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Article

Enhanced Load Frequency Control of Power Systems Using GA Optimization in MATLAB/Simulink

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Abstract: The load frequency control (LFC) of a single-area power system under various load conditions is examined in this paper utilizing various control algorithms. Using MATLAB/Simulink, a dynamic model that includes the steam turbine, generator, load, and control system is created and put into use. In three different scenarios—without a controller, with a traditional PID controller, and with a PID controller optimized with a genetic algorithm (GA)—the study assesses system performance. To establish baseline performance, the traditional PID controller is first used with non-optimized parameters. The ideal set of PID gains is then found using a GA with the goal of improving system stability and dynamic response. Key measures such frequency stability, load tracking capabilities, overshoot, settling time, and disturbance rejection are used to evaluate the performance of both controllers. The suggested GA-PID controller much outperforms the traditional PID method, according to simulation findings. In particular, it achieves better robustness against load perturbations, quicker settling times, and less overshoot. These enhancements demonstrate how well GA-based optimization works to adjust controller parameters for intricate power system applications. The results verify that the GA-PID controller offers a dependable and effective way to preserve frequency stability in single-area power systems, which makes it a viable strategy for contemporary power system control.

Keywords: PID, LFC, AVR, GA, GA-PID controller, power system control

1. Introduction

Power systems enable the production, transmission, and distribution of electrical energy to residential, commercial, and industrial consumers, making them an essential component of contemporary society's infrastructure. Utilizing a variety of generators to transform mechanical energy into electrical energy, power generation plants are essential to these systems. Among these, steam turbines are frequently used in thermal power plants because of their great efficiency and capacity for large-scale generation [1]. In order to drive electrical generators, steam turbines expand high-pressure, high-temperature steam and use rotational motion to transform thermal energy into mechanical energy. Advanced control techniques are necessary for the dependable operation of power systems in order to provide stability, security, and optimal performance under a variety of operating conditions. Each producing unit in an interconnected power system usually has Automatic Voltage Regulation (AVR) and Load Frequency Control (LFC) systems [2]. By consistently balancing power supply and load demand, LFC is in charge of keeping the system frequency at its nominal value. In reaction to load disruptions, this is accomplished by modifying the generator speed and controlling the input energy, such as steam flow. By regulating the excitation system in parallel, the Automatic Voltage Regulator (AVR) keeps the generator's terminal voltage within allowable bounds. The

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AVR maintains voltage stability during dynamic load variations by regulating the generator's magnetic field through suitable feedback control. When combined, LFC and AVR are essential to maintaining the general stability and dependability of contemporary power systems show Fig. (1) below [3][4][5].

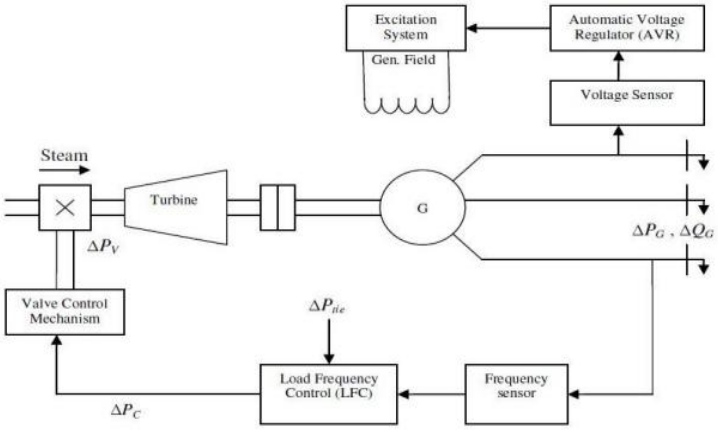

Figure 1. Schematic diagram of LFC and AVR of a synchronous generator.

In order to keep system frequency and voltage within predetermined bounds, controllers in power systems are usually built for certain operating conditions and can handle slight variations in load demand [1]. While variations in reactive power are generally linked to changes in voltage magnitude, variations in actual power are mostly linked to changes in the rotor angle and, hence, system frequency.

Maintaining the required voltage and frequency quality and guaranteeing power system stability depend on effective control strategies. Achieving a steady operating condition while reducing deviations brought on by load disturbances is the main goal of such control techniques. The creation of a load frequency control (LFC) model for a single-area power system is the main goal of this study. A Genetic Algorithm (GA) is used in the suggested method to optimize the parameters of a Proportional-Integral-Derivative (PID) controller [6]. The model is applied to a steam turbine system using the MATLAB/Simulink environment. The objective is to increase frequency regulation performance and system stability under different load scenarios. In [7], the comparison amongst three evolutionary approaches GA-PID, PSO-PID, and traditional PID controllers for LFC and VC is analysed for a hybrid generation system. [8] presents an optimized load frequency control (LFC) approach for interconnected power systems with conventional and renewable energy sources. A proportional integral derivative (PID) controller, tuned using particle swarm optimization (PSO) and genetic algorithm (GA) techniques, manages frequency in a thermal two-area tie-line IPS and a one-area multi-source power network. In [9], it is tried to employ a state-of-the-art multi-objective uniform-diversity genetic algorithm (MUGA) for Pareto optimization of PI/PID controllers in Load Frequency Control (LFC) of power systems. The [10] presents a new heuristic-based hybrid optimization technique to achieve the objective of automatic load frequency control. In particular, the proposed optimization technique regulates the frequency deviation and the tie-line power in multi-source power system. This study uses different control algorithms to analyze the load frequency control (LFC) of a single-area power system under different load situations. A dynamic model that incorporates the steam turbine, generator, load, and control system is developed and implemented using MATLAB/Simulink. The study evaluates system performance in three different scenarios: without a controller, with a conventional PID controller, and with a PID controller optimized with a genetic algorithm (GA). The conventional PID controller is initially employed with non-optimized parameters in order to determine baseline performance [1][2][3][5][11].

A. Power System Stability

It is impossible to address power system stability as a single, cohesive phenomenon because it is a complicated, multidimensional issue. Power system instability can take many different forms and is impacted by numerous variables. Power system stability is therefore frequently divided into discrete groups according to the type of instability and the system factors involved for efficient study and control.

1. Rotor Angle Stability:

The capacity of linked synchronous machines in a power system to maintain synchronism during typical operating conditions and after disruptions is known as rotor angle stability. The ability of the system to preserve or reestablish equilibrium between each generator's mechanical torque and electromagnetic torque is the fundamental determinant. In this instance, instability shows itself as rising oscillations in the rotor angle, which could eventually cause the generators to lose synchronism.

2. Voltage Stability:

The ability of a power system to sustain appropriate voltage levels at every bus both under typical circumstances and following disruptions is known as voltage stability. At some buses, voltage instability usually causes the voltage magnitude to gradually decrease or increase. In extreme circumstances, voltage collapse may result in load loss or even system-wide outages.

3. Frequency Stability:

The capacity of a power system to keep its frequency within reasonable bounds after major disruptions that result in an imbalance between total generation and load is known as frequency stability. It relies on the system's capacity to minimize load shedding while restoring the equilibrium between power supply and demand.

B. PID Controller

The proportional-integral-derivative (PID) controller's simplicity, robustness, and ease of implementation make it one of the most popular and successful control techniques in industrial applications. Based on the discrepancy between the system's measured output and the desired (reference) value, the PID controller produces a control signal. The control action is made up of three parts [6][7][12][13]:

1. Proportional (P) Control:

An output directly proportionate to the immediate mistake is produced by the proportional term. Although steady-state error cannot be totally eliminated, it increases the system's response time.

2. Integral (I) Control:

The integral term creates a control action proportionate to the integral of the error signal by accumulating the error over time. Although steady-state error is eliminated by this component, overshoot and shorter response times may be introduced.

3. Derivative (D) Control:

The derivative term uses the error's rate of change to forecast how it will behave in the future. By offering a dampening effect, it improves system stability and lowers overshoot.

Together, these three elements create the overall control signal, which modifies the system output to reduce error and attain the intended performance. A PID controller's efficacy is dependent on how well its parameters are tuned; these parameters must be chosen in accordance with the system dynamics and performance requirements.

C. Genetic Algorithm (GA)

A popular stochastic optimization method for resolving intricate and nonlinear issues is the Genetic Algorithm (GA). In contrast to traditional deterministic approaches, GA uses probabilistic search processes and works with a population of candidate solutions, often known as individuals or chromosomes, that iteratively evolve toward optimal solutions [14]. Natural selection and biological evolution serve as the foundation for GA. It creates new populations from preexisting ones via genetic operators including selection, crossover, and mutation. Individuals are assessed using a fitness function throughout each iteration (generation), and the best candidates are chosen to create the subsequent generation, gradually raising the quality of the solutions. GA is very useful for optimizing control system settings because of its robustness and global search capacity. The Proportional–Integral–Derivative (PID) controller's parameters are optimized in this work using GA. By limiting frequency deviations, lowering overshoot, and increasing settling time in the power system's load frequency control, the goal is to improve system performance [8][9][14].

2. Methodology

This study methodology is based on modeling, simulation, and comparative performance evaluation of a single-area power system subjected to various control strategies. A dynamic model consists of steam turbine, governor, generator, and load to simulate the behavior of the power system under varying load conditions is developed under MATLAB/Simulink environment. Transfer functions are used to derive the mathematical representation of each subsystem and integrated to form a global plant model. The paper then continue developing through three simulation scenarios to assess system performance, i.e. uncontrolled system (open-loop), a system using a conventional PID controller with initially chosen parameters and a system using a PID controller tuned by a Genetic Algorithm (GA). In the second case, we take some baseline PID gains to try to see some improvements of the general response of the system. The following three scenarios are also studied with GA, the third of which uses GA for the tuning of PID parameters where the controller gains are coded in chromosomes and evaluated based on a fitness function based on an Integral Time-Weighted Absolute Error (ITAE) [23]. Mimicking the process of natural selection, the GA continues to evolve these solutions through selection, crossover, and mutation until there is a defined maximum benefit. All the simulations are performed for the same operating condition and load disturbance. The performance metrics like overshoot, settling time, rise time, and frequency deviation from all scenarios are noting and compared. By following such structured analysis we can effectively evaluate the success of GA-aided optimization in load frequency control and system stability enhancement.

3. Result and Discussion

Load Frequency Control System and Mathematical Model

Reliable power system performance depends on maintaining the steady operation of interconnected power plants and controlling the relationship between generator speed and system frequency [15]. Despite variations in load demand, load frequency control, or LFC, makes sure that the system frequency stays within reasonable bounds. Frequency regulation in the power system is primarily influenced by the following factors:

1. **Turbines:**

Mechanical energy is transformed into electrical energy by turbines. The turbine blades revolve quickly as steam or water passes past them. A crucial component of frequency management is the turbine's rotational speed, which must be constantly modified in response to the electrical network's real-time demands.

2. **Governors:**

Turbine governors control the turbine shaft's rotational speed to balance power production with load demands. The difference between the desired reference value and the measured system frequency is used to generate the control signal for the governor. The governor increases turbine speed to boost power output when the frequency drops below the nominal level; conversely, it decreases turbine speed to decrease power generation when the frequency rises over the nominal level.

3. Generators:

The turbine's mechanical energy must be transformed into electrical energy via generators. Because their output is controlled by the governor signal, the generator can sustain system frequency under a range of load scenarios.

The LFC system consists of these main parts as well as a measurement system that tracks load and frequency and a central control unit. In order to maintain steady frequency regulation and the best possible system performance, these subsystems offer feedback to modify the turbine and generator characteristics.

A. Basics of Turbine Speed Mechanisms

Whether a steam turbine is operating independently to serve a small system or as part of a big, linked power network, the speed governor is the main component in charge of controlling the turbine's rotational speed. The governor makes sure that, in spite of changes in load, the turbine-driven generator keeps a steady frequency. Fig. (2) shows a schematic of a typical steam turbine speed-governing system, which is used to regulate generator output and maintain a consistent frequency. The following are the system's primary parts.

1. Speed Governor:

The fly-ball speed governor, which detects changes in turbine speed or system frequency, is the central component of the system. The flyballs travel outward when turbine speed rises, which causes linkage point B to shift downward; the opposite is true when speed falls. The turbine valve position is adjusted by translating this motion into control signals.

2. Linkage Mechanism:

The governor motion is sent to the control valve via the linkage system, which consists of rigid links ABC and CDE that pivot at positions B and D. The control valve moves in response to the turbine speed change that is sensed. In order to guarantee steady and precise valve positioning, Link L4 receives data from the steam valve.

3. Hydraulic Amplifier:

To operate the main steam valve against high-pressure steam, the hydraulic amplifier transforms low-power pilot valve motion into high-power piston motion. Its primary piston and pilot valve magnify the control signal to efficiently manage steam flow.

4. Speed Changer:

The steady-state power output of the turbine is determined by the speed changer. Under steady conditions, the speed changer's downward movement opens the top pilot valve, allowing more steam to enter and raising turbine output. On the other hand, in order to preserve system balance, upward movement decreases steam flow, which lowers turbine output [15][16].

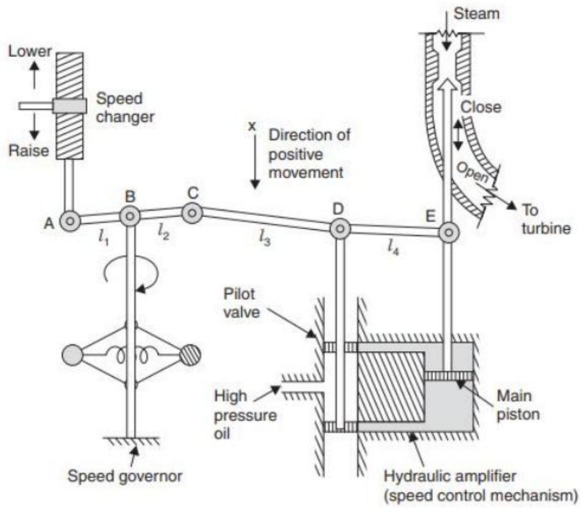

Figure 2. Turbine speed governing system.

B. Mathematical System model

modelling of an isolated power system constitutes:

1. Speed Governor Model

Assuming the linkage mechanism is stationary, the pilot valve is closed, the steam valve is opened by a specific magnitude, the turbine output balances the generator output, the turbine or generator is operating at a specific speed when the system frequency is (f_0), the generator output is P_{G0}, and the steam valve setting corresponding to these conditions is X_0E, we examine the steady state condition Fig. (2). The linear model of the system around these operating circumstances is now obtained. Let the point The commanded increase in power is ΔP_c when A of the speed changer is lowered by ΔX_A. Therefore, $\Delta X_A = K_1 \Delta P_c$. The connection point's movement A modifies the linkage points C and D's ΔX_C and ΔX_D positions slightly. Pressure oil enters the hydraulic amplifier from the top of the main piston when D moves upward by ΔX_D. This causes the steam valve to move downward a short distance ΔX_E, increasing turbine torque and, consequently, power ΔP_G. This leads to a further rise in speed and, consequently, generation frequency. The link point B moves downward a little distance ΔX_B proportionate to Δf when the frequency Δf increases. If the points move lower, we consider the movements to be positive. We have a linear relationship since every movement is tiny. The migration of C is influenced by two factors [15] [17]:

i. Increase in frequency causes B to move by ΔX_B when the frequency changes by Δf as then the fly-ball moves outward, and B is lowered by ΔXB. Therefore, this contribution is positive and is given by $K_1 \Delta f$.

ii. The lowering of the speed changer by an amount ΔX_A lifts the point C upwards by an amount proportional to ΔX_A, i.e., let this be $K_2' \Delta X_A$ or $K_2 \Delta P_c$.

$$\Delta X_C = K_1 \Delta f - K_2 \Delta P_c. \quad (1)$$

The length of the linkage arms AB and BC, as well as the proportional constants of the speed changer and speed governor, determine the positive constants K_1 and K_2. The movements of C and E contribute to the movement of D. Consequently, when D goes upward, C and E move downward.

$$\Delta X_D = K_3 \Delta X_C + K_4 \Delta X_E. \quad (2)$$

The positive constants K_3 and K_4 are dependent on the linkage CD and DE lengths. Assuming that the oil flow into the hydraulic cylinder is proportionate to the pilot valve's position ΔX_D, the value of ΔX_E may be found using: $\Delta X_E = K_5 \int_0^t \Delta X \, dt.$ (3) The fluid pressure and the cylinder and orifice geometries determine the constant K_5. We obtain by using the Laplace transform of Equations (1 to 3).

$$\Delta X_C(s) = K_1 \Delta F(s) - K_2 \Delta P_C(s). \quad (4)$$

$$\Delta X_D(s) = K_3 \Delta X_C(s) + K_4 \Delta X_E(s). \quad (5)$$

$$\Delta X_E(s) = -\frac{K_5}{s} \Delta X_D(s). \quad (6)$$

Eliminating the variables ΔX_C and ΔX_D, we obtain

$$\Delta X_E(s) = \frac{K_1 \, K_2 \, \Delta P_C(s) K_1 K_3 \, \Delta F(s)}{K_4 + s \, K_5}. \quad (7)$$

$$\Delta X_E(s) = \frac{K_G}{1+sTG} [\Delta P_C(s) - \frac{1}{R} \Delta F(s). \quad (8)$$

Where:

$R = \frac{K2}{K1}$ Speed regulation of the governor, $K_G = \frac{K2K3}{K4}$ Gain of speed governor, $T_G = \frac{1}{K4\,K5}$ Time constant of a speed governor show Fig. (3).

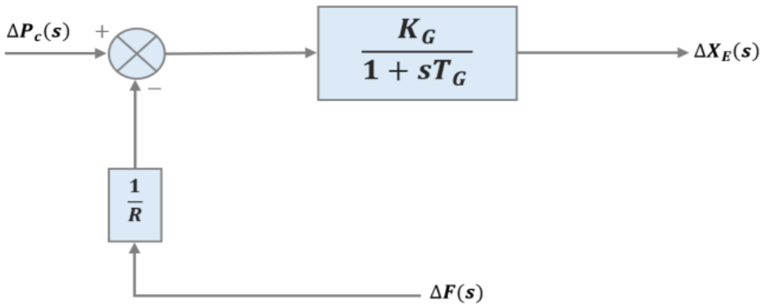

Figure 3. Block diagram represents the transfer the function of the speed governor system.

2. Turbine Model

The thermal energy contained in high-pressure, high-temperature steam is converted by the steam turbine into mechanical rotational energy, which is then converted into electrical energy by a generator. Steam is accelerated to a high velocity in each turbine stage by a number of revolving blades installed on the rotor and stationary vanes [18]. The idea of mass continuity is used to derive the mechanical power output and the input–output mathematical representation of the steam turbine, which is usually written as a transfer function see Fig. (4).

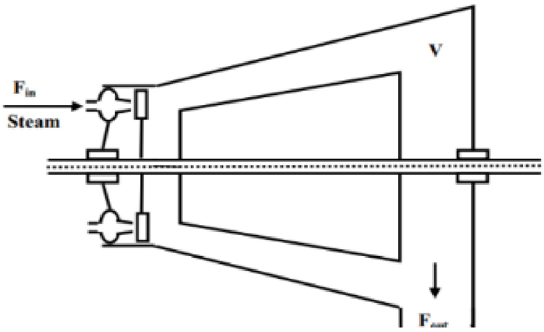

Figure 4. The Steam turbine unit.

$\frac{dw}{dt} = V\frac{dp}{dt} = F_{in}(t) - F_{out}(t).$ (9)

W = the weight of steam in turbine [kg], V = volume of turbine [m3], p = density of steam [kg/m3], F = steam mass flow rate [kg/s], t = time [sec.].

Assuming the flow out of the turbine to be proportional to pressure in the turbine.

$F_{out} = P\frac{F_0}{P_0}.$ (10)

P = pressure of steam in the tur
bine [kPa], P_0 = rated pressure
F_0 = rated flow out of the turbine.

With constant temperature in the turbine:

$\frac{dp}{dt} = \frac{dp}{dt}\cdot\frac{\partial p}{\partial t}.$ (11)

From equations (8) to (10), result the mathematical model:

$F_{in}(t) - F_{out}(t) = \mathrm{V}\frac{\mathrm{dp}}{\mathrm{dt}}\cdot\frac{\partial \mathrm{p}}{\partial \mathrm{t}} = \mathrm{V}\frac{\partial \mathrm{p}}{\partial \mathrm{t}}\cdot\frac{P_0}{F_0}\cdot\frac{\mathrm{d}F_{out}}{\mathrm{dt}}.$ (12)

Where $T_t = \mathrm{V}\frac{\partial \mathrm{p}}{\partial \mathrm{t}}\cdot\frac{P_0}{F_0}$ is the time constant [sec.].

Substituting into Equation (12) yields:

$$F_{in}(t) - F_{out}(t) = T_t\cdot\frac{\mathrm{d}F_{out}}{\mathrm{dt}}.$$

$\therefore F_{in}(t) = T_t\cdot\frac{\mathrm{d}F_{out}}{\mathrm{dt}} + F_{out}(t).$ (13)

After the Laplace transform, the transfer function of a steam turbine unit:

$$\frac{F_{out}(s)}{F_{in}(s)} = \frac{1}{1+ST_t}. \quad (14)$$

∴The transfer function of a steam turbine:

$$\frac{\Delta P_m(s)}{\Delta X_E(s)} = \frac{1}{1+ST_t}. \quad (15)$$

3. Generator–Load Model

By applying the swing equation of a synchronous machine [10], the dynamic behavior of the generator–load system can be described as follows:

$$\frac{2H}{w_s}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e. \quad (16)$$

By Laplace transform

$$\Delta F(s) = \frac{1}{2Hs}(\Delta P_m - \Delta P_e). \quad (17)$$

The speed-load characteristics of composite load are approximated by:

$$\therefore \boldsymbol{\Delta F(s) = \frac{1}{2Hs+D}(\Delta P_m - \Delta P_L)}. \quad \textbf{(18)}$$

Theory of PID Control

In industrial control systems, a proportional-integral-derivative (PID) controller is a commonly used feedback control mechanism. It works by continually computing the error signal, which is the difference between the desired setpoint and the measured process variable. Corrective action is then applied by adjusting the controlled variable to minimize the error. The proportional (P), integral (I), and derivative (D) terms are the three basic components of the PID control algorithm, which is why it is frequently referred to as a three-term controller. Each component makes a distinct contribution to the control action; the derivative term forecasts future error behavior based on the rate of change of the error signal; the integral term takes into account the accumulation of previous errors; and the proportional term is reliant on the current error. These three components are combined to provide the total control signal, which allows for efficient system regulation. Only one or two of these control actions can be used in some situations to obtain sufficient performance by setting the other parameters to zero. As seen in Fig. (5) below, the dynamic response and stability characteristics of the controlled system are shaped by the proportional, integral, and derivative gains, which determine the corresponding influence of each term [19].

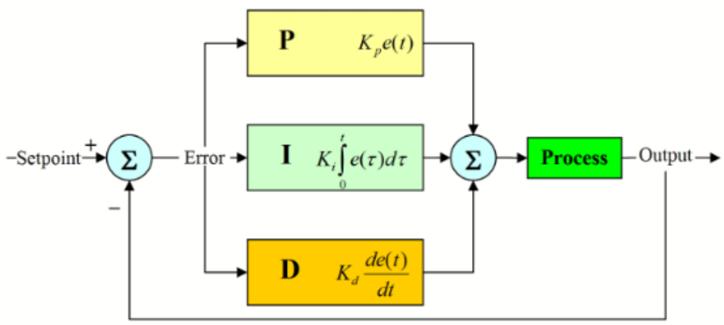

Figure 5. Block diagram of PID Controller.

A. PID Controller Tuning

A PID controller's tuning is a crucial and delicate procedure that aims to strike the ideal balance between stability and quick system responsiveness. Unwanted system behavior, such as excessive oscillations, a long settling period, or instability, can arise from improper controller parameter selection. The process of figuring out the ideal proportional, integral, and derivative gain values to guarantee the intended dynamic performance of the controlled system is known as PID tuning. Rise time, overshoot, steady-state error, and overall stability are all greatly impacted by these parameters. For clarity, Table (1) usually summarizes the effects of various parameters in tabular form. To obtain optimal performance, PID controllers can be tuned using a variety of techniques. These techniques encompass both manual and analytical methods, as well as automated methods using computer tools. The best PID settings are found in this work by using MATLAB software tools and an automatic tuning technique based on a genetic algorithm [19][20].

Table 1. Effects of PID Controller gains on system response.

Response	Rise Time	Overshoot	Settling Time	S.S Error
KP	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Small Change	Decrease	Decrease	Small Change

B. Genetic Algorithm

Stochastic optimization methods known as genetic algorithms (GAs) are motivated by Darwinian concepts of genetics and natural selection. They are members of an evolutionary algorithm class that uses operators like crossover, mutation, and selection to iteratively develop solutions toward optimality. In situations where traditional approaches might not be sufficient, GAs are especially useful for addressing complicated and nonlinear optimization problems because of their resilience and adaptability [19][20][21]. To find the optimum (or near-optimum) of an objective function defined over a given search space, a genetic algorithm does a global search. Candidate solutions are first encoded into chromosomes that represent members of a population. Although the first population is usually created at random, it should guarantee enough diversity to serve as a representative base for later generations. As illustrated in Fig. (6), the basic working process of a genetic algorithm can be summed up as follows: **Step 1:** Create an initial population of potential solutions and set the parameters of the algorithm. Population size, crossover rate, mutation rate, number of generations, and encoding strategy are some of these variables.

Step 2: Use a predetermined objective (fitness) function to assess each population member's fitness.

Step 3: Create a new generation of potential solutions by using genetic operators like as crossover, mutation, and selection.

Step 4: Continue the assessment and procreation procedure until a termination requirement is met, such as attaining a desired fitness value or a maximum number of generations.

Through iterative evolution, the genetic algorithm converges toward an optimal or near-optimal solution, making it a powerful tool for parameter optimization in control systems and engineering applications [22][23].

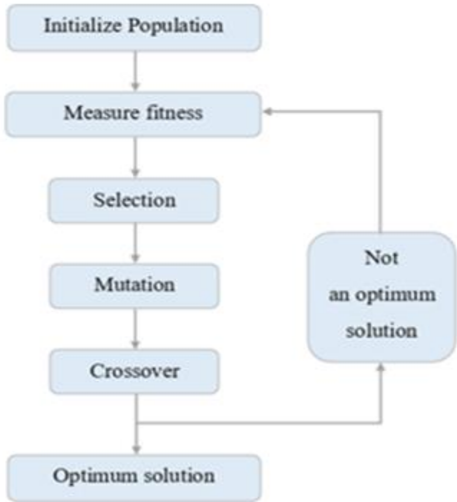

Figure 6. Flow diagram of genetic algorithm.

D. Optimization of PID Controller Using a Genetic Algorithm

The best proportional-integral-derivative (PID) controller parameters are found using the genetic algorithm (GA) in order to attain the required system performance. With this method, a set of PID gains is represented by each chromosome that is used to encode possible solutions. Each candidate is assessed using a fitness function that measures system performance after an initial population of potential solutions is created within predetermined constraints. The GA-based PID optimization's main elements are explained as follows [23][24][25]:

1. **Chromosome Representation:**

The proportional (P), integral (I), and derivative (D) parameters, which correspond to the PID controller gains, are encoded on each chromosome.

2. **Search Space Definition:**

The PID parameters' achievable ranges are defined to guarantee that all produced solutions stay within stable, physically significant bounds. Each parameter is given an upper and lower limitation to limit the optimization process.

3. **Fitness Evaluation:**

A fitness function is used to evaluate each prospective solution's performance. This function usually takes into account factors including oscillatory behavior, tracking accuracy, steady-state error, and transient response characteristics in PID optimization.

4. **Selection Mechanism:**

To find excellent options for reproduction, a selection approach is used. Fitness-proportionate selection, tournament selection, and rank-based selection are common techniques used to promote higher-achieving individuals to next generations.

5. **Crossover Operator:**

Crossover is the process of merging genetic information from parent chromosomes to produce new offspring. Methods like single-point or multi-point crossover are frequently used to improve solution space exploration.

6. **Mutation Operator:**

By changing gene values, mutation creates random variations into the population. By making it possible to explore new areas in the search space, this method helps preserve genetic diversity and avoids premature convergence.

7. **Termination Criteria:**

When certain criteria are met, such as reaching a maximum number of generations, reaching a desirable fitness level, or seeing population convergence, the algorithm ends.

All things considered, the GA-based optimization framework offers a reliable and efficient way to adjust PID controller parameters, especially in complex systems where conventional tuning techniques might not be sufficient [24][25].

System Simulation and Results Environment

The three primary subsystems of the suggested system are each characterized by a unique transfer function that describes its dynamic behavior. These subsystems are integrated to create a cohesive representation in order to acquire the overall system model. This is accomplished by merging the transfer functions obtained in (8), (15), and (18) to produce the whole system model depicted in the block diagram in Fig. (7) below.

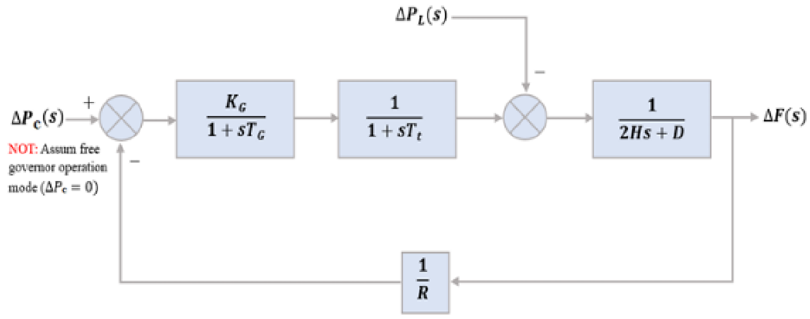

Figure 7. Block diagram of System.

The Simulink environment is utilized for analysis and simulation. An easy-to-use interface for system design and simulation is offered by Simulink, a graphical modeling tool included into MATLAB. It removes the need for lengthy coding by enabling numerical solution of system equations using a visual programming approach. For modeling intricate dynamic systems in engineering applications, this makes it especially appropriate. Among the many benefits that Simulink provides are:

a. The ability to create graphical representations of system dynamics that are accurate.
b. Effective time-domain modeling of system behavior.
c. The ability to handle a variety of model types, such as multi-domain, probabilistic, and detailed models.
d. A deeper comprehension of system performance and the capacity to assess the effects of design changes.

To thoroughly analyze the system response and evaluate the effectiveness of the control strategy, simulations are conducted under three different scenarios:

a. System without a controller.
b. System with a PID controller.
c. System with a PID controller optimized using a genetic algorithm (GA).

The system is always run in the free governor mode in order to highlight the control approach for frequency regulation and to examine the quick dynamics of load variations. In this mode, the load demand is permitted to fluctuate while the speed changer is fixed (i.e., $\Delta P_C = 0$).

The system parameters are initialized in accordance with predetermined values during the simulation process, as indicated in Table 2.

Table 2. Values of the System Parameters

Parameters	**Value**
Turbine Time constant (Tt)	0.5 sec
Governor Time constant (TG)	0.2 sec
Governor Gain (KG)	1
Governor Speed Regulation (R)	0.05 p.unit
Generator inertia constant (H)	5 sec
Load Varies (D)	0.8
Load Change ($\Delta \boldsymbol{PL}$)	0.2 p.unit
Frequency (f)	60 Hz

A. Simulation of the System Without Controller

The system is first simulated without any control mechanism (i.e., in an open-loop configuration) in order to precisely characterize the behavior of the system and assess its reaction to load variations. This method makes it possible to comprehend the dynamics of the system more clearly, especially how load disturbances affect frequency deviation. It also sheds light on the simulation framework, the frequency value calculation process, and the system reaction that results.

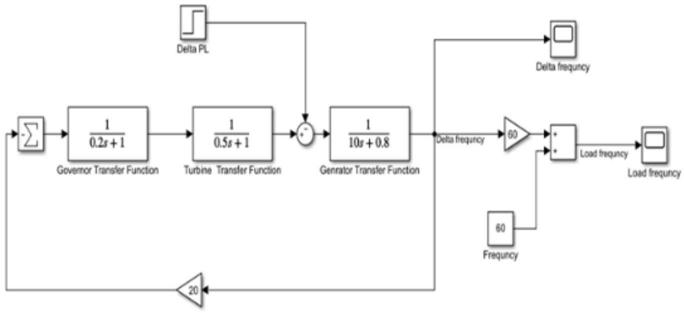

Figure 8. The Simulink diagram of the System without a Controller.

The parameters and structure needed to implement the system model in the Simulink environment are provided in Fig. (8) and Table (2). The generator transfer function's output shows the frequency deviation in units (p.u.). The following relationships are used to transform this variation into the actual frequency:

$\Delta f_{\text{actual}} = \Delta f_{\text{p.u.}} \times f_{\text{nominal}}$ (Deviation value of actual frequency)

$f_{\text{actual}} = f_{\text{nominal}} + \Delta f_{\text{actual}}$ (Value of actual frequency)

Following the construction of the simulation model, the simulation parameters are set up as follows: a total simulation time of 20 seconds, a relative tolerance of, and the use of the ode23s solver, which works well for systems with both fast and slow dynamic responses, as shown in Fig. (8). There is a discernible drop in load frequency, according to the simulation data. The reaction first decreases before oscillating and stabilizing at about 59.4 Hz. This frequency deviation is explained by an increase in load demand, which the system cannot adequately offset without a controller. As a result, as shown in Fig. (9) below, the system is unable to maintain frequency stability under these circumstances. This finding emphasizes how important it is to have a suitable control approach that can control frequency and guarantee system stability in the face of load disruptions. The essential performance indicators that describe the system reaction in this uncontrolled scenario are compiled in Table 3.

Table 3. Response Parameters without Controller.

Parameters	Value
Rise Time	0.4138 sec
Overshoot	0.9709
Settling Time	6.8902 sec
Settling Min	59.1065 Hz
Settling Max	59.5339 Hz
Peak	60 Hz
Peak Time	0 sec

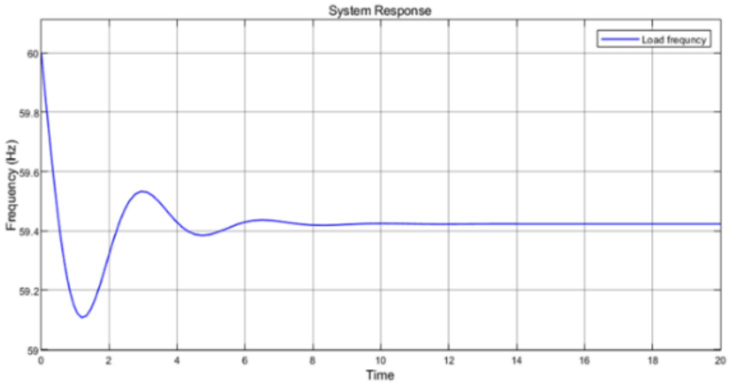

Figure 9. The System Response without Controller.

B. Simulation of the System with PID Controller

It is clear from the observations from the uncontrolled example that the system needs a control mechanism to improve overall stability and make up for the decrease in load frequency. In order to assess the system's efficacy in enhancing dynamic response and frequency management, a proportional-integral-derivative (PID) controller is incorporated into a new simulation. The PID controller block, as seen in Fig. (10), is added to the same Simulink model that was utilized in the preceding scenario.

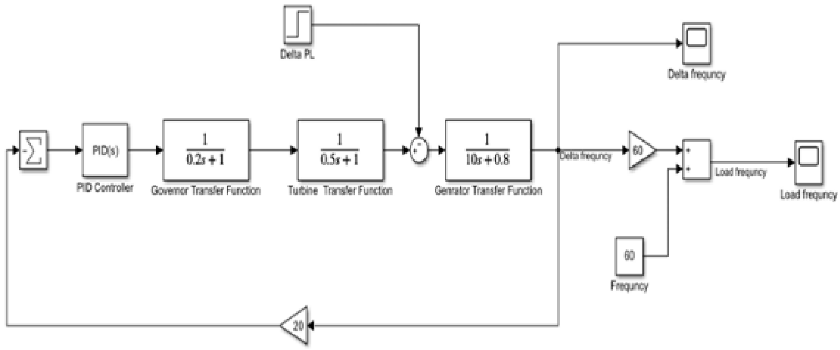

Figure 10. The Simulink diagram of the System with PID Controller.

The related graphic shows the simulation diagram that was produced. Precise tuning of controller parameters is not taken into consideration at this point because the main goal of this section is to examine the qualitative influence of the PID controller on system stability. Rather, the controller gains are chosen at random as $K_P = 2$, $K_I = 2$, and $K_D = 1$. The controller receives these data directly, while all other simulation parameters remain unaltered. After the simulation is run, it is shown that the system response significantly improves over the uncontrolled scenario even with non-optimized (randomly selected) controller parameters. This enhancement demonstrates the PID controller's innate ability to increase system performance. By pushing the system output closer to the nominal value, the controller effectively reduces the frequency drop, as seen by the system response. In particular, the disturbance causes the load frequency to drop at first, then gradually rebound and show damped oscillations until converging to the steady-state value of 60 Hz. This behavior suggests greater system frequency management, decreased oscillations, and increased stability. Nevertheless, even with these advancements, optimal performance cannot be ensured by using arbitrarily chosen controller parameters. To provide the required transient and steady-state characteristics, the PID gains must be precisely tuned. Therefore, to further improve system performance, sophisticated tuning strategies like automated or optimization-based approaches are needed. The major performance indices that describe the system reaction for this controlled example are summarized in the results Table 4 and Fig. (11).

Table 4. Response Parameters with PID Controller.

Parameters	Value
Rise Time	1.2585e-06 sec
Overshoot	0.0800
Settling Time	5.5090 sec
Settling Min	59.9930 Hz
Settling Max	60.0480 Hz
Peak	60.0480 Hz
Peak Time	2.9006 sec

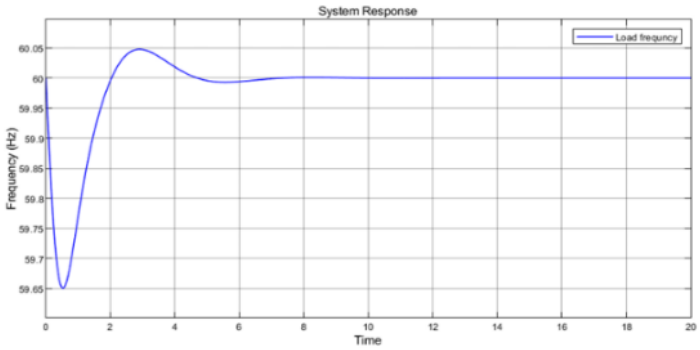

Figure 11. The System Response with PID Controller.

C. Simulation of the System with GA-Based PID Controller

A proportional-integral-derivative (PID) controller's performance is largely dependent on how well its parameters are chosen. The prior simulation instance, in which non-optimized (randomly picked) gains led to inferior system performance, amply illustrated this dependency. As a result, numerous automatic tuning methods have been created to identify the ideal controller parameters. The PID controller gains are optimized in this work using a Genetic Algorithm (GA). To assess the degree of performance increase in comparison to the earlier scenarios, the system is then re-simulated using the modified parameters. As shown in the related Fig. (12), the simulation model for this scenario is generated from the second case by adding an extra block for calculating the performance index.

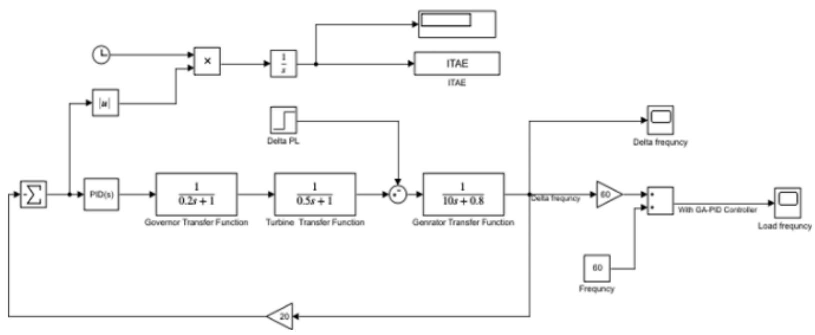

Figure 12. The Simulink diagram of the System with GA-PID Controller.

The performance of the controller is evaluated using the Integral Time-Weighted Absolute Error (ITAE) criterion, which is mathematically defined as:

$$\text{ITAE} = \int_0^t t \mid e(t) \mid dt$$

where t stands for time, e(t) is the system error signal, and ITAE stands for the Integral Time-Weighted Absolute Error. The genetic algorithm's fitness function, which is used to assess potential solutions inside each generation and direct the selection process for creating succeeding generations, incorporates this performance metric. The algorithm converges in a matter of minutes after setting the GA parameters and starting the optimization process, producing ideal PID gain values. The matching Table 5 contains a list of the discovered optimal parameters.

Table 5. The PID parameters by auto-tuning with the GA.

K_P	K_I	K_D
937.2636417285281	726.6998091847418	674.5657671524017

After applying these optimized gains to the PID controller, the system is simulated once more. As seen in Fig. (13) below, the resulting system responsiveness shows a notable improvement and can be regarded as almost perfect.

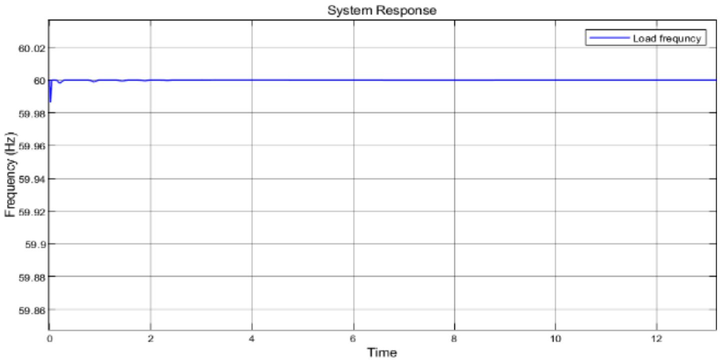

Figure 13. The System Response with GA-PID Controller.

When the PID controller's settings are properly adjusted based on the dynamics of the system, the reaction validates the controller's efficacy. Specifically, the load frequency stays constant with a very small initial fluctuation, usually less than 0.05%, which is insignificant enough for everyday use. Additionally, Table 6 below demonstrates the system's quick settling time, reduced oscillations, and outstanding steady-state accuracy.

Table 6. Response Parameters with GA-PID Controller.

Parameters	**Value**
Rise Time	7.3799e-07 sec
Overshoot	8.5346e-05
Settling Time	1.9467 sec
Settling Min	60.0000 Hz
Settling Max	60.0001 Hz
Peak	60.0001 Hz
Peak Time	3.7978 sec

The system responses in three simulation scenarios are also compared in this section: (i) without a controller, (ii) with a PID controller using randomly chosen parameters, and (iii) with a GA-optimized PID controller. The comparison, which is summed up in Table 7 and shown in Fig. (14), demonstrates the significant improvement attained by using the evolutionary algorithm for controller tuning.

Table 7. Response Parameters with Response in all cases..

Parameters	Without controller	PID controller	GA-PID controller
Rise Time	0.4138 sec	1.2585e-06 sec	7.3799e-07 sec
Overshoot	0.9709	0.0800	8.5346e-05
Settling Time	6.8902 sec	5.5090 sec	1.9467 sec

Settling Min	59.1065 Hz	59.9930 Hz	60.0000 Hz
Settling Max	59.5339 Hz	60.0480 Hz	60.0001 Hz
Peak	60 Hz	60.0480 Hz	60.0001 Hz
Peak Time	0 sec	2.9006 sec	3.7978 sec

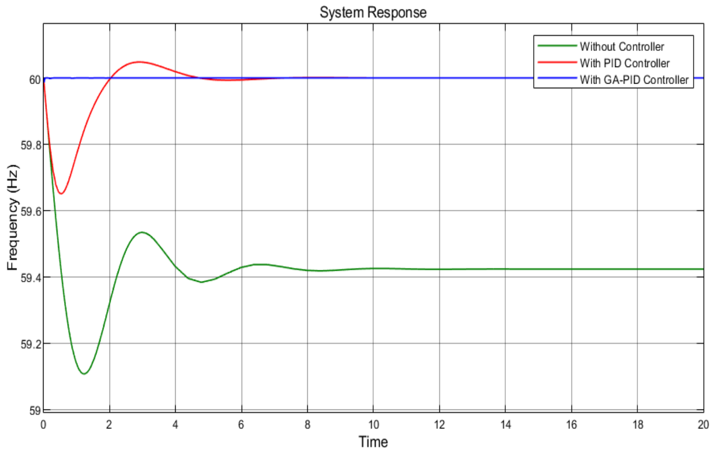

Figure 14. The System Response in all cases.

4. Conclusion

The goal of this study is to optimize the PID controller's parameters using a Genetic Algorithm (GA) in order to enhance the control system's performance. Finding the best controller gains to reduce load frequency disturbances and guarantee that it is regulated at the nominal value is the main goal. Three scenarios were used to examine the system: one without a controller, one with a PID controller that used non-optimized (random) parameters, and one with a GA-optimized PID controller. An extensive performance review was carried out based on the simulation findings obtained for each situation. The results show that the Genetic Algorithm-tuned PID controller outperforms the other options. In particular, the GA-based PID controller improves overall dynamic response, greatly lowers frequency deviations, and substantially increases system stability. On the other hand, the PID controller with random parameters only moderately improved the frequency fluctuations in the unmanaged system. Additionally, the oscillatory behavior seen in the uncontrolled situation is well mitigated by the optimized controller, guaranteeing that the load frequency quickly approaches its nominal value with little variance. This demonstrates how well the Genetic Algorithm works to find the best controller values based on the dynamics of the system. In summary, the combination of PID control and Genetic Algorithm optimization offers a reliable and effective way for controlling load frequency in power systems, outperforming traditional techniques in terms of stability and disturbance rejection.

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