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# Comparison and Analysis of Dynamic Behavior of Load Frequency Control in Power System with Steam, Hydro and Gas Power Plants

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## Abstract

Various methods are used to produce electrical energy, each of which has its own advantages and disadvantages. The power plant is one of the important parts of the power system, which is responsible for the proper production of electrical energy. In this study, the dynamic behavior of load frequency control is compared and analyzed for three power systems, each including a steam power plant, a hydro power plant, and a gas power plant. The state equations of each system are separately expressed, and then using the analysis of eigenvalues (system modes), the dynamic behavior of the power system is shown for changes in the consumption load. The power system model is simulated in MATLAB software showing the correctness of the analysis of eigenvalues. In addition, the power system model in Simulink MATLAB for each power plant is separately designed and the correctness of the results is shown. The frequency response of the transfer function, i.e., frequency changes to load demand changes, is shown in each production unit. The results of simulation and examination of the power system modes reveal that the steady state response of the three production units is similar to step changes in load demand, and only the speed of reaching the steady state will be different in them.

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## 1. Introduction

Energy plays an important, vital role in the development and progress of society and industrial economy. In other words, with the availability of energy in time and in sufficient quantity, economic development can be possible1,2] ]. Required energy sources exist in different forms and can be stored in different ways3] ]. Energy sources are divided into non-renewable and renewable groups. Renewable energy sources can be regenerated in a short time, whereas non-renewable energy sources cannot be regenerated in a short time 4,5]].

Electrical energy is the most common form of energy which is used for various applications [6,7]. The task of a power system is to meet the demand for electricity, changing from moment to moment due to changes in commercial and residential activities and weather [8,9].

Different power plants produce electricity using different sources, such as nuclear energy, fossil fuels, and renewable sources [10,11]. The advantages and disadvantages of each power plant depend on various factors such as start-up cost and maintenance cost, location of the power plant, and availability of energy sources [12,13].

The automatic generation control system consists of automatic voltage regulator and load frequency control [14,15], which respectively track the voltage deviation and frequency deviation in the multi-area interconnected power system [16,17]. Due to the increase in load demand, frequency is a common factor throughout the power system; therefore, the good performance of the power system entails almost constant frequency [18,19]. The frequency of the power system depends on the active power balance [20,21]. A change in real power at any point in the power system affects the frequency throughout the power system [22,23]. In addition, the balance between production and consumption of active power is subject to disturbances that can be predicted, but unfortunately, the time of occurrence of the disturbance cannot be predicted [24,25].

Due to the continuous variability of the load demand, the output of the production units should be changed automatically [26,27]. So far, various studies have been carried out on the load frequency control, each of which has chosen a method for study [28,29].

A neural network controller is proposed for power system load-frequency control [30], which the steam turbine reheating effect and governor dead-band nonlinearity effect are considered.

A static synchronous compensator along with a variable frequency drive for voltage and frequency control of a small-hydro turbine driven self-excited induction generator system is proposed in [31]. In this compensator, a control algorithm based on adaptive noise cancellation filter is used to control the static synchronous compensator.

A high voltage direct current tie-line is modeled based on a simple first-order transfer function and proposed for multi-area interconnected power system to enhance load frequency control and automatic generation control [32].

An improved ant colony optimization algorithm optimized fuzzy PID (proportional-integral-derivative) controller for load frequency control of multi area systems and a modified objective function to improve the performance of the controller are proposed in [33]..

PID LFC strategy with the help of intermittent control method is proposed in [34], which is used in multi-area interconnected double fed induction generator-based wind power systems under periodic denial of service attacks to fix the frequency.

The accurate modeling of high voltage direct current (HVDC) links for the dynamic studies of automatic generation control/load frequency control of the multi-area interconnected power system is presented in [35], which the comparative analysis has been performed to demonstrate error being accrued due to the use of the conventional model of HVDC links.

To overcome the frequency deviation due to power system disturbance, a Kalman filter and linear quadratic regulator are presented in [36], which is based on combined mode estimation and optimal control. The simulation results show the performance of the controller in different conditions such as a sudden change in Renewable Energy Source.

The effect of frequency control system in a combined cycle gas turbine power plant is studied in [37]. First, the dynamic model of a combined cycle gas turbine power plant is developed in Simulink MATLAB software, which shows the use of it and the response of the power system to frequency changes.

Optimal load frequency control using adaptive neural fuzzy inference system for multi-interconnected system consisting of renewable energy sources is presented in [38]. To check the proposed algorithm, two systems are modeled, one of which has two photovoltaic power plants connected to the grid and a thermal power plant.

An overview of different types of deregulated power system structures, market models, contracts agreements and various control methodologies/techniques to mitigate the various LFC issues in a deregulated power system is provided in [39], which the detailed analysis of various control methodologies based on classical control, robust and self-tuning control, and various soft computing control techniques are discussed.

A survey on LFC mechanism is presented in [40], which reveals the investigation of soft computing based optimization technique, application of energy storage system, and high voltage direct current-link in LFC. In addition, the different control techniques of LFC are mentioned, including all the recent application of flexible ac transmission systems devices.

An optimal predictive control model for the design of LFC in three multi-connected systems including different renewable energy sources in is provided [41]. For optimization, the sooty tern's optimization algorithm has been used.

In this study, power system frequency changes in load frequency control are compared in three generation units including steam power plant with reheater, hydro power plant with transient droop compensation and gas power plant. To display the model of different parts of the power plants, the first order transfer function is used. The system equations are expressed in state space. Then, using the analysis of eigenvalues of the system matrix, the dynamic behavior of the production unit is investigated. The simulation results in the time domain have been obtained using MATLAB software, and they show the correctness of the analysis of the system modes.

## 2. System Model in State Space

The first step in the process of designing control systems in the power system is to determine the appropriate mathematical models for the system [42,43]. In this section, the model of three power plants is shown as a transfer function, and the dynamic equations of each power plant are expressed in the state space [44,45]. The equations of each power plant are expressed as follows [46,47]:

$$\begin{cases} \frac{d}{dt}X = AX + BU + LS \\ Y = CX + DU \end{cases} \tag{1}$$

Where X is the vector of state variables, U is the input vector (signal control), S is input disturbance vector and Y is the output vector. Further, A is the system matrix and B is the input matrix. The control matrix is denoted by C and the output matrix is denoted by D. L is disturbance matrix.

In all three cases studied, the output variables are system frequency changes ($x_1=\Delta f$) and generator output mechanical power changes ($x_2=\Delta P_m$). Also, the changes of the consumption demand load ($u_1=\Delta P_d$) are considered as disturbance input, and the controlled input is the frequency control input signal ($u_2=\Delta P_c$) of the second loop. Therefore, Y, U and S are as follows:

$$Y = [\Delta f \quad \Delta P_m]^T \tag{2}$$

$$U = [\Delta P_c] \tag{3}$$

$$S = [\Delta P_d] \tag{4}$$

The load and mass equivalent circuit for all three generation units are considered with inertia constant ($J_M$) and damping constant ($K_D$).

## 2.1. Steam power plant

Steam power plants usually have a high power generation capacity and they work with the Rankine cycle [48,49]. Diesel fuel or natural gas is used to produce steam by the boiler and to move the blades of the turbine and the rotor of the generator. Additionally, the dry and wet cooling system is used to cool the water resulting from the condensation of steam exiting from the steam turbine [50,51].

Fig. 1 shows the block diagram of the power system including the steam power plant with reheater based on the transfer functions of each part, where $T_T$ is turbine time constant, $T_G$ is governor time constant, $T_H$ is reheat time constant and $F_H$ is turbine high pressure constant. $R_S$ is regulation of the speed of the governor. The gain of the governor is considered to be constant $K_G$.

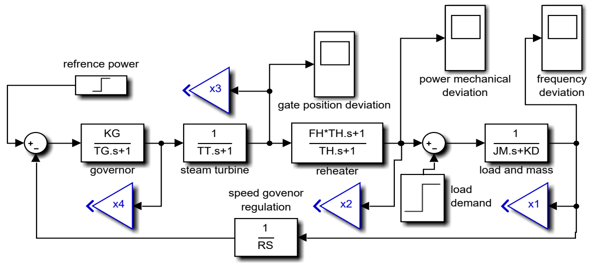

**Fig. 1. Block diagram of power system including steam power plant with re-heater**

In steam flow control in turbine power, reheater has the largest time constant; therefore, the response of reheat turbines is much slower than non-reheater turbines. To represent the first order differential equations in the state space, four state variables are selected.

$$\frac{d}{dt}x_1 = -\frac{K_D}{J_M}x_1 + \frac{1}{J_M}x_2 - \frac{1}{J_M}u_1 \tag{5}$$

$$\frac{d}{dt}x_2 = -\frac{1}{T_H}x_2 + \left(\frac{1}{T_H} - \frac{F_H}{T_T}\right)x_3 + \frac{F_H}{T_T}x_4 \tag{6}$$

$$\frac{d}{dt}x_3 = -\frac{1}{T_T}x_3 + \frac{1}{T_T}x_4 \tag{7}$$

$$\frac{d}{dt}x_4 = -\frac{K_G}{T_G R_S}x_1 - \frac{1}{T_G}x_4 + \frac{K_G}{T_G}u_2 \tag{8}$$

## 2.2. Hydro power plant

Hydroelectric power plant is a renewable source of energy. In a hydropower plant, water is directed to the turbines of the power plant through channels and ducts, and they cause the rotors of the generators to move in order to produce electricity [52,53]. Among their advantages are quick start-up, fast load change, no change in efficiency over time, and independence of energy production cost from the load power factor [54,55]. For stable operation of control due to water inertia in hydro turbines, a transient droop compensator is needed [56].

The block diagram of hydro power plant considering the first order transfer function for different parts is shown in Fig. 2, where $T_W$ is water starting time, $T_G$ is governor time constant, $T_R$ is reset time, $R_H$ is permanent droop and $R_T$ is temporary droop. By choosing four state variables, the first order differential equations are written as follows:

$$\frac{d}{dt}x_1=-\frac{K_D}{J_M}x_1+\frac{1}{J_M}x_2-\frac{1}{J_M}u_1 \tag{9}$$

$$\frac{d}{dt}x_2=\frac{2K_G}{R_T T_G}x_1-\frac{2}{T_W}x_2+\left(\frac{2}{T_W}+\frac{2R_H}{T_R R_T}\right)x_3 -\frac{2T_R R_T}{R_H}\left(1-\frac{T_R}{T_G}\right)x_4+\frac{2K_G R_T}{T_G R_H}u_2 \tag{10}$$

$$\frac{d}{dt}x_3=-\frac{K_G}{R_T T_G}x_1-\frac{R_H}{T_R R_T}x_3+\frac{R_H}{T_R R_T}\left(1-\frac{T_R}{T_G}\right)x_4+\frac{K_G R_H}{T_G R_T}u_2 \tag{11}$$

$$\frac{d}{dt}x_4=-\frac{K_G}{R_H T_G}x_1-\frac{1}{T_G}x_4+\frac{K_G}{T_G}u_2 \tag{12}$$

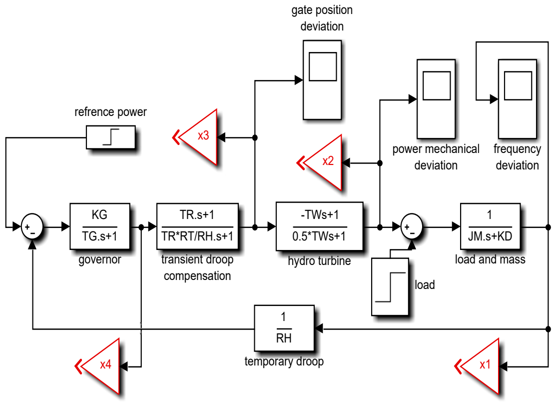

**Fig. 2. Block diagram of power system including hydro power plant with transient droop compensator**

## 2.3. Gas power plant

A gas power plant is a power plant that works on the Brayton cycle and has three main components: A compressor, a combustion chamber, and a gas turbine [57,58]. Low capital cost, and high reliability and flexibility in operation are the advantages of gas power plant. Other advantages are the ability to start quickly and the ability to use a wide range of fuels [59,60].

Fig. 3 shows the model of the gas power plant, showing the different parts of the first order transfer function, where $K_V$ is valve position gain, $T_F$ is fuel time constant, $X_G$ is time constant of the speed governor lead, $Y_G$ is time constant of the speed governor lag, $T_S$ is time delays of the combustion reaction, $T_D$ is time constant of the compressor discharge volume, $R_G$ is speed governor regulation and $T_V$ is time constant of the valve position [61,62].

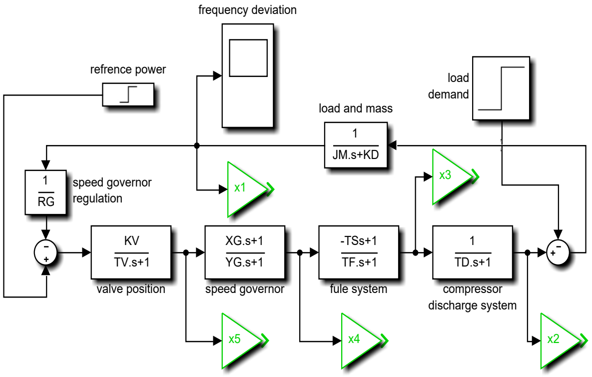

**Fig. 3. Block diagram of power system including gas power plant**

Five state variables are used to represent the first order differential equations of the gas power plant in the state space.

$$\frac{d}{dt}x_1=-\frac{K_D}{J_M}x_1+\frac{1}{J_M}x_2-\frac{1}{J_M}u_1 \tag{13}$$

$$\frac{d}{dt}x_2=-\frac{1}{T_D}x_2+\frac{1}{T_D}x_3 \tag{14}$$

$$\frac{d}{dt}x_3=\frac{K_V X_G T_S}{T_V R_G Y_G T_F}x_1-\frac{1}{T_F}x_3 +\frac{1}{T_F}\left(1+\frac{T_S}{Y_G}\right)x_4+\frac{T_S}{T_F Y_G}\left(\frac{X_G}{T_V}-1\right)x_5-\frac{K_V T_S X_G}{T_F T_V Y_G}u_2 \tag{15}$$

$$\frac{d}{dt}x_4=-\frac{K_V X_G}{T_V R_G Y_G}x_1-\frac{1}{Y_G}x_4-\frac{1}{Y_G}\left(\frac{X_G}{T_V}-1\right)x_5+\frac{K_V X_G}{T_V Y_G}u_2 \tag{16}$$

$$\frac{d}{dt}x_5 = -\frac{K_V}{T_V R_G}x_1 - \frac{1}{T_V}x_5 + \frac{K_V}{T_V}u_2 \qquad (17)$$

## 3. Simulation Results

In this section, simulation parameters are selected for three generation units according to table (1). Each generation unit is simulated separately. To better compare the dynamic behavior of generation units, the same parameters should be selected.

The system modes for three generation units with water turbine, steam turbine and gas turbine are shown in tables (2), (3) and (4), respectively.

The damping coefficient along with the frequency of the oscillating modes is also given in the tables. As can be seen, the oscillation mode frequency of the production unit with gas turbine is higher than the other two units.

Fig. 4 shows the frequency changes of the power system for step changes in load demand for three production units. As observed, the steady state response of three production units is the same. At the beginning of the changes, the frequency droop in the gas unit is less, and it is more in the water unit. The frequency oscillations in the steam unit are less than the other two production units.

Fig. 5 shows the power mechanical changes of the power system for step changes in load demand for three production units. At the beginning of the mechanical power changes, it decreases in the water turbine, but the steady state response of all three production units is the same. In this case, the response of the steam turbine is slower than the other two turbines.

Fig. 6 shows the changes in turbine output mechanical power for step changes in consumption load for three production units.

**Table. 1. Parameters of system for simulation and analysis of dynamic behavior**

| Quantity | Symbol | Value |
|---|---|---|
| Steam power plant with reheat | $T_T$ | 0.3 |
| | $T_G$ | 0.06 |
| | $T_H$ | 10.2 |
| | $F_H$ | 0.3 |
| | $R_S$ | 0.2 |
| Hydro power plant with transient droop compensator | $T_W$ | 1.1 |
| | $T_G$ | 0.2 |
| | $T_R$ | 4.9 |
| | $R_H$ | 0.2 |
| | $R_T$ | 28.749 |
| Gas power plant | $X_G$ | 0.6 |
| | $Y_G$ | 1.1 |
| | $T_V$ | 0.5 |
| | $T_S$ | 0.01 |
| | $T_D$ | 0.2 |
| | $T_F$ | 0.239 |
| | $K_V$ | 1 |
| | $R_G$ | 0.2 |
| Load and mass | $J_M$ | 6 |
| | $K_D$ | 1 |

**Table. 2. Eigenvalues for the hydro turbine generating unit ($J_M$=6)**

| Mode | Damping coefficient | Oscillation frequency (Hz) |
|---|---|---|
| -02114 | 1 | 0 |
| -6.1696 | 1 | 0 |
| -03556±j0.7889 | 41.09% | 12.56% |

**Table. 3. Eigenvalues for the steam turbine generating unit ($J_M$=6)**

| Mode | Damping coefficient | Oscillation frequency (Hz) |
|---|---|---|
| -2.7108 | 1 | 0 |
| -5.3695 | 1 | 0 |
| -0.2818±j0.2902 | 69.66% | 4.62% |

**Table. 4. Eigenvalues for the gas turbine generating unit ($J_M$=6)**

| Mode | Damping coefficient | Oscillation frequency (Hz) |
|---|---|---|
| -0.2201±j0.8931 | 23.93% | 14.21% |
| -5.1053±j1.5491 | 95.69% | 24.65% |
| -1.7437 | 1 | 0 |

The main task of the load-frequency control system is to minimize the frequency changes as much as possible to achieve the stability of the power system to an acceptable level.

### 3.1. Inertia constant increase

The unit of kinetic energy divided by the rated capacity at the rated speed is called inertial constant. The inertia of the power system is changing due to the replacement of conventional units with renewable energy sources [63]. Power systems have different generators, each of which has different inertia. The change of the constant of interest affects the transient stability of the power system, especially when the generators have a small constant of interest. Based on the units used in the power system, the inertia constants are in the range of 2 to 10 seconds [64,65]..

The modes of generation units for constant increase of inertia are given in Tables 5 to 7. Fig. 7 shows the frequency changes of production units for constant increase of inertia. As it is seen, the constant change of interest does not affect the steady state value of frequency changes. However, increasing the inertia constant will reduce the fluctuations. Furthermore, the amount of maximum frequency changes decreases with the increase of inertia.

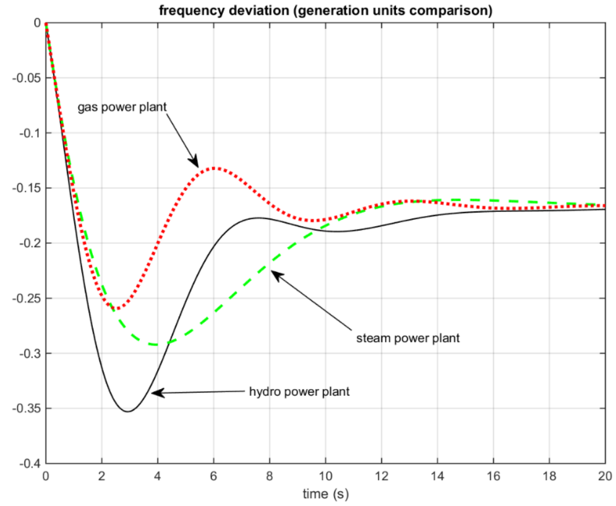

**Fig. 4. Comparison of frequency changes of production units for stepwise increase in load demand**

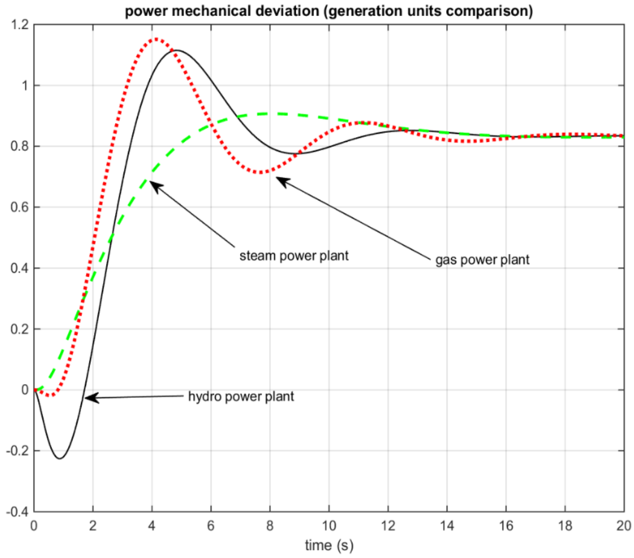

**Fig. 5. Comparison of power mechanical changes of production units for stepwise increase in load demand**

The constant increase in inertia does not affect the permanent state value of mechanical power changes, while it affects the initial drop and initial increase of mechanical power changes, and causes them to decrease.

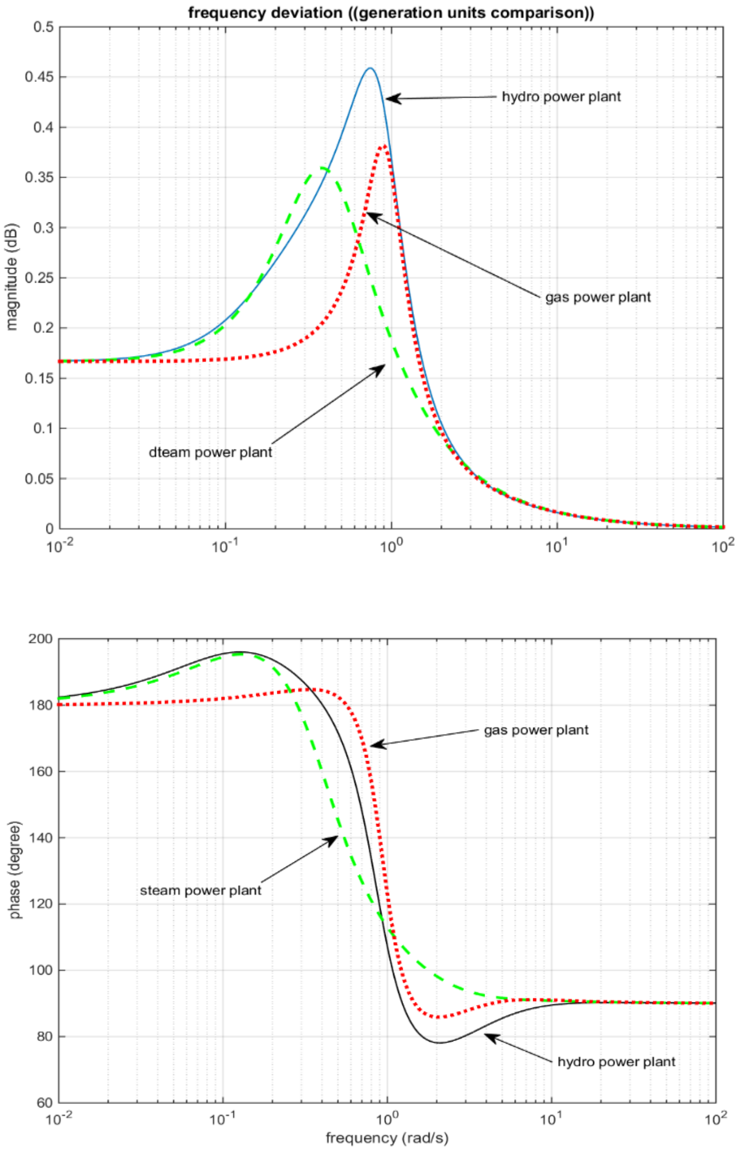

**Fig. 6. Comparing the frequency response of production units**

**Table. 5. Eigenvalues for the hydro turbine generating unit ($J_M$=10)**

| Mode | Damping coefficient | Oscillation frequency (Hz) |
|---|---|---|
| -0.2679 | 1 | 0 |
| -5.7709 | 1 | 0 |
| -0.4934±j0.3681 | 80.15% | 5.86% |

**Table.6. Eigenvalues for the steam turbine generating unit ($J_M$=10)**

| Mode | Damping coefficient | Oscillation frequency (Hz) |
|---|---|---|
| -2.9558 | 1 | 0 |
| -5.2386 | 1 | 0 |
| -0.1909±j、,2363 | 62.84% | 3.76% |

**Table. 7. Eigenvalues for the gas turbine generating unit ($J_M$=10)**

| Mode | Damping coefficient | Oscillation frequency (Hz) |
|---|---|---|
| -0.3619±j0.6529 | 48.48% | 10.39% |
| -4.9699±j1.2409 | 97.02% | 19.73% |
| -1.7941 | 1 | 0 |

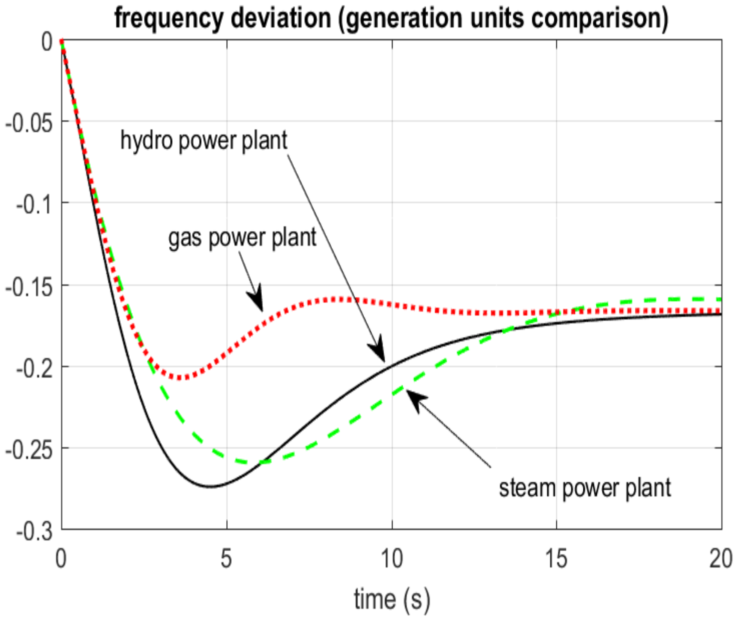

**Fig. 7. The effect of constant increase of inertia on frequency changes**

## Conclution

Today, energy is an important and effective factor in the development and creation of various industries. All production units react to the overall change in production due to the change in load, and the position and location of the load change is not important for them. In this research, the load frequency control system for three production units was studied and compared independently using power system modes. For step changes in load demand, power system frequency changes were shown. The simulation results showed that the steady state response of frequency changes was the same in three production units. The steady state deviation of frequency and mechanical power was the same for all three production units, but their transient response was different from each other. The steam turbine was slower than the other two turbines. Frequency fluctuations in the gas turbine were more than the other two turbines.

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