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Study and simulation of small signal stability of gas turbine plant with combined LFC and AVR control loops in single area power system

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Abstract

In order to manage voltage and frequency stability, a hybrid model of two control loops including load frequency control and automatic voltage regulation is used in power systems. This paper focuses on a hybrid model that integrates load frequency control (LFC) and automatic voltage regulator (AVR) to ensure voltage and frequency stability in a single-area power system with a gas turbine power plant. The effect of these two control loops in a single-zone power system is investigated and simulated. The single-zone power system includes a gas turbine power plant, and a small-signal model is used to analyze the dynamic behavior of the power system. The system equations are represented in the state space model, and the simulation results are analyzed by calculating the system states. Also, to check the accuracy of the simulation results, the power system model is implemented in the MATLAB Simulink environment, which shows the accuracy of the simulation results and their analysis.

Keywords: Automatic voltage regulator, Gas turbine, Load frequency control, Small signal model, Stability.

1- Introduction

As industry advances and demand for electrical energy increases, providing energy to consumers such as industrial centers and commercial centers is of great economic importance while respecting environmental issues [1,2]. The penetration of renewable energy sources has caused extensive changes in modern power grids, and has complicated the architecture of the power grid. In a power system, frequency or voltage disturbances can cause problems in the system operation, so the nominal voltage and frequency must be provided to the consumers without any delay [3,4]. The load is always dynamic, and is always changing, and therefore the imbalance between power generation and load has an adverse effect on the frequency and voltage of the power system [5,6]. Electrical energy cannot be stored on a large scale with high efficiency, and therefore one of the main operating conditions is to balance demand and grid consumption at any given moment [7,8]. The most important task of a control system in power systems is to manage power to reduce frequency variations, voltage variations and zero the power exchange between different areas [9,10]. The system frequency is mainly affected by active power variations, while reactive power mainly depends on voltage variations. Load imbalance can cause changes in active power and reactive power. In the LFC control loop, frequency variations are controlled by adjusting the active power, and terminal voltage variations are regulated by adjusting the reactive power in the AVR control loop. By adjusting the excitation of generators according to the reactive power demand in AVR, the generator terminal voltage will be within the specified limit. However, to provide active power, the turbine input in LFC must be continuously adjusted [11,12]. The imbalance between generated power and consumed load is one of the most important reasons for voltage and frequency instability in the power system. The quality of the power supply system is determined based on the dynamic performance of the two control loops LFC and AVR with respect to frequency and voltage. Therefore, AVR-LFC hybrid systems are used to support the reliability and performance of power generation systems [13,14].

So far, various studies have been conducted on LFC and AVR control loops, most of which have considered these loops separately [15,16].

A review of advances in load frequency control (LFC) for interconnected multi-area power systems (IMAPS) is presented in [17], which focuses on frequency instabilities, the application of modern technologies, and addressing emerging challenges such as renewable energy integration, smart grids, and cybersecurity. It covers classical control methods, modern technologies, and future strategies.

A particle swarm optimization controller - deep neural network (PSO-DNN) for optimizing LFC in a microgrid (MG) with vehicle-to-grid (V2G) interactions is investigated in [18], where the challenges of high frequency deviations caused by the unpredictable nature of renewable energy sources, variable loads, and electric vehicle integration are considered. The PSO-DNN controller is compared with traditional proportional-integral-derivative (PID) and PSO-optimized PID (PSO-PID) controllers, and shows superior performance in terms of efficiency, transient response, and stability. While the focus is on LFC, the PSO-DNN approach can be extended to AVR for simultaneous frequency and voltage control, and to address coupled dynamics in microgrids.

Frequency and voltage control in a multi-zone power system with automatic load frequency control (ALFC) loop and AVR loop is investigated in [19], where wind farms based on doubly fed induction generators (DFIG) are used for inertia control to inject active power into the power system. The results show the improvement of frequency and voltage deviations under transient conditions due to the coordinated operation of the DFIG.

The parameters of the AVR-LFC system controllers have been selected using the metaheuristic method in [20] [1] to be optimal based on the proposed objective function. Also, the fractional-order proportional–integral–derivative controller has been used to analyze the load changes for the AVR-LFC system, and it is shown in the simulation results.

The combination of automatic generation control (AGC) and AVR in a hybrid interconnected system is investigated in [21], where a cascade fractional order controller is used to suppress oscillations. The optimal parameters for the AVR-AGC system are determined using the coot algorithm optimization technique.

The performance of the inter-line power flow controller and power system stabilizer in a two-zone hybrid system is analyzed and investigated in [22], where the proportional plus integral fraction plus derivative fraction with filter controller is considered for the ALFC and AVR control loops. The results show that the combined control performance of IPFC and PSS has a greater impact on the system dynamics than their individual use.

An approach to improve LFC and AVR systems in a two-zone interconnected power system using a fast fuzzy-order slope integral derivative controller (HFF-FOTIDC) is presented in [23]. This controller integrates fast fuzzy control logic and fractional-order slope integral derivative (FOTID) control logic, and its parameters are optimized using the Aquila optimization technique based on the covariance matrix adaptive evolution strategy (CMAESAO). This study evaluates the controller's performance against step disturbances in zone 1 and compares it with traditional proportional-integral (PI) and integral (I) controllers. Simulation results show that the proposed method minimizes frequency and voltage deviations more effectively than PI/I controllers. By damping inter-zone power and frequency fluctuations, it returns the system to nominal values (frequency, voltage) more quickly.

In this paper, a small signal model of a single-zone power system including a gas turbine power plant is considered, and the effect of interactions between the two control loops LFC and AVR is simulated and investigated. To analyze the simulation results, a power system state space model has been used, and the results have been analyzed by calculating the modes of the system matrix. Also, the system model has been implemented in the MATLAB Simulink environment, which shows the correctness of the analysis results.

Among the highlights of this study, the following can be mentioned:

- The importance of coordinated control between LFC and AVR to ensure robust power system performance.
- The use of a gas turbine power plant is relevant for modern grids, where such plants are common due to their flexibility and fast response.
- Simulation of control strategies and theoretical analysis with implementation in MATLAB Simulink environment

The process of investigating the two control loops in a gas turbine power plant in this study is shown in Fig. 1.

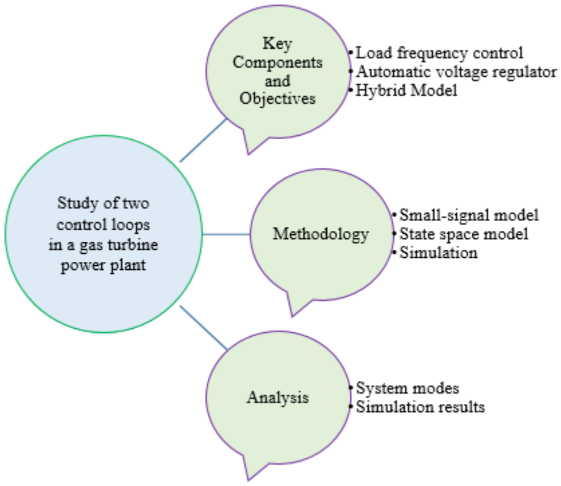

Fig. 1 The process of investigating and simulating two control loops in a gas turbine power plant

2- Gas Turbine Power Plant

A gas power plant is a power plant that uses the thermal energy of gaseous and liquid fossil fuels to produce hot gas and consume it in a gas turbine to generate electricity. In this power plant, ambient air is used as the fluid to rotate the turbine [24,25]. A gas turbine power plant is a thermal power plant that uses a gas turbine to generate electricity. It is very quick to install and is available in a variety of configurations, including simple cycle, combined cycle, and combined heat and power. Gas turbines are very fast to start up, and are suitable for meeting peak demand and providing backup power. Gas turbines can also adjust their output to meet demand fluctuations, thus playing an important role in grid stability [26,27]. The advantages of gas power plants include the lack of water requirement, rapid construction, high maneuvering speed, and quick start-up. The disadvantages of this type of power plant include low efficiency, short life, low production range, and high cost of electricity produced. The disadvantages of a steam power plant compared to a gas power plant include the need for water, lower maneuvering speed, higher cost of electricity produced, and longer construction time. The gas power plant operates on the Brayton cycle. The components of a gas power plant are shown in Fig. 2 [28,29].

3- Combined LFC-AVR Model

Synchronous generators play an important role in providing uninterrupted and high-quality electrical energy to the grid. Automatic voltage regulator and load frequency control are two main control systems in power systems for stable power delivery, used to maintain voltage and frequency, respectively [30,31]. These two control loops work together to ensure voltage and frequency stability in the power system [32,33]. Fig. 3 shows a synchronous generator with the above two control loops. Fig. 4 shows the single-zone power system model implemented in MATLAB Simulink, which consists of a gas turbine power plant with two control loops, LFC and AVR. As can be seen, the governor constitutes the first level of frequency control, and the second level of frequency control is formed using an integral-gear controller [34,35]. If ΔP_E is the internal electrical power deviation which is sensitive to the load characteristics, ΔP_M is the deviation in power generation and ΔP_L is the change in load demand or the change in real power, the linearized oscillation equation is expressed as follows [36,37]:

$$\frac{d}{dt}\Delta f = -\frac{1}{T_{PS}}\Delta f + \frac{K_{PS}}{T_{PS}}\Delta P_M - \frac{K_{PS}}{T_{PS}}\Delta P_E - \frac{K_{PS}}{T_{PS}}\Delta P_L \qquad (1)$$

$$\frac{d}{dt}\Delta\delta = 2\pi(\Delta f) \qquad (2)$$

where K_{PS} and T_{PS} are power system equivalent gain and time constant respectively [38,39].

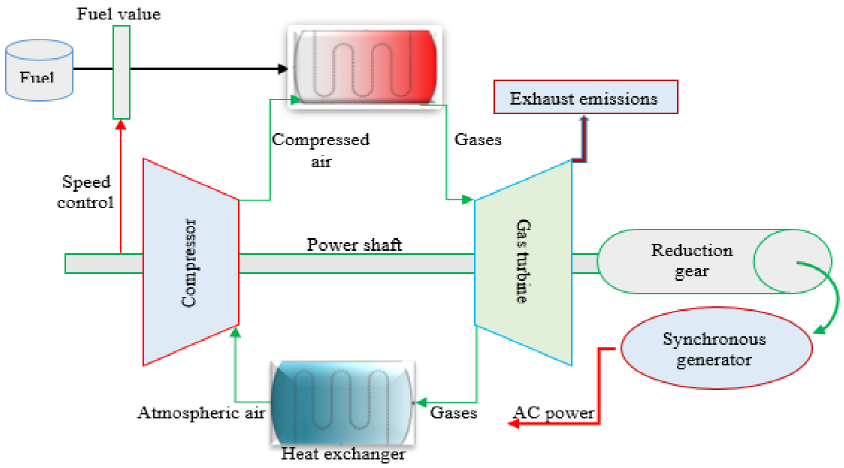

Fig. 2 Open cycle gas turbine electric power generation configuration

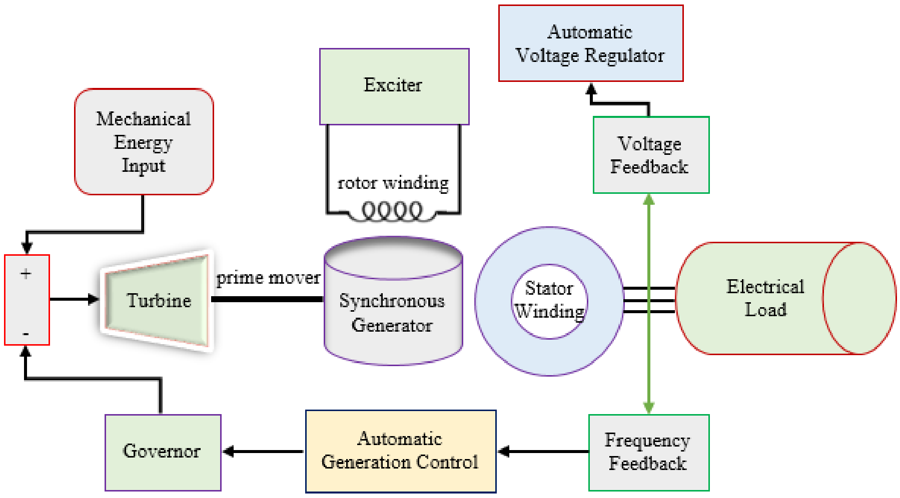

Fig. 3 Combined LFC and AVR model in single area power system

Also Δδ is deviation of torque angle and Δf is deviation of load frequency. In power system stability studies, the Heffron-Phillips constants K_1 through K_6 are a set of parameters used in a linearized model to describe the dynamic relationships between rotor speed, voltage, and excitation. These constants are derived from the machine's physical parameters and operating conditi-ons and are crucial for analyzing and des-igning control systems like the automatic voltage regulator (AVR) and power system stabilizer (PSS) to maintain grid stability. Using constants K_1 through K_6, a dynamic model of the synchronous generator and its control system can be developed to predict its stability and performance.

The deviation of internal electrical power (P_E) is determined using the linearization of the electrical power relationship, and are expressed in terms of the constants K_1 and K_2 [40]:

$$\Delta P_E = K_1 \Delta\delta + K_2 \Delta E_{pq} \tag{3}$$

where ΔE_{pq} is q-axis transient voltage. K_1 is the synchronizing power coefficient and K_2 is the change in power due to the change in stator electromotive force with the constant rotor angle [41].

The generator terminal voltage variation is determined by linearizing the terminal voltage (U_T) relationship, and is expressed in terms of constants K_5 and K_6:

$$\Delta U_T = K_5 \Delta\delta + K_6 \Delta E_{pq} \tag{4}$$

where K_5 is the change in terminal voltage for a small change in the rotor angle with constant stator electromotive force and K_6 is the change in terminal voltage for a small change in stator electromotive force at a constant rotor angle.

The first-order equations of the LFC loop according to the model shown in the MATLAB Simulink environment are:

$$\frac{d}{dt}\Delta P_{CD} = -\frac{1}{T_{CD}}\Delta P_{CD} + \frac{1}{T_{CD}}\Delta P_F \tag{5}$$

$$\frac{d}{dt}\Delta P_F = -\frac{1}{T_F}(\Delta P_F + \Delta P_G - T_{CR}\frac{d}{dt}\Delta P_G) \tag{6}$$

$$\frac{d}{dt}\Delta P_G = -\frac{1}{T_G}(\Delta P_G + \Delta P_{VP} - T_L\frac{d}{dt}\Delta P_{VP}) \tag{7}$$

$$\frac{d}{dt}\Delta P_{VP} = -\frac{1}{T_V}(\Delta P_{VP} + K_V \Delta P_C - \frac{1}{R_G}\Delta f) \tag{8}$$

$$\frac{d}{dt}\Delta P_C = -K_{IF}\beta\Delta f \tag{9}$$

where K_V and T_V are gain and time constant of valve position, T_L and T_G are time constant of gas governor, T_{CR} and T_F are time constant of fuel system and T_{CD} is time constant of compressor discharge system.

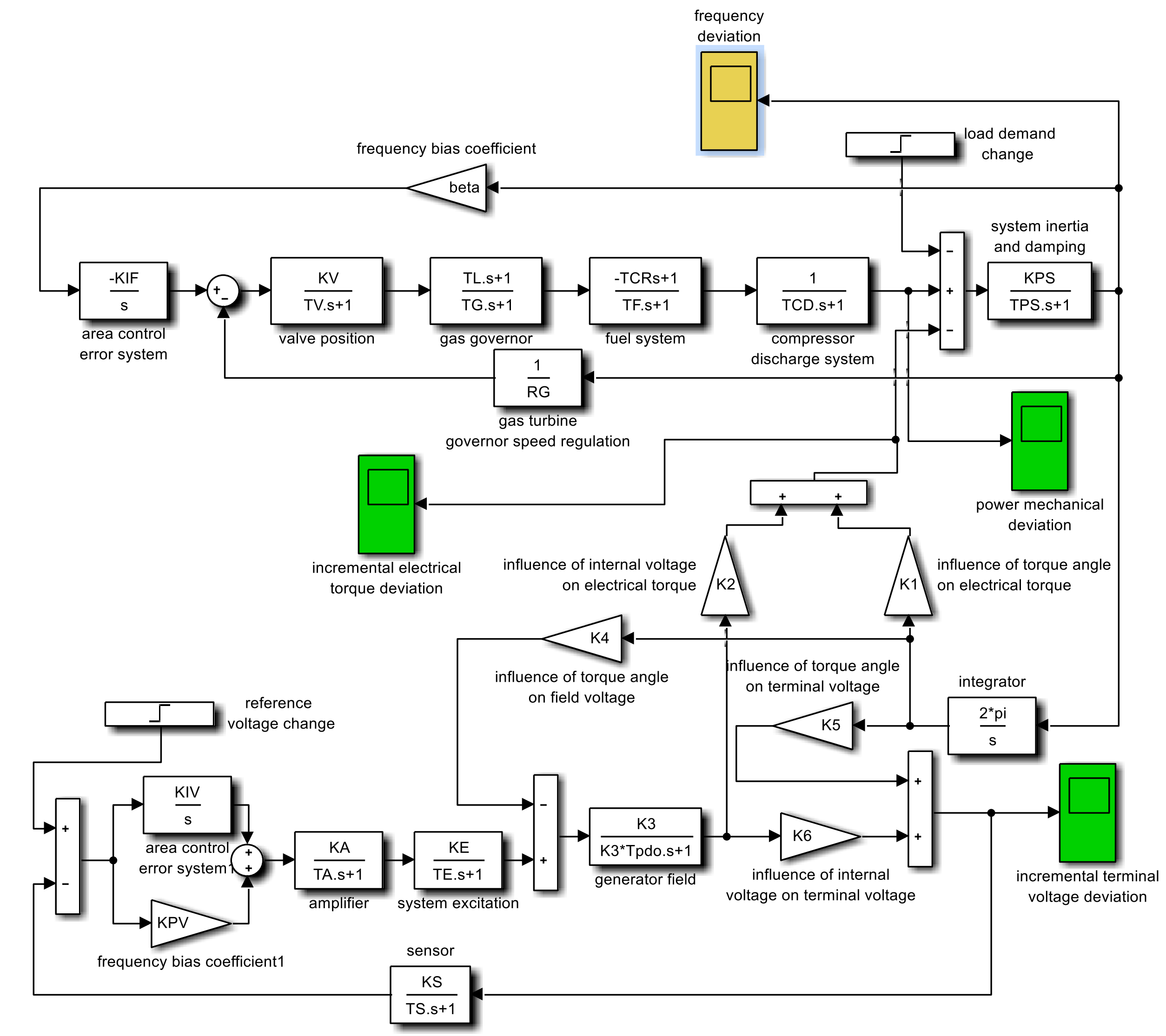

Fig. 4 Mathematical model of gas turbine power plant with combined LFC and AVR loops

The area gain of control system is K_{IF}.

The output signals of the load frequency control section blocks of the gas turbine power plant are: ΔP_{CD}, ΔP_F, ΔP_G, ΔP_{VF} and ΔP_C.

The first-order equations of the AVR loop are expressed as follows by choosing five state variables:

$$\frac{d}{dt}\Delta E_{pq} = -\frac{1}{T_{pdo}}\Delta E_{pq} + \frac{K_3}{T_{pdo}}(-K_4\Delta\delta + \Delta P_{ES}) \tag{10}$$

$$\frac{d}{dt}\Delta P_{ES} = -\frac{1}{T_E}\Delta P_{ES} + \frac{K_E}{T_E}\Delta P_A \tag{11}$$

$$\frac{d}{dt}\Delta P_A = -\frac{1}{T_A}\Delta P_A + \frac{K_A}{T_A}\Delta P_{CA} - \frac{K_A K_{PV}}{T_A}\Delta P_S + \frac{K_A K_{PV}}{T_A}\Delta U_R \tag{12}$$

$$\frac{d}{dt}\Delta P_{CA} = K_{IV}(-\Delta P_S + \Delta U_R) \tag{13}$$

where K_S is sensor gain, K_A is amplifier gain, T_A is amplifier time constant, K_E is exciter gain, T_E is exciter time constant, K_3 is generator field gain and T_{pdo} is generator field time constant. The output signals of the automatic voltage regulator section blocks of the gas turbine power plant are: ΔP_{pq}, ΔP_{ES}, ΔP_A and ΔP_{CA}.

4- Simulation Results Analysis

The first-order equations representing the dynamic behavior of the single-area power system under study are expressed in state space as follows:

$$\begin{cases} \frac{d}{dt}X = AX + BU \\ Y = CX \end{cases} \quad (14)$$

where A is the system matrix, B is the input matrix, and C is the control matrix [42]. The system order is 12 based on the selected state variables. The input vector U and the output vector Y are considered as follows:

$$U = [\Delta P_D \quad \Delta U_R]^T \quad (15)$$

$$Y = [\Delta f \quad \Delta P_M \quad \Delta U_T \quad \Delta P_E]^T \quad (16)$$

In this section, the system modes are determined based on the system matrix. Base voltage changes are assumed to be equal to unity. Load changes are assumed to be stepwise.

The values of the coupling coefficients are taken as: K_1=1.5, K_2=0.2, K_3=0.8, K_4=1.4, K_5=-0.1 and K_6=0.5.

Fig. 5 shows the frequency changes for step load changes. As can be seen, the frequency changes tend to zero in the steady state. Also, Figs. 6 and 7 show the changes in the turbine output mechanical power and the changes in the electrical power, respectively, which indicate the elimination of oscillations in the steady state. Fig. 8 shows the terminal voltage changes, which, as expected, have reached the set value according to the input signal in the steady state.

The modes (eigenvalues) of the system matrix along with the damping coefficient of the oscillatory modes are given in Table 1. As can be seen, all the modes are located on the left side of the imaginary axis, which indicates that the system under study is stable.

Table 1: Modes (eigenvalues) of the system matrix

Mode	Damping ratio	Un-damped frequency
-0.1879±j1.1132	0.1664	1.1289
-0.5110±j0.1510	0.5328	0.1784

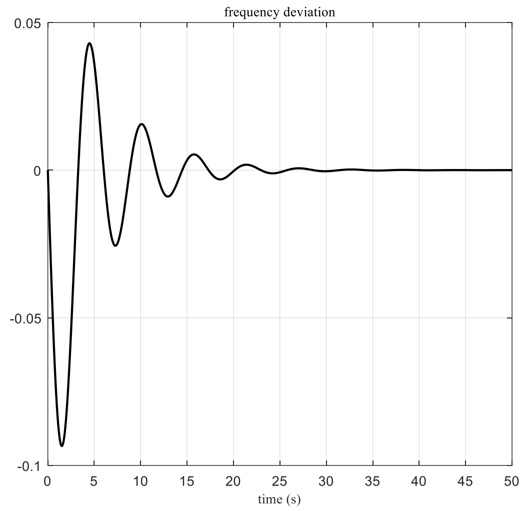

Fig. 5 Frequency deviation step response

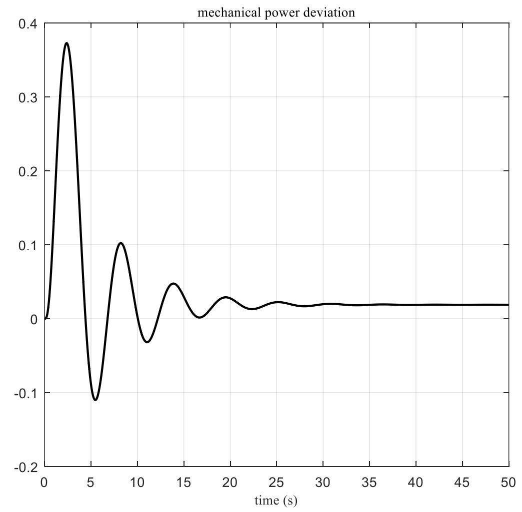

Fig. 6 Power mechanical deviation step response

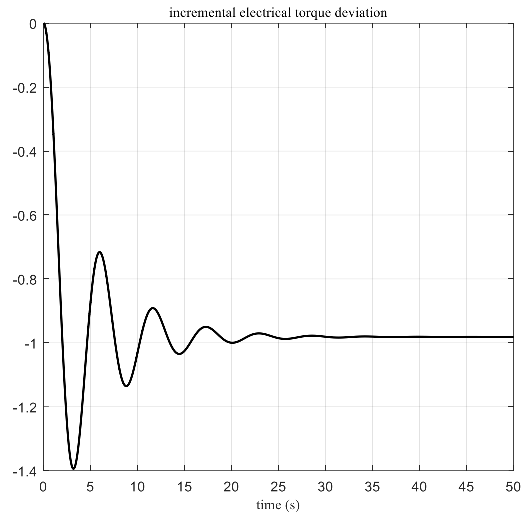

Fig. 7 Electrical torque deviation step response

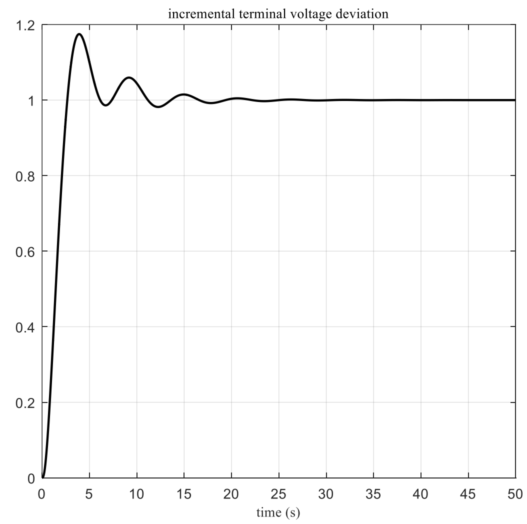

Fig. 8 Terminal voltage deviation step response

5- Conclusion

The primary aim of a power system is to provide uninterrupted and high-quality electrical energy. The integration of distributed generation sources, poses challenges that can impact grid stability and security due to their inherent nonlinearity and uncertainty. AVR and LFC systems are essential for maintaining the stability and security of power systems, especially with the increasing penetration of distributed generation. Their ability to regulate voltage and frequency mitigates the challenges posed by nonlinearity and uncertainty, ensuring reliable and high-quality electricity delivery. The intermittent and unpredictable nature of renewable sources complicates load forecasting and generation scheduling, posing challenges for AVR and LFC systems. The decentralized nature of distributed generation also requires advanced coordination between AVR and LFC systems to ensure that they operate in harmony across multiple generation sources and microgrids. To address the stability and security concerns arising from the integration of distributed generation, the use of advanced control strategies and energy storage systems can be mentioned.

Modern inverters in distributed generation systems can also simulate the behavior of synchronous generators, and increase voltage and frequency stability by actively participating in the AVR and LFC functions.

In this paper, a small-signal model of a single-zone power system with a gas turbine power plant is presented, and the interactions between the load-frequency control (LFC) and automatic voltage regulator (AVR) loops are analyzed. A state-space model and MATLAB/Simulink simulations are used to study the system stability by analyzing the system modes. The small-signal model linearizes the nonlinear dynamics of the power system around a given operating condition, allowing the analysis of small disturbances in voltage and frequency. Gas turbines have faster response times, but lower inertia than steam turbines, which may enhance the LFC-AVR interactions and require careful controller design.

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