

Research article

Small signal stability analysis of dynamic behavior of gas turbine power plant with secondary control loop in electric power system

Ghazanfar Shahgholian^{1,2}, Majid Moazzami^{1,2*}, Mohammad Amin Honarvar^{1,2}

¹Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

²Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran

*majid.moazzami@gmail.com

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Abstract

Low changes in active power demand cause changes in the frequency of the power system. The purpose of using a load frequency control (LFC) system is to maintain the frequency balance in the power system, using active power control to minimize frequency changes to achieve acceptable power system stability. In this paper, the investigation of small signal stability in the power system including a gas power plant is presented. The linear model of the gas power plant has been used to study and simulate the load frequency control system. The frequency depends on the parameters of the power system, and small changes in the parameters cause slight deviations in the frequency of the power system. To provide good quality output power, LFC should have good robustness against uncertainty of power system parameters and sudden changes. The first order differential equations of the system in the state space have been used in MATLAB software to simulate the dynamic behavior. The effect of changes in different parameters on frequency deviation and stability of the power system has been investigated. Analysis of system modes show the correctness of the simulation results. The analysis of the system modes shows that the damping coefficient of the uncontrolled system is 0.3230 and the controlled system is 0.2146.

Keywords: Eigenvalues analysis, Gas turbine, Hierarchical control, Load frequency control, Small signal stability

1- Introduction

The power system is a complex system, and it will become more complex with the increase in demand for electric power and the complexity of load patterns, and it has great importance for socio-economic development [1,2]. The power system consists of various components, each of which has a different dynamic behaviour. Loads are random, and constantly changing over time [3, 4]. In addition to this, the influence of scattered production sources in power

systems and the launch of new technologies such as microgrids, causes challenges for frequency exploitation and stability [5, 6]. The effect of continuous load change in the power system causes the frequency to change. The purpose of frequency regulation is to maintain the frequency of the power system at a nominal value. Frequency is important in the operation of the power system, and must remain approximately constant. Frequency deviation may cause system instability and load

shedding [7, 8]. Therefore, to ensure the synchronization of generators and loads and prevent frequency deviation, frequency adjustment is necessary [9,10]. By adjusting the speed, fuel and load demand, it is possible to increase or decrease the output power of generators and the power of loads and adjust the frequency of the power system [11, 12].

Complementary control is used to assist the power system in abnormal conditions to correct inconsistencies. Load frequency control is important for the operation and control of power systems, in order to maintain the power supply of consumers along with the quality and security requirements. Imbalance between production and load changes the frequency of the power system. Therefore, the active output power of the generator must be continuously changed in the frequency control loop to meet the load demand, and the frequency should remain constant at the nominal value. For this reason, load frequency control is an essential part of power system control [13, 14]. By examining the studies conducted in the field of frequency load control, the division according to Fig. 1 can be considered [15]. Until now, various strategies and control structures have been presented for frequency load control in power systems in order to better dynamic response, and transmission of connection line power in their programmed values, for normal and abnormal conditions [16,17]. Proportional-derivative-integrator controller (PID) is one of the common examples of feedback control algorithm, which is widely used in industrial control systems to reduce steady state error. The implementation of the PID controller is simple, and its parameters are easily adjusted [18, 19].

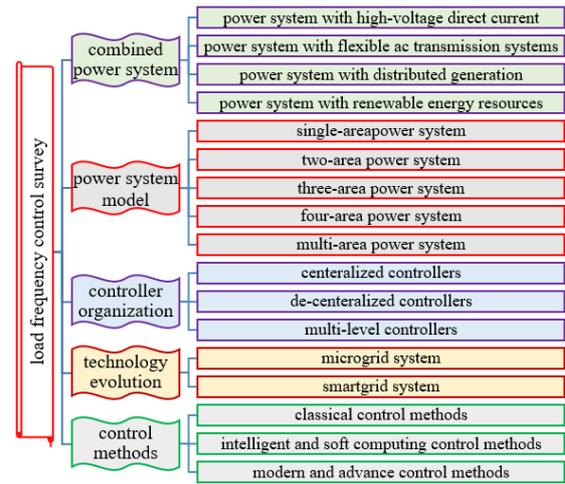


Fig. 1 Classification of studies conducted in the field of frequency load control

PID controller may have long settling time in frequency transient response. In addition, it is not resistant enough to the disruption and uncertainty of the power system. Various control techniques and optimization methods have been presented by researchers for the application of PID controller in frequency load control system [20, 21]. A literature review on the design of a PID controller for load frequency control in power systems is briefly presented in [22], that controller tuning schemes are classified into soft computing techniques, robust control schemes, design based on fractional order, and design based on internal model control. Fractional order PID controller is designed for single area power system in [23], which power system includes steam turbine without preheater, steam turbine with preheater and water turbine. The simulation results show that the fractional order PID controller has good robustness. Optimization of the controller parameters and evaluation of the robustness of the control method have been done using the integral error criterion. The small signal model for the study of automatic production control is developed in [24] based on Rowan's large signal model. The methods of Ziegler-Nichols

(conventional tuning), simulated annealing (search-based tuning) and fuzzy gain programming (adaptive tuning) are used to tune the secondary controller. The results show that the PID controller with simulated annealing has a better response than the other two controllers in both models in the heavy gas turbine design. The design of optimal PID controller based on quadratic regulator approach with pole compensation technique for load frequency control problem is presented in [25], which is done in single-zone and multi-zone power system. The optimal method based on the optimal time response characteristics for setting the PID controller for a hydraulic turbine with transient loss compensator is proposed in [26]. To avoid non-optimal solutions at local minimum points, the nonlinear problem is solved in two steps. This method has the advantage of setting the PID controller in harmony with the transient loss compensator with low calculation time. In [27], the performance of load frequency control for a thermal, water and gas power plant unit with a PID controller is presented, that the PID controller is a sub-controller, to stabilize the system performance, when there is a sudden demand in the power system.

In this paper, the small signal stability of the gas turbine power plant with the secondary control loop in the electric power system is investigated using system mode analysis. The secondary control loop system or load frequency control is designed to bring the frequency deviation to zero. To design the controller, the characteristic equation of the closed loop according to the open loop equation of the system has been used. The innovation of this research can be mentioned as follows:

- Brief review and classification of studies done in the field of load frequency control

along with the classification of gas turbine types

- Expressing the first-order equations of a single-area power system with a gas turbine equipped with a secondary control loop in the state space
- Determining the characteristic equation of the closed loop system according to the coefficients of the characteristic equation of the open loop system

The structure of the paper is as follows. After stating the problem and the importance of the issue along with the division made in the field of load frequency control studies, the structure of the gas turbine power plant is given in section 2. The multi-level control system is explained in section 3. The first-order equations of the single-area power system are stated in section 4. The simulation results are shown in section 5 for step changes in consumption load. Also, the effect of changes in system parameters on frequency deviation is shown along with the analysis of eigenvalues. Finally, the conclusion is stated in section 6. The process of studying the simulation of the power system with gas turbine is shown in Fig. 2.

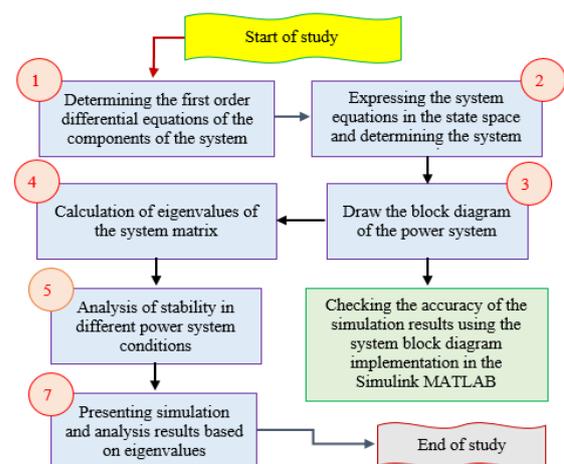


Fig. 2 The process of simulating the studied system and investigating the impact of the photovoltaic system

2- Gas Turbine Power Plant

A gas turbine power plant is a fossil fuel power plant, and it works to produce electricity in the Brayton cycle [28]. This power plant has better flexibility to produce electricity than other power plants. A gas turbine does not need a condenser, and therefore uses less water. Also, its maintenance cost has been low, and it is ready to work without losses and quickly enters the circuit [29,30]. It also requires a smaller area than a steam power plant with the same capacity.

One of the disadvantages of this type of power plant is the high operating cost compared to other power plants [31, 32]. Also, its net power output is low, and the overall efficiency is as low as that of a conventional steam power plant. The thermal efficiency of the power plant directly affects fuel consumption and operating costs. The gas power plant is divided into three groups: open loop gas turbine [33], closed loop gas turbine [34] and combined cycle gas turbine [35, 36]. According to Fig. 3, gas turbines are divided into four groups. The three main components of a gas turbine are: compressor, combustion chamber and turbine.

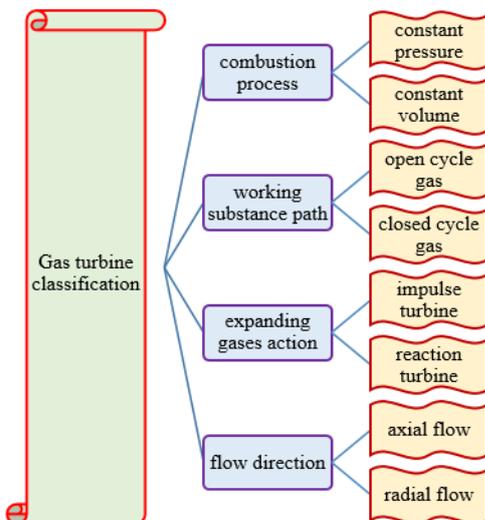


Fig. 3 Classification of gas turbines into four groups

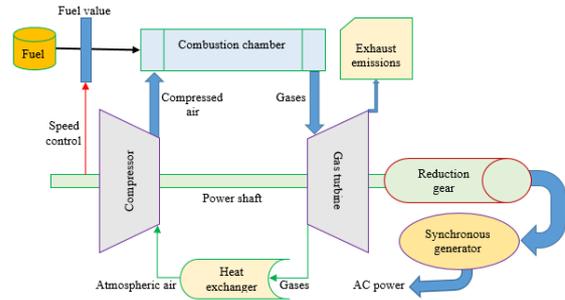


Fig. 4 Open cycle gas turbine electric power generation configuration

The relationship between components in a simple gas turbine power plant for electricity generation is shown in Fig. 4.

3- Multi-Layer Control System

Hierarchical control is a coordinated approach, which uses different levels of controllers to regulate the voltage and frequency of power systems. Frequency load control has a hierarchical structure with three levels of control according to Fig. 5 [37,38]. Frequency stabilization is done in the first level controller. In the controller of the second level, the frequency returns to the nominal value. In the third level controller, economic distribution is done for optimal electricity production. The power system frequency is usually controlled using two primary and secondary control loops. In the primary control loop, by using governor droops, it prevents immediate frequency changes that may cause steady state error. The first level control is an automatic function, and its response period is about a few seconds, so it is the fastest control among the three control levels. Secondary control or load frequency control is used to adjust the frequency of the power system to its nominal value in the network [39,40]. The second level control, which has automatic function, the power exchange between the power systems is restored, and the frequency returns to its nominal value. Additi-

onal production and stopping the production capacity or increasing the consumption load increase the frequency and decrease the frequency, respectively. The third level control has the task of recovering the reserve margin used in the second level. This level of control is set by the transmission system operator (TSO).

4- Studied System Overview

In this section, the structure of the studied power system and its equations in the state space are expressed. Also, the power system model with secondary control loop is determined based on transfer functions. Fig. 6 shows the small signal model of the gas turbine power plant. The transfer function of the blocks along with the input signals and output signals (chosen as state variables) and the task of each block are listed in Table 1. System parameters along with their nominal values are introduced in Table 2 [41, 42].

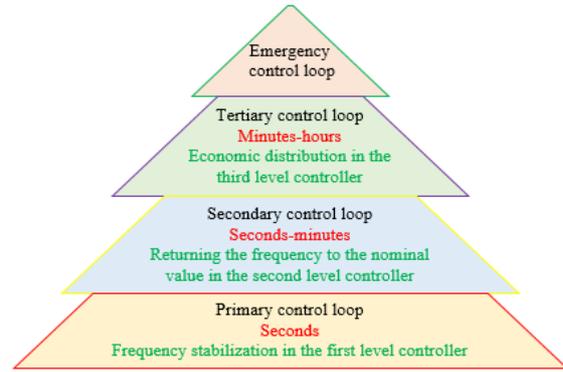


Fig. 5 Hierarchical structure in load frequency control

4-1- Transfer Function Model

The transfer function model describes the relationship between input and output signals of a system. In the open loop mode, the frequency changes of the system are determined in terms of two inputs as follows.

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

where $H_{PD}(s)$ and $H_{PC}(s)$ are defined as the open loop transfer function of the system frequency changes in relation to the load changes and in relation to the speed position changes.

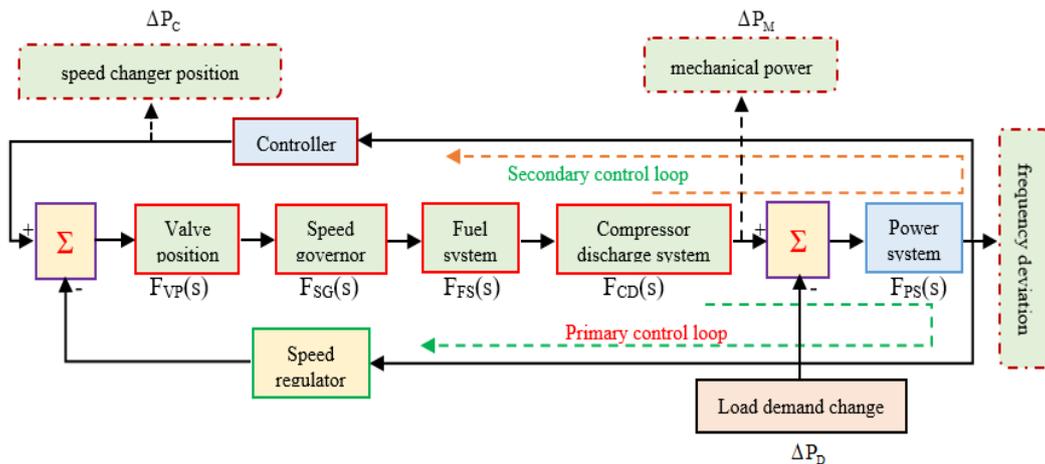


Fig. 6 Small signal model of gas turbine power plant

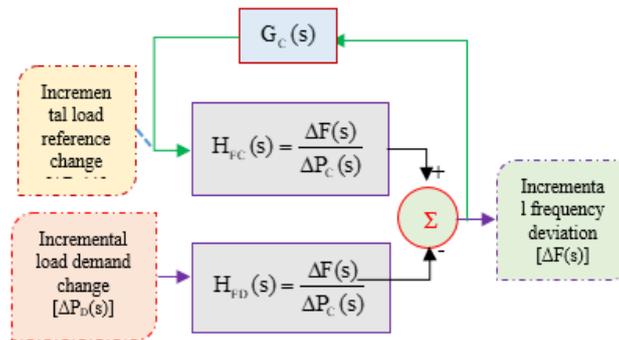


Fig. 7 Closed loop model of gas turbine power plant with controller according to transfer functions

Table 1: Transfer functions with input and output signals of each block

| Name | Transfer function | Input signal | Output signal (State variable) |
|-----------------------------|--|---------------------------------------|--------------------------------|
| Valve position | $F_{VP}(s) = \frac{K_V}{1 + T_V s}$ | $\Delta P_C + \frac{1}{R_G} \Delta F$ | ΔP_{VP} |
| Speed governor | $F_{SG}(s) = \frac{1 + T_L s}{1 + T_G s}$ | ΔP_{VP} | ΔP_{SG} |
| Fuel system | $F_{FS}(s) = \frac{1 - T_{CR} s}{1 + T_F s}$ | ΔP_{SG} | ΔP_{FS} |
| Compressor discharge system | $F_{CD}(s) = \frac{1}{1 + T_{CD} s}$ | ΔP_{FS} | ΔP_M |
| Rotating mass and load | $F_{PS}(s) = \frac{K_{PS}}{1 + T_{PS} s}$ | $\Delta P_M - \Delta P_D$ | ΔF |
| Controller | $G_C(s) = K_P + \frac{K_I}{s}$ | ΔF | ΔP_C |

Table 2: Parameters of small signal model transmission blocks of gas power plant

| Name | Block function | Parameter | Symbol | Value |
|-----------------------------|--|--|----------|-------------|
| Valve position | Placing the valve in the correct position by increasing or decreasing the air load pressure on the actuator | Valve positioner constants | K_V | 1 |
| | | Time constant of the valve positioner | T_V | 0.049 sec |
| Speed governor | Frequency and load control based on operation mode and balancing the required load of power and frequency deviations | Lead time constant of the gas turbine speed governor | T_L | 0.6 sec |
| | | Lag time constant of the gas turbine speed governor | T_G | 1.1 sec |
| | | Speed governor regulation | R_G | 2.4 Hz/puMW |
| Fuel system | Delivering gas fuel to turbine combustion chambers at proper pressure and flow rate | Time constant of the gas turbine fuel | T_F | 0.239 sec |
| | | Gas turbine combustion reaction time delay | T_{CR} | 0.01 sec |
| Compressor discharge system | Bringing the air flow in the gas turbine compressor to a very high pressure | Time constant of the compressor discharge volume | T_{CD} | 0.20 sec |
| Rotating mass and load | Equivalent representation of the power system | Gain of the power system | K_{PS} | 70 Hz/pu |
| | | Time constant of the power system | T_{PS} | 12 sec |
| Controller | Frequency controller in the secondary loop | Proportional gain constant | K_P | 0.1 |
| | | Integral gain constant | K_I | 0.1 |

The open-loop transfer function of the single-area power system with gas turbine is considered as follows, where the roots of the polynomials $N_D(s)$ and $N_C(s)$ are the zeros of the open-loop transfer function and the roots of the polynomials $\Delta_o(s)$ are the poles of the open loop transfer function of the power system.

$$H_{FC}(s) = \frac{N_C(s)}{\Delta_o(s)} = \frac{c_2s^2 + c_1s + c_0}{s^5 + a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0} \quad (2)$$

$$H_{FD}(s) = \frac{N_D(s)}{\Delta_o(s)} = \frac{d_4s^4 + d_3s^3 + d_2s^2 + d_1s + d_0}{s^5 + a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0} \quad (3)$$

If the demand load changes to the value of ΔP , the frequency deviation in permanent mode is determined from the following equation.

$$\Delta f(\infty) = \frac{d_0}{a_0} \Delta P \quad (4)$$

Fig. 7 shows the closed loop small signal model of gas turbine power plant with controller based on transfer functions. As can be seen, the output signal of system frequency changes is selected as the input signal of the controller, and the output signal of the controller is added as the reference signal of load changes. In this case, the single-area system has one input and one output, which are the load changes and system frequency changes, respectively. Frequency changes in the closed loop power system are:

$$\Delta F(s) = -\frac{H_{FD}(s)}{1 + G_C(s)H_{FC}(s)} \Delta P_D(s) \quad (5)$$

where $G_C(s)$ is the transfer function of the controller. Also $H_{FD}(s)$ show frequency changes to load changes and $H_{FC}(s)$ frequency changes to speed set point changes.

Therefore, the characteristic equation of the closed loop system is determined according to the following equation.

$$\Delta_C(s) = \Delta_o(s) + \left(K_P + \frac{K_I}{s}\right) N_C(s) \quad (6)$$

The integral part of the controller makes the response of the frequency deviation tend to zero in the steady state. The proportional part of the controller has no effect on the steady state value of the frequency deviation response.

The characteristic equation of the gas turbine single-area power system, with the second level controller, based on the coefficients of the characteristic equation of the open loop power system, is expressed as follows:

$$\begin{aligned} \Delta_C(s) = & s^6 + a_4s^5 + a_3s^4 + (a_2 + K_P c_2)s^3 \\ & + (a_1 + K_P c_1 + K_I c_2)s^2 + (a_0 + K_P c_0 + K_I c_1)s \\ & + K_I c_0 \end{aligned} \quad (7)$$

4-2- State Space Model

By choosing the state variables defined for the small signal model blocks of the gas turbine power plant, the first-order equations of the single-area power system with the gas turbine are expressed as follows:

$$\frac{d}{dt} \Delta f = -\frac{1}{T_{PS}} \Delta f + \frac{K_{PS}}{T_{PS}} \Delta P_M - \frac{K_{PS}}{T_{PS}} \Delta P_D \quad (8)$$

$$\frac{d}{dt} \Delta P_M = -\frac{1}{T_{CD}} \Delta P_M + \frac{1}{T_{CD}} \Delta P_{FS} \quad (9)$$

$$\begin{aligned} \frac{d}{dt} \Delta P_{FS} = & \frac{K_V T_L T_{CR}}{T_V R_G T_G T_F} \Delta f - \frac{1}{T_F} P_{FS} \\ & + \frac{1}{T_F} \left(1 + \frac{T_{CR}}{T_G}\right) \Delta P_{SG} + \frac{T_{CR}}{T_F T_G} \left(\frac{T_L}{T_V} - 1\right) \Delta P_{PV} \\ & - \frac{K_V T_{CR} T_L}{T_F T_V T_G} \Delta P_C \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{d}{dt} \Delta P_{SG} = & -\frac{K_V T_L}{T_V R_G T_G} \Delta f - \frac{1}{T_G} \Delta P_{SG} \\ & - \frac{1}{T_G} \left(\frac{T_L}{T_V} - 1\right) \Delta P_{VP} + \frac{K_V T_L}{T_V T_G} \Delta P_C \end{aligned} \quad (11)$$

$$\frac{d}{dt} \Delta P_{VP} = -\frac{K_V}{T_V R_G} \Delta f - \frac{1}{T_V} \Delta P_{VP} + \frac{K_V}{T_V} \Delta P_C \quad (12)$$

By adding the secondary frequency control loop, the first order equation for the controller output is:

$$\frac{d}{dt} \Delta P_C = -K_I \Delta f - K_P \frac{d}{dt} \Delta f \quad (13)$$

Substituting the frequency variation equation, we will have:

$$\begin{aligned} \frac{d}{dt} \Delta P_C = & \left(K_I + \frac{K_P}{T_{PS}} \right) \Delta f - \frac{K_P K_{PS}}{T_{PS}} \Delta P_M \\ & + \frac{K_P K_{PS}}{T_{PS}} \Delta P_D \end{aligned} \quad (14)$$

5- Simulation results

In this section, the first order equations in the state space of the studied power system are simulated using MATLAB software. Also, the modes of the power system are determined using the system matrix.

The order of the power system without the controller is 5, and considering the PI controller, the order of the system changes to 6. The dynamic response of the power system is obtained for a step load perturbation. Table 3 shows the eigenvalues of the system with open and closed secondary loop. The real part of the eigenvalues in the open loop are on the left side of the imaginary axis, in other words, the response of the system will be stable. But the frequency deviation will not tend to zero in a permanent state. The real parts are negative in the closed-loop eigenvalues, and the stability condition of the system holds.

Figs. 8 and 9 show the frequency deviation response and the mechanical power response for the power system without control loop. Also, Fig. 10 shows the frequency response of the transfer function of frequency changes relative to load demand changes.

The results show that the frequency changes do not tend to zero in the permanent state.

The response of deviation of frequency changes and deviation of turbine output mechanical power changes for the power system with secondary control loop are shown in Figs. 11 and 12. It can be seen that the frequency changes desire to zero in the steady state. As can be seen, three real eigenvalues in two cases remained almost unchanged, but in the controlled system, one real eigenvalue was added to the system. The real pole added to the system with secondary loop control is closer to the imaginary axis than other poles, so it will have an important effect on the dynamic response. Also, the system has a mixed eigenvalue in two states, which is the damping coefficient of 0.3230 in the uncontrolled system and 0.2146 in the controlled system.

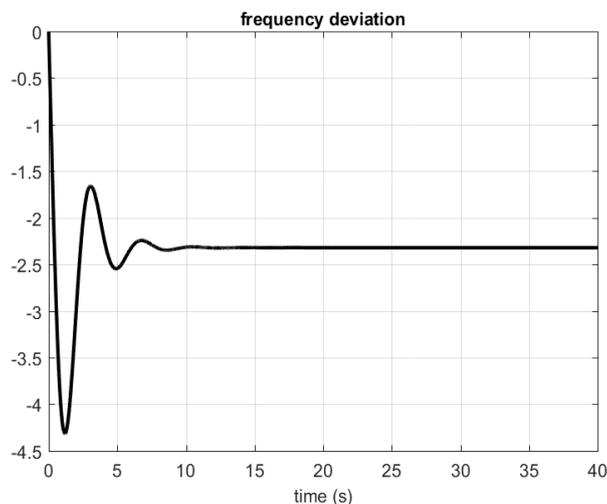


Fig. 8 Dynamic response of system frequency changes without control loop (Frequency changes in Hz)

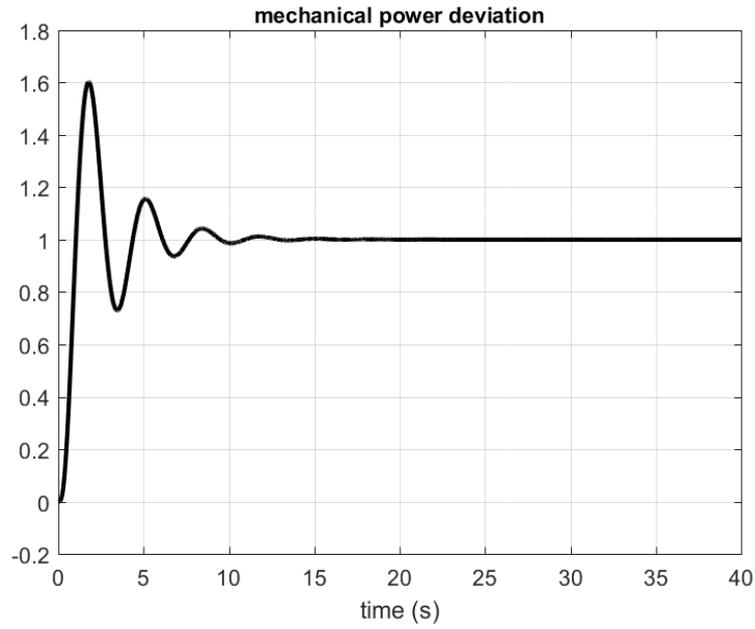


Fig. 9 Dynamic response of mechanical power output without control loop (Mechanical power changes in per-unit)

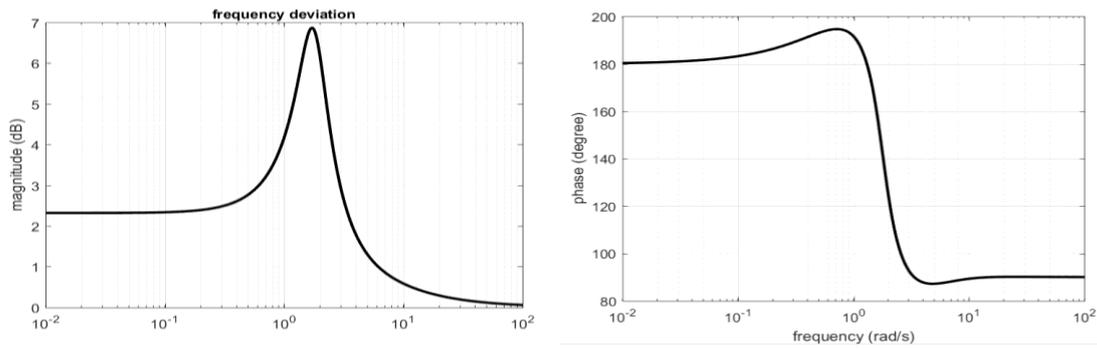


Fig. 10 Frequency response of the transfer function of frequency changes in the uncontrolled system

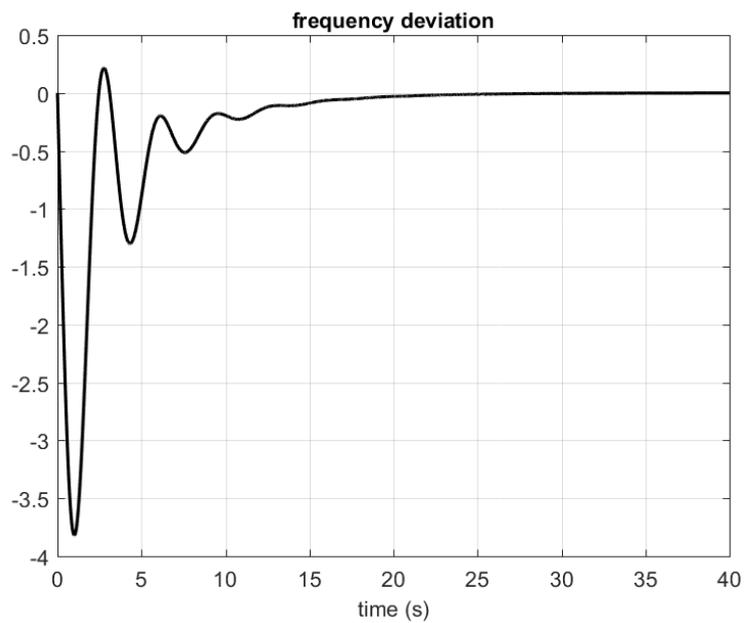


Fig. 11 Dynamic response of system frequency changes with secondary control loop

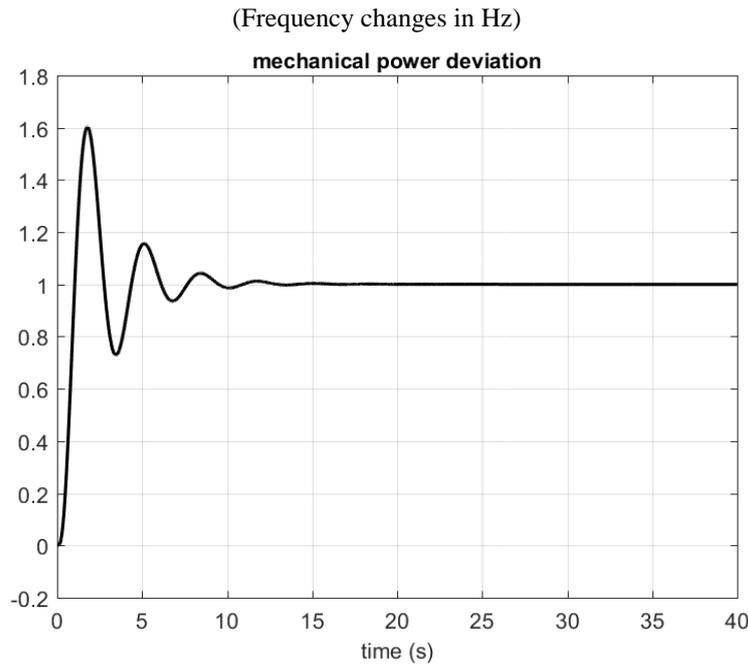


Fig. 12 Dynamic response of changes in turbine output mechanical power with secondary control loop (Mechanical power changes in per-unit)

Table 3: Eigenvalues of single-area power system with open and closed secondary loop

| Open loop | Close loop |
|-----------------------|-----------------------|
| -2.1330 | -0.1997 |
| -7.0072 | -2.0701 |
| -20.2764 | -7.2396 |
| $-0.5791 \pm j1.6970$ | -20.2455 |
| | $-0.4149 \pm j1.8879$ |

6- Conclusion

The main purpose of the power system is to provide continuous power with acceptable quality for consumers. Load frequency control is an important control system in the power grid, whose main purpose is to adjust the output power of each generator to limit frequency fluctuations. Load frequency control is necessary to create better utilization and control for less impact on the frequency and power changes of the connection line, after disturbance in the demand load. The closed-loop controller of the system will add a real mode to the system modes, which will be on the left side of the imaginary axis and close to it.

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