HYDROGEN, FUEL CELL & ENERGY STORAGE

Small signal stability analysis and frequency control in a single-area multi-source electrical energy system

Ghazanfar Shahgholian | Majid Dehghani* | Mohammad Reza Yousefi
Sayyed Mohammad Mehdi Mirtalaei

Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran
* Corresponding author, Email: dehghani@pel.iaun.ac.ir

Article Information

Article Type
Research Article

Article History
Received: *17 Mar 2024*
Revised: *20 May 2024*
Accepted: *10 Jun 2024*
Published Online: *10 Jun 2024*

Keywords

Gas turbine power plant
Hybrid power system
Load frequency control
Thermal power plant

Abstract

One of the important parameters in power system stability is frequency. The importance and difficulty of frequency control in a multi-area power system increases with the integration of several power generation sources. One of the important tasks of frequency load control is to eliminate frequency deviation error. The analysis of small signal stability using linearized model of single-area power system with different power sources is presented in this study. Power system area includes three steam turbine power plants with reheater, hydro turbine power plant with transient compensator and gas turbine power plant. To eliminate the frequency deviation that occurs due to small disturbances in the system, a load frequency controller is used. The simulation results along with the analysis of the system modes (eigenvalues analysis) show the dynamic behavior of the system due to the changes in the parameters and the participation coefficients of the power plants. The dynamic behavior of the power system is simulated using MATLAB software.

Cite this article: Shahgholian, G., Dehghani, M., Yousefi, MR., Mirtalaei, SMM. (2024). Small signal stability analysis and frequency control in a single-area multi-source electrical energy system. DOI: 10.22104/HFE.2024.6799.1291

Publisher: Iranian Research Organization for Science and Technology (IROST)
DOI: 10.22104/HFE.2024.6799.1291

1 Introduction

Energy supply in critical conditions is one of the important parameters of passive defence [1,2]. With the introduction of renewable energy sources in the power system, better sources of electricity production from the environmental perspective will replace conventional production sources [3,4]. With the rapid development of industrial centres and increasing load demand by consumers, the energy demand in the world is increasing [5,6]. Due to limited energy sources and lack of electricity storage, energy supply has become more important in the world [7,8].

The growing demand for electricity has increased the generation of electrical energy and the transmission system has reached its maximum capacity [9,10]. However, in power plants, the output power must be kept at an appropriate level. Besides, a lot of money is needed in power plants to meet the demand of industrial, commercial centers and other consumer loads [11,12]. The balance of the hybrid power system is influenced by the increase in penetration of renewable energies into the power source. The intermittent nature of renewable resources may affect the power of the grid, which causes frequency fluctuations in the grid, and thus makes it difficult to control the grid frequency [13,14]. In order to have an efficient and stable operation of the power system, it is necessary to design effective controllers. Therefore, modelling is necessary and important for the optimal design of controllers [15,16]. Nominal frequency stability control and terminal voltage control in interconnected power system is always a challenging issue for researchers [17,18]. Many studies have been dealt with to reduce the frequency deviation in the power system [19,20].

The load frequency control of a power system with multi-source power generation including thermal dynamics with reheat turbine, hydro power plant and gas power plant is simulated in [21], which the appropriate production rate limits for thermal and hydropower plants are considered. Moreover, an optimal output feedback controller using only output state variables is proposed for frequency control. Load frequency control of a hybrid power generation system is investigated in [22], where first-order PID (proportional-integral-derivative) controllers are used. The hybrid system is based on thermal, wind and solar.

Two control methods to reduce frequency fluctuations in a large-scale wind farm and photovoltaic hybrid power system are presented in [23], where a high-voltage direct current connection line is used. A slot filter and a dead band are used for frequency control methods, and the simulation results are shown in a multi-machine power system.

A hybrid optimization method of three optimization methods, including firefly algorithm, particle swarm optimization, and gravitational search algorithm, is presented in [24] to adjust the frequency deviation and link power in a multi-source power system.

One of the most important actions, to maintain the balance between the production and demand of electrical energy in the power system, is the primary frequency control (frequency control in power systems by governors) in the network. In the primary control, the control loop of all generating units operates and causes the frequency to be brought close to the nominal value within a few seconds [25,26]. Therefore, the primary control system will have some error, which will be eliminated by the supplementary control system.

In this study, frequency load control in a single-area power system is studied and simulated. The hybrid power system consists of three generation units, including gas turbine power plant, heat turbine power plant with reheater and hydro turbine power plant. Using the linear model, the stability of the small signal of the power system is checked by determining the modes of the system. The results of the simulation show the frequency changes of the power system due to load changes and changes in the participation of production units in supplying the required power.

The structure of the study is as follows. In section 2, the description of the system is given, which consists of three different power plants. In section 3, the transfer functions of the studied system are stated, where the steady-state frequency changes are given for the step changes of the demand load. In section 4, the simulation results using MATLAB software are given. The simulation results have been checked using system mode analysis, and the accuracy of the results has been shown. Finally, the conclusion is stated in section 5.

2 System description

A combined system, consisting of a steam power plant with reheater, a hydropower plant and a gas plant is considered.

2.1 Thermal power plant

The steam turbine power plant is one of the most important thermal power plants, which have a large contribution to the production of electrical energy. In this power plant, steam is used as a fluid and driving agent and it works based on the Rankine cycle. Reheater are designed to increase the saturated steam temperature and help control the outlet steam temperature [27,28]. These power plants are widely used all over the world to generate electricity. Steam reheating is one of the ways to increase the efficiency of the steam cycle in this power plant [29,30].

To describe the linearized model of steam turbine power plant equipped with reheater, four state variables are needed: incremental frequency deviation, changing the position of the incremental governor valve, incremental generation change, and incremental changes in turbine output. Further, the model has two inputs: incremental changes in speed changer position and incremental load demand change [31,32].

2.2 Hydro power plant

In a hydroelectric power plant, water at a high altitude passes through the blades of a hydro turbine, and electricity is produced by converting the potential energy of water into kinetic energy [33].

The most important advantage of the water turbine power plant is the elimination of the cost of fuel supply. Moreover, compared to thermal power plants, they have a longer average life [34,35]. In this case, four state variables are needed to display the linear model, which is similar to the steam power plant. The input signals are also similar to the steam turbine power plant.

2.3 Gas turbine power plant

Due to the vastness of the network and the diversity of the power of the gas turbine power plant, this power plant is used to supply electricity. Quick installation, no need for water, and high start-up speed are the advantages of this power plant. Disadvantages of gas power plant include low efficiency, environmental pollution, and short life [36,37]. The working principle of a gas turbine power plant is the same as a steam turbine power plan. The only difference is that they use compressed steam for a steam power plant, and compressed air for a gas power plant, to drive their turbines [38,39].

The working fluid in the gas power plant is air and it works based on the Brayton cycle. The three main components of the power plant are compressor, combustion chamber, and gas turbine. Gas turbine power plants are very sensitive to load changes and disturbances [40,41]. The gas turbine has a complex system, and its overall performance is highly nonlinear.

Determining a high-quality performance model of gas turbine under different load conditions is necessary and important [42,43]. In gas turbine power plant model, 5 state variables are needed to describe the linearized model of the gas power plant. Further, like the previous two models, there are two similar independent inputs in the model.

3 Transfer function model of the power system under study

Power systems are nonlinear and complex, where the system parameters are a function of the operating point, and the load in the power system is constantly changing and not constant [44,45]. For this reason, modelling in the power system is important and necessary to study the behavior and design of the controller [46,47]. During the power outage of the national grid, it is a high priority to maintain the stability of the subsystems. The problems of the frequency load control system are more concentrated on small disturbances in the demand load [48,49]. The purpose of the small signal stability analysis of the power system is to analyze the stability for the occurrence of small disturbances in the power system [50]. This type of stability is influenced by various factors such as the initial operating conditions of the system, the ability of the electrical connections between the system components, and the characteristics of the control devices [51,52].

Figure 1 shows the single-area power system with several energy sources under study. This system includes three sources of water, gas and heat energy production. The contribution factors of thermal unit with reheater, hydro turbine energy facility and gas turbine energy facility are K_{S}, K_{H} and K_{G}, respectively. Notably, the main focus of the block diagram is to show the frequency variation, which is taken as the overall output of the system.

The number of state variables (system order) required to express the first order differential equations of power sources in the state space is 4, 4, and 5 for steam power plant, hydro power plant, and gas power plant, respectively. In the single-area power system, with multiple sources, the rotating mass and load system model is considered once. Therefore, the power system consists of three generation units without secondary control loop, it has 11 order. The transfer function of frequency changes to load demand changes in each single generation unit, respectively, for hydro, gas and steam units are:

$$\Delta F_{\mathrm{H}}(s)=\frac{G_{\mathrm{M}}(s)}{1+\frac{G_{\mathrm{M}}(s)G_{\mathrm{H}}(s)}{R_{\mathrm{H}}}}\left[-\Delta P_{\mathrm{D}}(s)+G_{\mathrm{H}}(s)\Delta P_{\mathrm{C}}(s)\right] \quad (1)$$

$$\Delta F_{\mathrm{G}}(s)=\frac{G_{\mathrm{M}}(s)}{1+\frac{G_{\mathrm{M}}(s)G_{\mathrm{G}}(s)}{R_{\mathrm{G}}}}\left[-\Delta P_{\mathrm{D}}(s)+G_{\mathrm{G}}(s)\Delta P_{\mathrm{C}}(s)\right] \quad (2)$$

$$\Delta F_{\mathrm{S}}(s)=\frac{G_{\mathrm{M}}(s)}{1+\frac{G_{\mathrm{M}}(s)G_{\mathrm{S}}(s)}{R_{\mathrm{S}}}}\left[-\Delta P_{\mathrm{D}}(s)+G_{\mathrm{S}}(s)\Delta P_{\mathrm{C}}(s)\right] \quad (3)$$

where R_{H}, R_{G} and R_{S} are speed governor regulation of hydro, gas and steam units. Also, ΔP_{C} is incremental speed changer position and ΔP_{D} incremental load demand change.

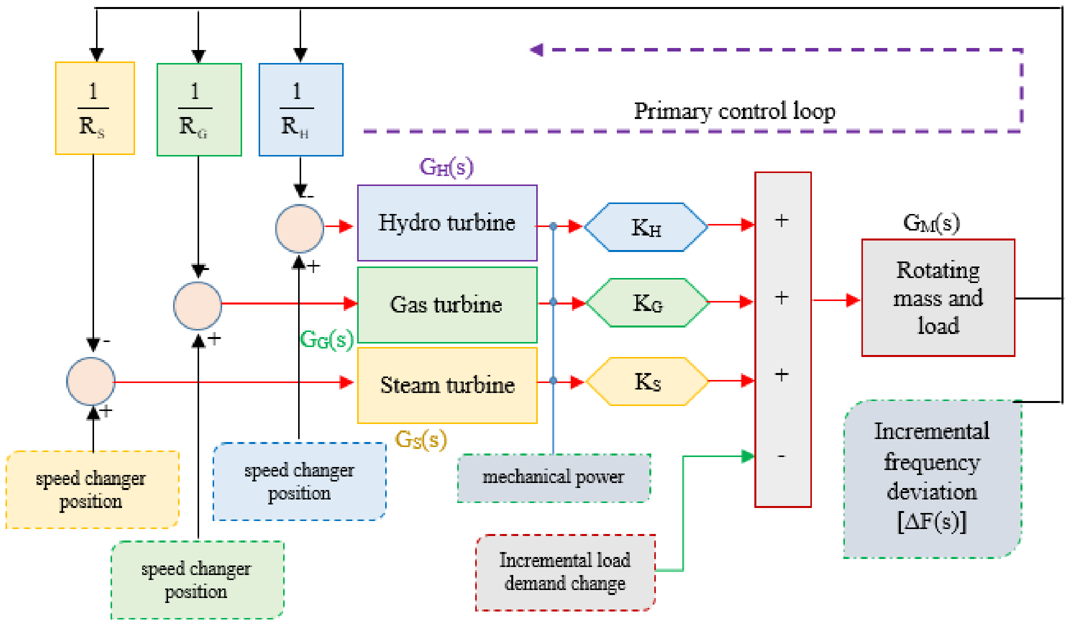

Fig. 1. Single-area power system with multiple energy sources under study.

The transfer function of each generation unit, which is the product of the transfer functions of the components of the generation unit, is represented by $G_{\mathrm{H}}(s)$, $G_{\mathrm{G}}(s)$, and $G_{\mathrm{S}}(s)$, respectively, for the three hydro, gas, and steam generation units:

$$G_{\mathrm{H}}(s) = G_{\mathrm{SM}}(s)G_{\mathrm{HY}}(s)G_{\mathrm{TD}}(s) \quad (4)$$

$$G_{\mathrm{G}}(s) = G_{\mathrm{VP}}(s)G_{\mathrm{SG}}(s)G_{\mathrm{CD}}(s)G_{\mathrm{CR}}(s) \quad (5)$$

$$G_{\mathrm{H}}(s) = G_{\mathrm{ST}}(s)G_{\mathrm{RH}}(s)G_{\mathrm{SD}}(s) \quad (6)$$

The transfer functions of different parts of power plants are defined in Table 1. The steady-state value of the frequency changes when the demand load changes are step, for different power sources, is determined from the following equation:

$$\Delta f_i(\infty) = \lim_{s\to 0} s\Delta F_i(s)\,, \qquad i = \mathrm{H,G,S} \quad (7)$$

Therefore, for each generating source, the steady state value of frequency changes for step changes of demand load is determined as follows:

$$\Delta f_{\mathrm{H}}(\infty) = -\frac{R_{\mathrm{H}}}{1 + R_{\mathrm{H}}K_{\mathrm{D}}}\,, \quad (8)$$

$$\Delta f_{\mathrm{G}}(\infty) = -\frac{R_{\mathrm{G}}}{K_{\mathrm{V}} + R_{\mathrm{G}}K_{\mathrm{D}}}\,, \quad (9)$$

$$\Delta f_{\mathrm{S}}(\infty) = -\frac{R_{\mathrm{S}}}{1 + R_{\mathrm{S}}K_{\mathrm{D}}}\,. \quad (10)$$

4 Results of simulation

In this section, frequency changes in the time domain are shown for step load changes and the effect of parameters on the response is investigated.

Simulation results are shown for different participation coefficients. Three different cases are considered. In each case, the contribution factor of the steam plant is constant, and the other two contribution factors change.

4.1 Changing the participation coefficients of power plants

Tables 2 and 3 show the eigenvalues of the single-area multi-source power system according to the participation coefficients of different production units. The modes of the power system are determined using the eigenvalues of the system matrix. The matrix of the system is determined from the expression of the first order differential equations in the state space. As can be seen, in all three scenarios, the system modes lie to the left of the imaginary axis, and the power system is stable.

When the participation coefficient of the hydro power plant is constant, with the increase of the participation coefficient of the gas power plant and the decrease of the participation coefficient of the steam power plant, the oscillation mode approaches the imaginary axis and moves away from the real axis.

Meanwhile, some of the non-oscillating modes are close to the imaginary axis and some are far away. The closest non-oscillatory mode to the imaginary axis moves away from the imaginary axis with the increase of the participation factor of the hydropower plant.

In these two cases, the participation constant of the hydro power plant is considered constant.

Table 1. Nominal parameters of the studied power system

Generation unit	Transfer function	Parameter	Symbol	Nominal Value
Rotating mass and load	$G_M(s) = \frac{1}{J_M s + K_D}$	System damping coefficient	K_D	$1\,\text{pu}\cdot\text{MW/Hz}$
		Combined inertia constant of the system	J_M	6 pu
Gas turbine power plant	$G_{VP}(s) = \frac{K_V}{1 + T_V s}$	Valve positioner gain	K_V	1
		Time constant of the valve positioner	T_V	0.05 s
	$G_{SG}(s) = \frac{1 + T_L s}{1 + T_G s}$	Time constant of the speed governor lead	T_L	0.6 s
		Time constant of the speed governor lag	T_G	1 s
	$G_{CD}(s) = \frac{1}{1 + T_{CD} s}$	Time constant of the compressor discharge volume	T_{CD}	0.2 s
	$\frac{1}{R_G}$	Speed governor regulation	R_G	$0.2\,\text{Hz/pu}\cdot\text{MW}$
	$G_{CR} = \frac{1 - T_{CR} s}{1 + T_F s}$	Fuel time constant	T_F	0.23 s
		Time delays of the combustion reaction	T_{CR}	0.3 s
Steam turbine power plant	$G_{RH}(s) = \frac{F_H T_H s + 1}{T_H s + 1}$	Steam turbine re-heat coefficient	F_H	0.3
		Re-heat time constant	T_H	7 s
	$G_{ST}(s) = \frac{1}{T_T s + 1}$	Steam turbine time constant	T_T	0.3 s
	$\frac{1}{R_S}$	Speed governor regulation	R_S	$0.2\,\text{Hz/pu}\cdot\text{MW}$
	$G_{SG}(s) = \frac{1}{T_G s + 1}$	Speed governor time constant	T_G	0.8 s
Hydro turbine power plant	$G_{TD} = \frac{T_R s + 1}{T_P s + 1}$	Speed governor rest time	T_R	5 s
		Transient droop time constant	T_P	28.75 s
	$G_{HY}(s) = \frac{-T_W s + 1}{0.5 T_W s + 1}$	Hydro turbine time constant	T_W	1 s
	$\frac{1}{R_H}$	Speed governor regulation	R_H	$0.2\,\text{Hz/pu}\cdot\text{MW}$
	$G_{SM} = \frac{1}{T_G s + 1}$	Main servo time constant	T_G	0.2 s

Table 2. Eigenvalues (modes) of the power system according to the contribution coefficients of different energy sources ($K_H = 0.5$).

Scenario		1	2	3
Contribution coefficients	K_H	0.5	0.5	0.5
	K_S	0.4	0.3	0.2
	K_G	0.1	0.2	0.3
System Eigenvalues		$-0.5419 \pm j0.6093$	$-0.5325 \pm j0.6822$	$-0.5239 \pm j0.7412$
		-0.1201	-0.1217	-0.1240
		-0.2820	-0.2332	-0.2003
		-1.0230	-1.0862	-1.1310
		-3.1983	-3.2225	-3.2509
		-4.0923	-4.0042	-3.9170
		-5.0000	-5.0000	-5.0000
		-5.0000	-5.0000	-5.0000
		-5.8666	-5.9379	-6.0040
		-20.4037	-20.3992	-20.3947
Frequency change value in steady-state		-0.1667	-0.1667	-0.1667
Mechanical power change value in steady-state		0.8333	0.8333	0.833

Table 3. Eigenvalues (modes) of the power system according to the contribution coefficients of different energy sources ($K_H = 0.4$).

Scenario		1	2	3
Contribution coefficients	K_H	0.4	0.4	0.4
	K_S	0.4	0.3	0.2
	K_G	0.2	0.3	0.4
System Eigenvalues		$-0.5635 \pm j0.6175$	$-0.5570 \pm j0.6860$	$-0.5505 \pm j0.7432$
		-0.1180	-0.1194	-0.1213
		-0.2536	-0.2161	-0.1890
		-1.1384	-1.1845	-1.2196
		-3.1703	-3.1969	-3.2290
		-3.9981	-3.9099	-3.8209
		-5.0000	-5.0000	-5.0000
		-5.0000	-5.0000	-5.0000
		-5.8653	-5.9343	-5.9987
		-20.3992	-20.3947	-20.3902
Frequency change value in steady-state		-0.1667	-0.1667	-0.1667
Mechanical power change value in steady-state		0.8333	0.8333	0.8333

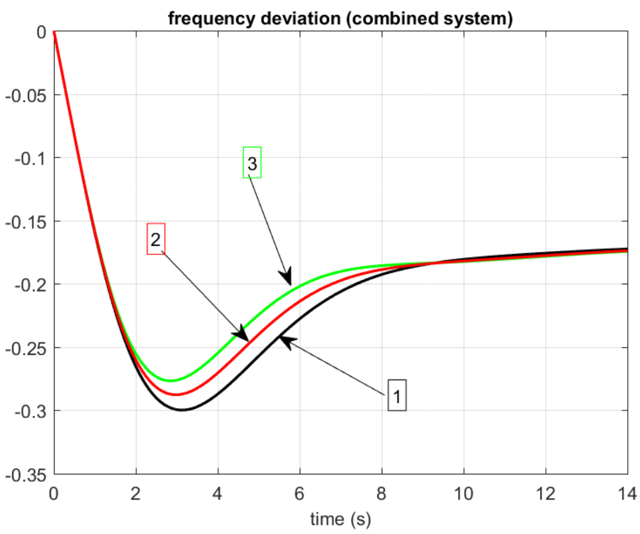

Fig. 2. Frequency deviation of the power system for step changes in the demand load ($K_H = 0.5$).

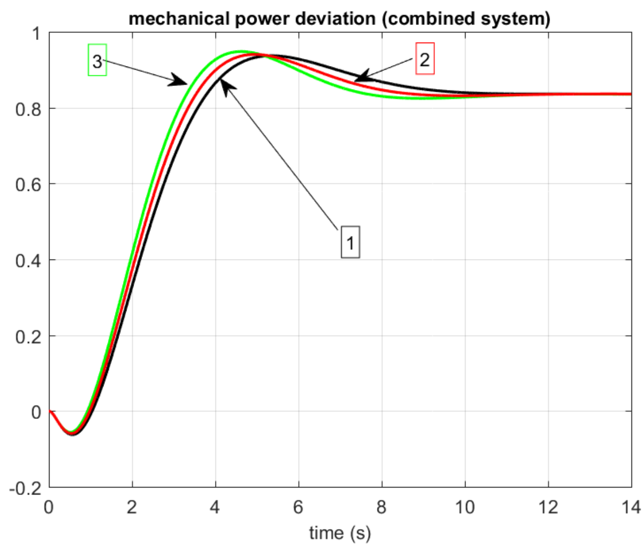

Fig. 3. Step response of mechanical power deviation changes for step changes in the demand load ($K_H = 0.5$).

In each case, two scenarios have been investigated, in which the participation constant of the other two power plants is changed. In each scenario, the value of frequency changes and total mechanical power changes in steady-state is given.

Figures 2 and 3 show the system frequency changes in three scenarios. As can be seen, the frequency droop in steady-state is almost equal for the three scenarios, but scenario 1 has the lowest frequency droop among the three scenarios.

Figures 4 and 5 show changes in mechanical power. As can be seen, in all three scenarios, the final value of mechanical power changes is the same. But in scenario 1, the amount of overshoot is less, and in scenario 3, the amount of response overshoot is more.

4.2 Constant change of inertia of rotating mass and load

In this case, 3 different values of inertia constant are considered. The participation coefficients of steam, hydro and gas power plants are considered to be $K_S = 0.6$, $K_H = 0.3$ and $K_G = 0.1$, respectively. Frequency changes and mechanical power changes are shown in Figures 6 and 7, respectively. As seen, the change of inertia constant has no effect on the amount of frequency deviation and change of mechanical power in steady-state. As observed, with the increase of inertia constant, the maximum frequency droop decreases. Also, with the increase in the participation coefficient of the boiler plant, the transient response speed of frequency changes has decreased.

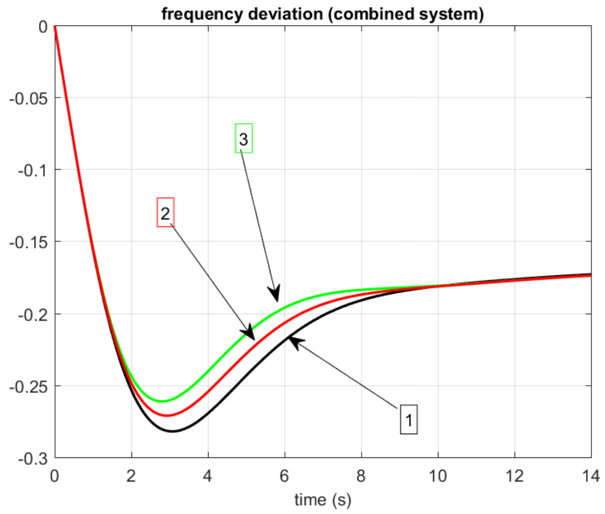

Fig. 4. Frequency deviation of the power system for step changes in the demand load ($K_{\mathrm{H}} = 0.4$).

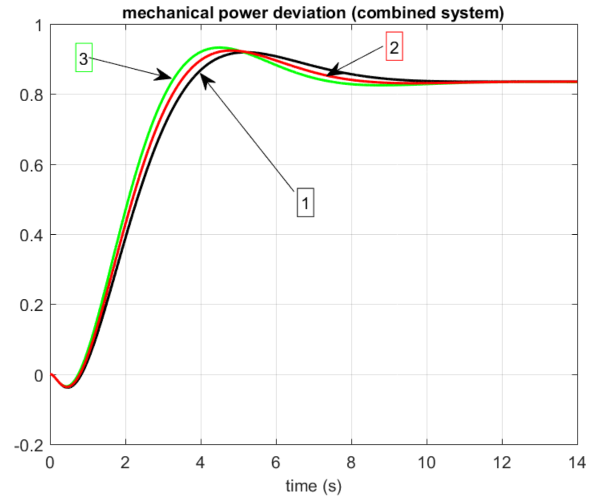

Fig. 5. Step response of mechanical power deviation changes for step changes in the demand load ($K_{\mathrm{H}} = 0.4$).

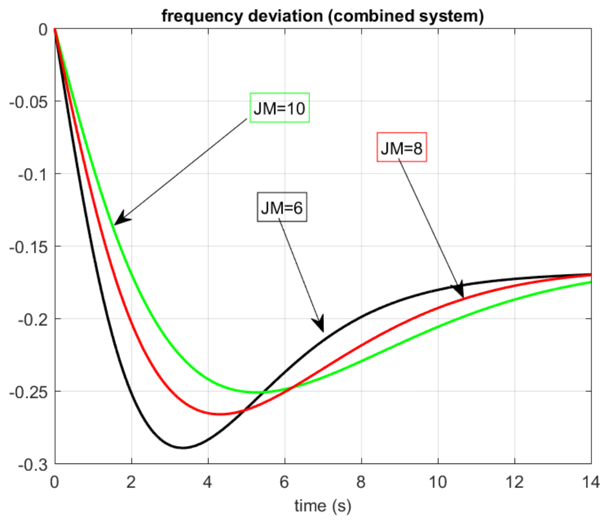

Fig. 6. Power system frequency changes for inertial constant changes.

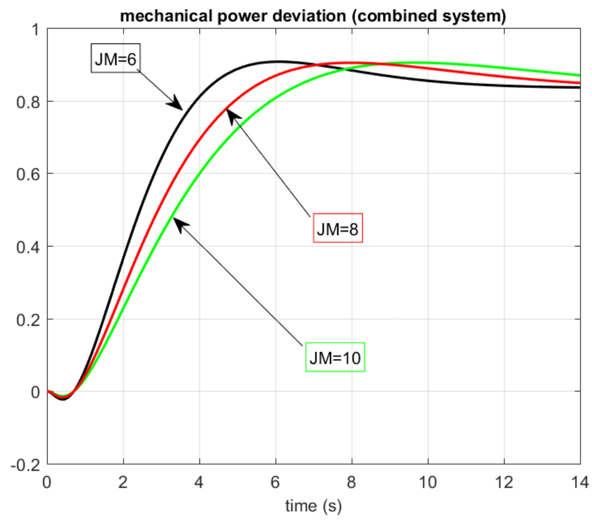

Fig. 7. Changes in the mechanical power of the power system for constant changes in inertia

5 Conclusion

Delivering reliable and sufficient power to load centers plays a vital and important role in power systems. Frequency deviation is one of the important issues in hybrid power generation system. In this study, the frequency changes of a single-area power system with multiple power sources were simulated for changes in the demand load. The simulation results using MATLAB show the behavior of each power source separately along with the frequency changes of the whole system.

The eigenvalues of the system also indicate the stable behavior of the power system. As can be seen from the simulation results, the changes in the contribution coefficients of energy sources have no effect on the values of frequency changes and mechanical power changes in steady-state. Also, with the reduction of the participation coefficient of the hydropower plant, the maximum amount of frequency reduction will also be lower.

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