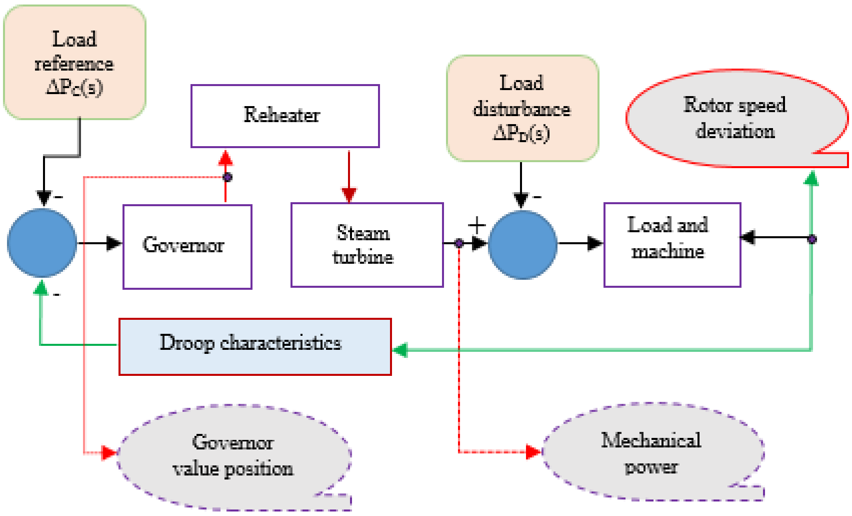

Fig. 2. Production unit structure with steam reheat turbine

Due to the expansion of the use of renewable energies, various studies have been carried out in the field of frequency load control [24-31].

The design of a LFC for power systems with steam turbines is presented in [32], which aims to reduce the oscillations of the output frequency deviations as quickly as possible. The proposed controller is based on H∞ polynomial robust control theory and sufficiently guarantees the internal stability and robust performance of the closed loop system.

A neural network controller is proposed for power system load-frequency control in [33], which the steam turbine reheating effect and governor dead-band nonlinearity effect are considered.

In the control loop for frequency regulation, an energy storage system is proposed in [34], to be used when the grid is under unstable conditions or where the average frequency between different connected areas is different from zero. The studied system consists of two connection lines that are connected between two areas and each one consists of a synchronous generator, renewable energy sources, energy storage system and load.

An optimal predictive control model for the design of LFC installed in the interconnected system including different renewable energy sources is proposed in [35], which method to identify the optimal predictive control parameters to minimize integral absolute time error frequencies and tie line power deviations are used.

Matching total system output with total load demand and system losses is a requirement for successful operation of the interconnected power system [36,37]. In this paper, the aim is to simulate the power system with a reheat steam turbine. The power system consists of two areas that are connected to each other through a tie line. The simulation results show the transient behavior of the power system in response to load demand changes in each area. The closed loop system of load frequency control tends to zero load frequency deviation changes. It also keeps the power transfer between the two areas constant at the specified value.

2. Single-Area Power System Model

In this part, the model of the load frequency control system in the single-zone power system is determined based on the transfer function and in the state space.

A) Steam production unit structure

The stored steam energy with high pressure and temperature in the steam turbine is converted into rotational energy, which will be converted into electrical energy by the generator [38,39]. In a reheat turbine, to improve efficiency, steam after leaving the high pressure section returns to the boiler and passes through a reheater before returning to the medium pressure section [40,41]. The block diagram of a production unit with the presence of a turbine equipped with a reheater is shown in fig. 2.

The uncontrolled system has two inputs, which are: $u_1 = \Delta P_D$ and $u_2 = \Delta P_C$. ΔP_c is the control set point from the secondary frequency control mechanism and ΔP_d is the total change in load/demand (electrical power output).

The highest time constant in controlling the steam flow and turbine power belongs to the reheater. Therefore, the responses of turbines with reheater are much slower than turbines without reheater. The steam turbine does not need a droop transient compensator.

B) Model based on transfer function

The display of single-area system based on transfer functions is shown in fig. 3. The frequency deviation changes in an uncontrolled area can be expressed based on transfer functions as follows:

$$\Delta F(s) = H_{FC}\Delta P_C(s) - H_{FD}\Delta P_D(s) \tag{1}$$

where the functions $H_{FC}(s)$ and $H_{FD}(s)$ are the ratio of frequency deviation to input load changes and set point changes, respectively.

The PID (proportional–integral–derivative) controller is one of the most practical examples of the closed loop control algorithm using the concept of feedback and is used in many industrial processes. This controller minimizes the error by adjusting the process control input. This controller has been used in different systems [42-45]. An integral controller is used in the load frequency control system.

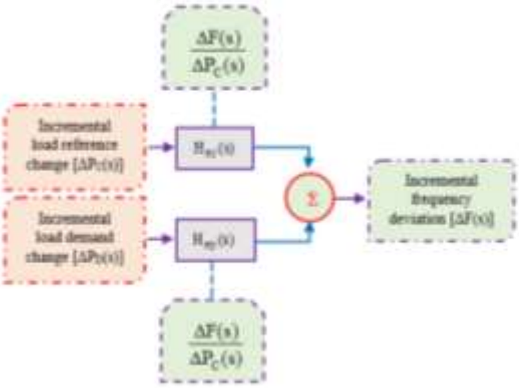

Fig. 3. Representation of a single-area power system based on transfer functions

Considering that the system load is constantly changing, the output of the generating units should change automatically. In the load frequency control system, the $\Delta P_C(s)$ (load reference set-point) input is determined by the system frequency deviation changes using the integrator controller:

$$\Delta P_C(s) = \frac{\beta K_I}{s}\Delta F(s) \tag{2}$$

Therefore, in the LFC system, the transfer function of the frequency deviation changes to the input load changes is as follows:

$$H_F(s) = \frac{\Delta F(s)}{\Delta P_D(s)} = \frac{-s\,H_{FD}(s)}{s + K_I\beta H_{FC}(s)} \tag{3}$$

C) Model in state space

The equations of the LFC for the single-area power system in the state space considering one input (u_1) are [46]:

$$\frac{d}{dt}x_1 = -\frac{1}{T_P}x_1 + \frac{K_P}{T_P}x_2 - \frac{K_P}{T_P}u_1 \tag{4}$$

$$\frac{d}{dt}x_2 = -\frac{1}{T_T}x_2 + \frac{K_T}{T_T}x_3 \tag{5}$$

$$\frac{d}{dt}x_3 = -\frac{K_G F_H}{T_G R_P}x_1 - \frac{1}{T_R}x_3 + \left(\frac{1}{T_R} - \frac{F_H}{T_G}\right)x_4 + \frac{K_G F_H}{T_G}x_5 \tag{6}$$

$$\frac{d}{dt}x_4 = -\frac{K_G}{T_G R_P}x_1 - \frac{1}{T_G}x_4 + \frac{K_G}{T_G}x_5 \tag{7}$$

$$\frac{d}{dt}x_5 = -K_I\beta x_1 \tag{8}$$

where x_1 shows the changes in the frequency deviation of the area and u_1 shows the changes in the load. Also, variable x_5 indicates the output of the integrator controller.

The droop parameter of the primary frequency is R_P, the time constant and gain of the governor are T_G and K_G, the time constant and gain of the turbine are T_T and K_T, the gain and time constant of the power system and load are K_P and T_P.

3. Two-Area Power System Model in State Space

There are many different types of electric power generating plants, such as: hydroelectric power plants, wind power plants, solar power plants, nuclear power plants and steam power plants.

Usually, the power system of an area is connected to its neighbouring areas through connecting lines. LFC is used in interconnected systems to reduce rotating storage and reduce frequency deviation changes in an area [47-49]. The equations of the LFC for the two-area power system are expressed as follows by choosing 11 state variables in the state space:

$$\frac{d}{dt}x_1=-\frac{1}{T_{P1}}x_1+\frac{K_{P1}}{T_{P1}}x_2-\frac{K_{P1}}{T_{P1}}x_{11}-\frac{K_{P1}}{T_{P1}}u_1 \tag{9}$$

$$\frac{d}{dt}x_2=-\frac{1}{T_{T1}}x_2+\frac{K_{T1}}{T_{T1}}x_3 \tag{10}$$

$$\begin{aligned}\frac{d}{dt}x_3=&-\frac{K_{G1}F_{H1}}{T_{G1}R_{P1}}x_1-\frac{1}{T_{R1}}x_3+\left(\frac{1}{T_{R1}}-\frac{F_{H1}}{T_{G1}}\right)x_4\\&+\frac{K_{G1}F_{H1}}{T_{G1}}x_5\end{aligned} \tag{11}$$

$$\frac{d}{dt}x_4=-\frac{K_{G1}}{T_{G1}R_{P1}}x_1-\frac{1}{T_{G1}}x_4+\frac{K_{G1}}{T_{G1}}x_5 \tag{12}$$

$$\frac{d}{dt}x_5=-K_{I1}\beta_1x_1+K_{I1}x_{11} \tag{13}$$

$$\frac{d}{dt}x_6=-\frac{1}{T_{P2}}x_6+\frac{K_{P2}}{T_{P2}}x_7-\frac{K_{P2}}{T_{P2}}x_{11}-\frac{K_{P2}}{T_{P2}}u_2 \tag{14}$$

$$\frac{d}{dt}x_7=-\frac{1}{T_{T2}}x_7+\frac{K_{T2}}{T_{T2}}x_8 \tag{15}$$

$$\begin{aligned}\frac{d}{dt}x_8=&-\frac{K_{G2}F_{H2}}{T_{G2}R_{P2}}x_6-\frac{1}{T_{R2}}x_8\\&+\left(\frac{1}{T_{R2}}-\frac{F_{H2}}{T_{G2}}\right)x_9+\frac{K_{G2}F_{H2}}{T_{G2}}x_{10}\end{aligned} \tag{16}$$

$$\frac{d}{dt}x_9=-\frac{K_{G2}}{T_{G2}R_{P2}}x_6-\frac{1}{T_{G2}}x_9+\frac{K_{G2}}{T_{G2}}x_9 \tag{17}$$

$$\frac{d}{dt}x_{10}=-K_{I2}\beta_2x_6+K_{I2}x_{11} \tag{18}$$

$$\frac{d}{dt}x_{11}=2\pi T_S(x_1-x_6) \tag{19}$$

where variables x_1 and x_6 show the frequency deviation changes in area 1 and 2, respectively. Also, the variable x_{11} shows the transmission power of the connecting line between the two areas. In these equations, the load changes in two areas are specified by $u_1=\Delta P_{D1}$ and $u_2=\Delta P_{D2}$, respectively.

4. Simulation Results

Unpredictable deviation of the load demand from the nominal value changes the operating point of the power system and therefore, deviations in the nominal frequency and planned power exchanges may be created in the system. The parameters of the studied two-area power system with reheat steam turbine are listed in Table 1.

Table.1.
Parameters of the studied power system

Parameters	***Area 1***	***Area 2***
K_P	1	1
T_P	10	20
T_G	0.2	0.3
K_G	1	1
R_P	0.05	0.04
K_T	1	1
T_T	0.3	0.5
T_R	7	10
F_H	0.3	0.5
β	0.5	0.5
K_I	0.4	0.4

Fig. 4 shows the frequency deviation changes for each area when they are independent from each other. As can be seen, after the load demand changes, the frequency deviation decreases in the steady state, which is higher in area 1 than area 2.

Also, as can be seen, the amount of overshoot in area 2 is lower than in area 1.

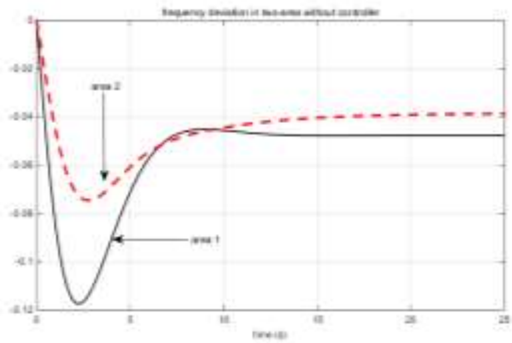

Fig. 4. Frequency deviation changes in single-area without controller (load changes in area 1)

Fig. 5 shows the frequency deviation changes for each area when they are connected but still not controlled. As can be seen, in this case, the frequency deviation will reach a steady state, but due to the connection between the areas, the frequency droop has decreased. This frequency droop difference in steady state is shown for area 1 in fig. 6.

The dynamic response of frequency deviation changes in areas 1 and 2, for step changes in load demand in area 1, are shown in fig. 7. Also, the changes in power transmission between two-area is shown in fig. 8. As can be seen, the power changes tend to zero in the steady state.

As can be seen, the overshoot of the response for area 1 is higher than the overshoot in area 2. Also, the changes in transmission power between the two areas reach zero in the steady state. For faster response, you can use PID controller.

In the same way, for step change of load demand in area 2, frequency deviation changes and power changes between two areas are shown in figs. 9 and 10, respectively.

In this case, the overshoot response of frequency deviation changes for area 2 is higher than area 1. This response is natural, because the area where the load demand changes have occurred is more inclined to respond to it. Therefore, in the relevant area, there are both higher fluctuations and higher overshoot.

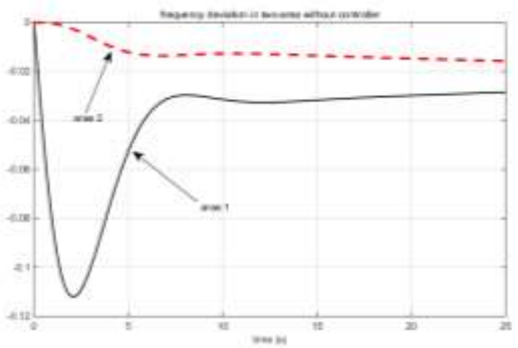

Fig. 5. Frequency deviation changes in two-area without controller (load changes in area 1)

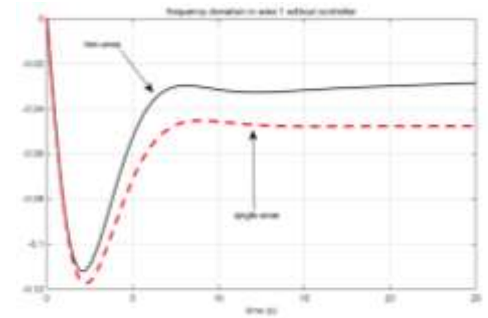

Fig. 6. Comparison of frequency deviation changes in two connection modes

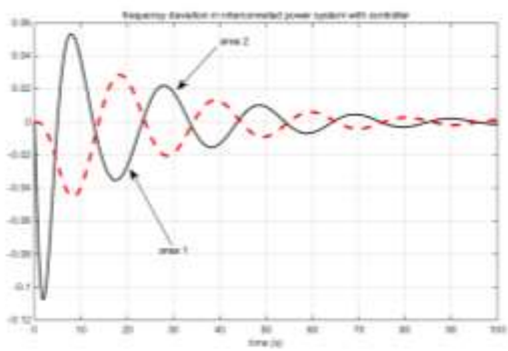

Fig. 7. Frequency deviation changes in area 1 (load changes in area 1)

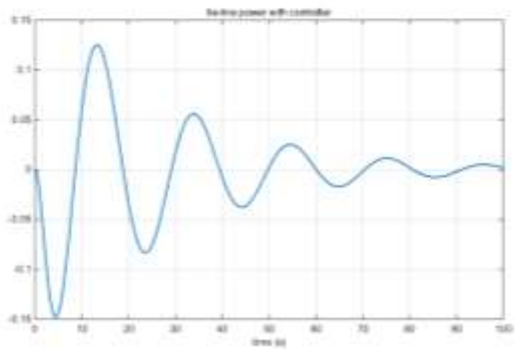

Fig. 8. Changes in power transmission between two-area (load changes in area 2)

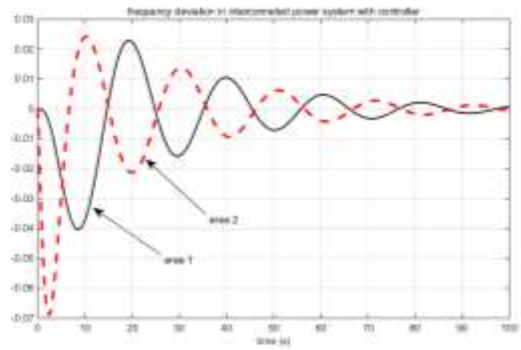

Fig. 9. Frequency deviation changes in area 1 (load changes in area 2)

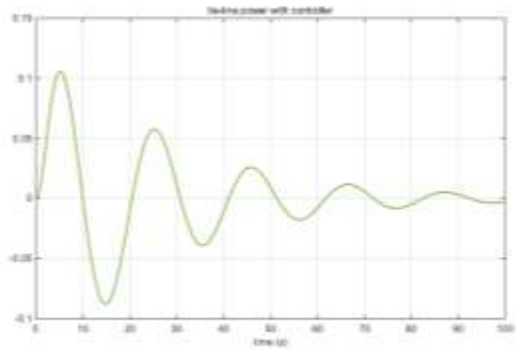

Fig. 10. Changes in power transmission between two-area (load changes in area 2)

5. Conclusion

Load frequency control is an important function in modern energy management systems. In this paper, the frequency deviation changes in the power system with reheat steam turbine were studied. Two areas were considered for the target system. The first order differential equations in the state space were expressed for two systems. Then, the simulation results were obtained using MATLAB software. The simulation results were obtained for an independent area, two interconnected areas without a controller and for two interconnected areas with a controller, and the transient behavior of the system was shown.

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