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An optimal area power system-based automatic load frequency control using a 1-D lookup table method

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HIGHLIGHTS

- Automatic load frequency control is an important part of auxiliary services in power systems
- Conventional PI control in single-area systems uses time-consuming trial-and-error to determine control gains
- The 1-D Lookup Table (1-DLuT) method is generalized to design LFC
- The ITAE index is a key criterion in control design, used to minimize the Integral of Time Absolute Error
- Artificial neural networks (ANNs) mimic the behavior of the human brain and nervous system in artificial intelligence

Keywords:
Automatic load frequency control
1-D Lookup Table
LFC
AI
MATLAB
Area Power Systems

ABSTRACT

Automatic load frequency control (ALFC) is an important part of auxiliary services in power systems. To sustain system accuracy and ensure the safety of power systems, ALFC system design is a vital issue. Power system networks must quickly address the imbalance between generation and demand, or else the power line frequency will depart from its nominal value. However, performance might be disappointing, and frequency deviation can occur when a substantial disturbance occurs, such as when a rapid, significant load change happens. In particular, an enormous number one- and two-dimensional lookup table is used; in this study, the 1-D Lookup Table (1-DLuT) method is generalized to design LFC in single area and two areas power system. The proposed controller reduces the effects of load disturbance in the frequency fluctuations and contributes to the stabilization of the power system. In PID controller design methods, the most common performance criteria are integrated absolute error (IAE), the integration of time weight square error (ITSE), and the integration of squared error (ISE), which can be evaluated analytically in the frequency domain. A common performance criterion for control system design is the Integral of Time multiplied by the Absolute Error (ITAE) index, which is used to minimize the integral of the time absolute error performance index. Finally, the proposed 1-DLuT-based interpolation algorithm is compared with two different controllers, including a PI and an ANN. In other words, the simulation results showed that the optimal proposed system performs better within different variations of the stated loads.

1. Introduction

Frequency regulation, with the title Load Frequency Control (LFC), is an important control issue in power system design and operation. Since the swift industry developments are increasing the complication of power systems, the power system's stability and security may be threatened by significant frequency deviations, which can also permanently harm facilities by causing under/over frequency relay operations that ultimately disconnect certain system loads and generate [1]. To put it simply, the LFC provides resilient performance when modeling uncertainties and non-linearities by adjusting the load reference point in the shift of load changes to bring system frequency and tie-line power as close to required values as possible [2]. As an auxiliary service in power systems, LFC plays a crucial part in preserving the proper degree of electrical system dependability. The power system area's functioning and system dependability may be directly impacted if the nominal frequency deviation exceeds guaranteed bounds. However, there are many studies on LFC in power systems using different control methods, such as conventional, optimal, suboptimal, and adaptive control, for the best dynamic response properties. Keeping all of the above-mentioned issues in mind, the researcher embarked on the research. To determine the control gains, the traditional PI control methods for one-area power systems use laborious try-and-error procedures. Under certain conditions, the best reaction might be given to the acceptable control gains. New and more effective control techniques, such as intelligent control systems, are suggested to enhance this [3]. A Genetic Algorithm is utilized in Mohammed et al., study [4] to adjust the controller parameters in Sumithra et al., study [5] using a fuzzy logic-tuned PI controller. Two intelligent controllers, FLC and ANN-NARMA-L2,

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have been proposed in Azeer et al., study [6] to challenge the response of classical PID controllers. A neural controller trained with the Levenberg- Marquardt algorithm to reduce variations in ALFC is taken into account by Nag and Philip [7]. The issue of Load Frequency Control (LFC) in power systems has been studied for many decades. Nearly all of these methods have a sluggish rate of convergence to global solutions and depend on the proper setup of input parameters. Additionally, in some cases, they might produce local rather than global solutions. The control gains obtained from the aforementioned algorithms fail to reduce the system error, considering the understanding of the problems above, this study strives to introduce a new optimization approach to address the control challenges of load frequency (LFC) in an interconnected electrical system. In this study, a new way to design an LFC is proposed, taking into account the type of 1-D Lookup Table (1-DLuT). The main contribution of this work is in demonstrating the improvement in the area power system performance during load increase with LFC to reduce frequency fluctuation and tie line power deviation to make the power system stable.

2. Control of the frequency of power system load

One of the most important aspects of power system operation is the balance of power generation and loads, which is resolved by load frequency control (LFC). In actuality, the power supply needs to be able to respond adequately to changes in the load in order to preserve grid stability [3]. Holding the frequency constant ($\Delta f = 0$) in the face of load variations is the primary goal of LFC [8, 9]. The tie-line must maintain the power flow to the distribution areas. Over the decades, the PI controllers have been frequently adapted to the LFC [10]. Power interchanges and frequency mismatches result from sudden changes in loads. For large load changes, even with a speed governor in generators, it is challenging to achieve zero-frequency deviation. Therefore, the LFC is necessary to resolve the mismatches problem, which can be broken down as follows [11]:

The primary control eliminates frequency differences by local automated control and restores the balance between load and power generation by modifying the generator's actual power generation and controllable load consumption. A specialized power unit speed governor handles primary control, which is crucial to the power system's stability. The generator's actual power output is adjusted by secondary control, which is a centralized automatic control that also returns frequency and exchanges with other systems to reach predetermined values. That is if the primary control is unable to prevent the frequency excursion, the secondary control will bring the frequency back to the desired level. The human modification of generator dispatch and commitment is known as tertiary control. Suppose secondary control is unable to complete the final task. In that case, tertiary control is used to manage transmission network congestion, restore primary and secondary frequency control reservations, and return frequency and exchange to target values [12].

2.1 Single Area Model

An electrically insulated area, where one generating unit or group of generating units is located, is called a single area system that is located nearby to distribute electricity to the same area. The frequency is set to a nominal value of 50 Hz, and the operating system functions normally with perfect power balance [13]. When more load is connected, the load demand rises by ΔP_{de} indicating a new load. In order to match the increased load, the generation instantly rises by ΔP_G. As a result, the speed and frequency change. Figure 1 shows the general block diagram of the power system, including one area.

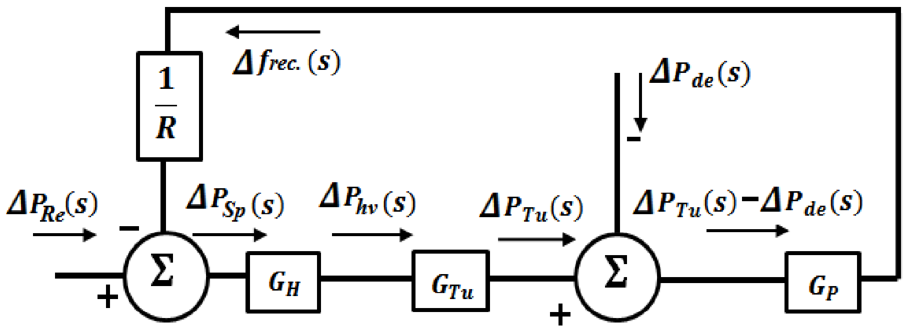


Figure 1: Block diagram of one area power system

Designing an efficient controller requires a thorough understanding of the dynamic and static characteristics of the system. Essentially, a single-area power system is a governor, turbine, and generator that organizes persistent feedback. The system also contains a step load change input to the area. The turbine-governor control stops the rotors from accelerating and decelerating in response to changes in load during normal operation. However, when the turbine-governor reference setting ΔP_r is at zero, there is a steady-state frequency inaccuracy Δf. Returning Δf to zero is one of LFC's goals [9]. Each turbine-governor working under LFC has a reference power setting change ΔP_r that is proportional to the integral of the area control error.The dynamic model can be described by Equations (1) and (2), respectively.

In the case of ACE $=\Delta f$, so that:

$$\Delta P_r = -K_i \int ACE\, dt = -K_i \int \Delta f dt \quad (1)$$

Taking Laplace transformation

$$\Delta P_r(s) = -\frac{K_i}{s}\Delta f(s) \quad (2)$$

The gain constant K_i controls the rate of integration and, thus, the reaction speed of the loop. The speed changer is controlled by an integrator whose output receives this signal, $\Delta f(s)$. As long as the error persists, the integrator's output will increase, which will cause the speed changer to move. The speed changer stops, and the integrator output stops when the frequency error is reduced to zero. For the reasons mentioned above, the integral controller will result in zero steady-state frequency error after a step load adjustment [13]. With reference to the integral controller in Figure 1 single control area block diagram, Equation (3) represents the input to G_{HT_u}:

$$-\frac{K_i}{s}\Delta f(s) - \frac{1}{R}\Delta f(s) \quad (3)$$

$$\text{i.e. } -\left[\frac{K_i}{s} + \frac{1}{R}\right]\Delta f(s) \quad (4)$$

Figure 2 shows an illustration of how to minimize the block diagram in Figure 1 [14].

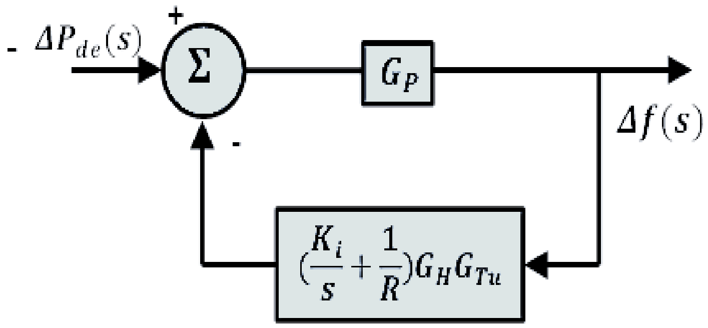


Figure 2: Model of the single area with the control

In Equation (5), the expression for $\Delta f(s)$ can be obtained by setting $K_i$to zero. The exact frequency error corresponding to the uncontrolled case is:

$$\Delta f(s) = \frac{G_P}{1+\frac{1}{R}G_H G_{Tu} G_P}\Delta P_{de}(s) \quad (5)$$

However, when the turbine-governor reference setting Δf changes to zero, there is a steady-state frequency inaccuracy Δf. The change in reference power setting for each turbine-governor operating under LFC is determined by the integral of the area control error $\Delta Pref$ [15, 16].

2.2 Two Area Model

Everywhere, the same frequency is used to describe the single area control. This is the same as stating that the area network is strong. This might use the single variable Δf to represent the frequency variation in the single region condition [17]. Assume that each of the two areas in the current scenario is powerful on its own. Thus, by connecting them with weak tie lines, it is assumed that two variables, $\Delta f1$ and $\Delta f2$, respectively, can represent the frequency variation in the two areas, as shown in Figure 3. Many loads are connected to numerous generators spread across various locations in the real-time power system. In Equations (6-12), the power flow on the tie line that connects regions 1 and 2 is as follows during regular operation:

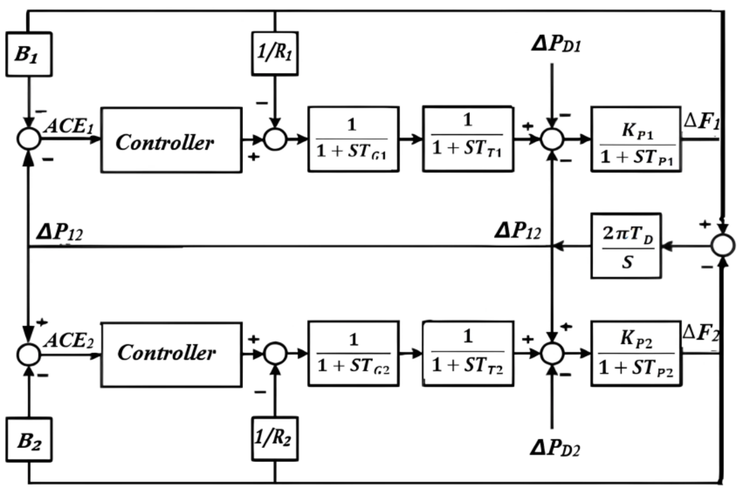


Figure 3: Block diagram of two-area power system

$$P_{12}^0 = \frac{|V_1^0|\,|V_2^0|}{x}\sin(\delta_1^0 - \delta_2^0) \quad (6)$$

where δ_1^0 and δ_2^0 are the angles of the termination voltages V1 and V2, respectively.

$$\Delta P_{12} = \frac{|V_1^0|\,|V_2^0|}{x}\cos(\delta_1^0 - \delta_2^0)(\Delta\delta_1 - \Delta\delta_2) \quad (7)$$

$$T^0 = \frac{|V_1^0|\,|V_2^0|}{x}\cos(\delta_1^0 - \delta_2^0)\ \text{MW/red} \quad (8)$$

$$\Delta P_{12} = T^0(\Delta\delta_1 - \Delta\delta_2)\ \text{MW} \quad (9)$$

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\frac{d\delta}{dt};\ i.e\ d\delta = 2\pi f dt \text{ Thus } \delta = 2\pi\int_0^t f dt \quad (10)$$

And hence $\Delta\delta = 2\pi\int_0^t \Delta f dt$

$$\Delta P_{12} = 2\pi T^0\left(\int_0^t \Delta f_1 dt - \int_0^t \Delta f_2 dt\right) \quad (11)$$

Taking Laplace transformation of the above equation, it can be get:

$$\Delta P_{12}(s) = \frac{2\pi T^0}{s}[\Delta f_1(s) - \Delta f_2(s)] \quad (12)$$

3. Approach of 1-D Lookup Table

With the 1-DLuT control method, controller parameters are subjected to be variable; hence, it is important to use a technique to adjust these parameters to convenient values. Lookup tables (LuTs) are a series of numbers that replace runtime calculations with simple indexing [18]. Lookup table approaches utilizing interpolation algorithms are widely used in industrial and manufacturing applications [19]. Actually, the most popular kind of nonlinear static model is a grid-based lookup table. A 1-D Lookup Table is implemented in order to maintain the balance between generation and consumption and to maintain the frequency at a nominal value. For the stable operation of the power system, it is very important to have a robust and automatic LFC mechanism to ensure a balance between power generation and consumption under all circumstances. Many one and two dimensional lookup tables are employed, especially in the control of modern combustion engines [20]. There are various applications for the look-up table. For instance, depending on the operation, the status of controller settings, such as gain or sample support parameters, can be recorded [21]. A lookup table's global online design is implemented using the suggested system technique. At the same time, a controller (C) is designed using the Vertex Placement Principle (VPP). In the event that a plant is unknown, the suggested theory states that a lookup table should be built based on the desired plant by approximating it online. In this work, the LuT algorithm involves signal processing to recapture the plant's input-output behavior. The lookup table always tries to provide a useful performance of the plant dynamics even though the plant behavior may be time-varying.

3.1 Characteristics of lookup table data

The look-up table (LuT) is used in various computers and embedded applications. NASA uses it to improve the pointing accuracy of the antenna [22]. The output of this LuT is a function of the input obtained by linear interpolation. There is a single scalar input and a single scalar output port. Parameter vectors must be sorted as shown in Equation (13). Because the input and output data are the same size to track errors, the data can be dimensioned consistently for 1-D lookup tables [23].

$$y = F(x_1, x_2, x_3, \ldots, xN) \quad (13)$$

3.2 Interpolation-extrapolation methods

The lookup table generates output from the input data using a variety of approaches. Adopting an appropriate interpolation algorithm is important to fit the target pose error based on the pose errors of adjacent grid points around the aim [18]. For 1-D LuT, the output of the Interpolation-Extrapolation method is the same element in the output vector if the value matches the input. The lookup table employs a linear internal update between the proper row and column values when inputs do not match the values of the row and column parameters. The lookup table uses the first or final two points for extrapolation if either or both of the inputs are lower than the first or higher than the values in the last row or column. It does not extrapolate beyond the x and y ends, although it does implement linear interpolation. The main pane of the Lookup Table (1-D) block appears as follows in Figure (3). The simulation of the 1-D LuT circuit generally has one input or one output [18]. For stable1-D LuT operation of circuits, a gain unit can be added to adjust the operating point of the Lookup table's function. This clearly demonstrates that the proposed 1-D Lookup table-based Interpolation-Extrapolation algorithm circuit is implemented closely with the fast transient response and less frequency deviation in comparison with those using the conventional PI controller. Figure 4 and Table 1 illustrate how a 1-D lookup table (Data 5x1) is configured.

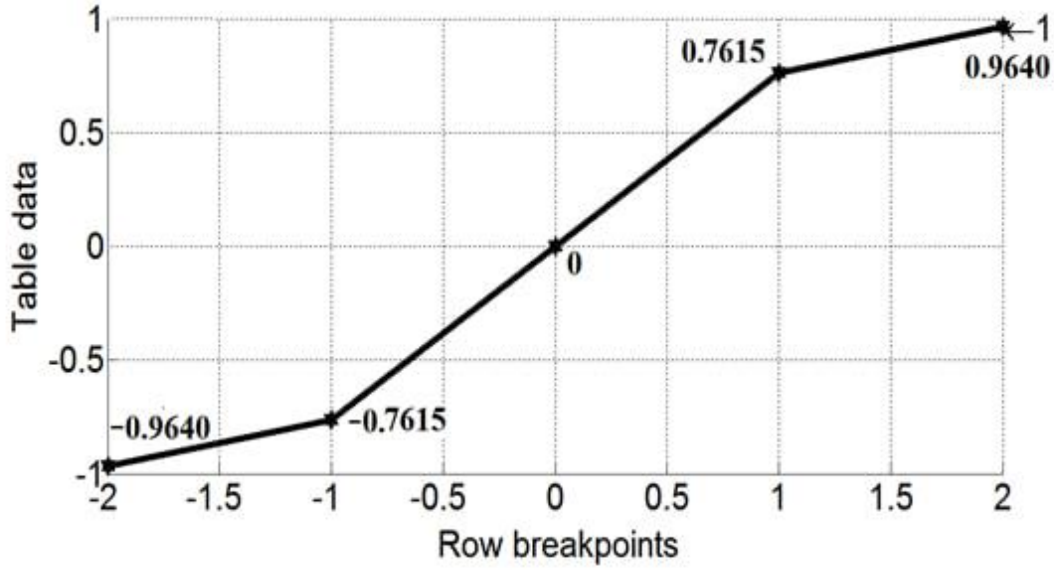


Figure 4: Membership functions for input

Table 1: Row x Column of a 1-D Lookup Table (Data 5x1)

Breakpoints	**Column**	**(1)**
Row	-------	---
(1)	-2	-0.9640
(2)	-1	-0.7615
(3)	0	0
(4)	1	0.7615
(5)	2	0.9640

3.3 The proposed power system-based 1-D lookup controller

The model of single and two-area power systems, which is shown in Figures 5 and 10, is the basis for the simulations, which are run using the system parameters listed in Tables 2 and 3. The flow chart explains the process of the proposed power system-based 1-D Lookup Controller, as shown in Figure 6.

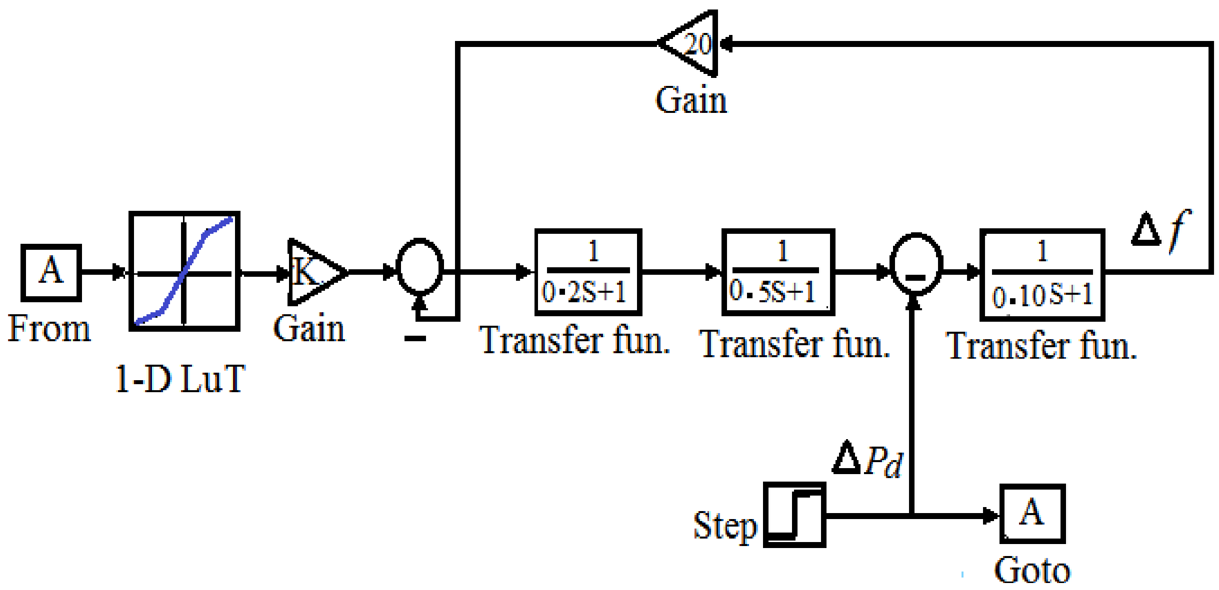


Figure 5: 1-D LuT Control in a single area power system

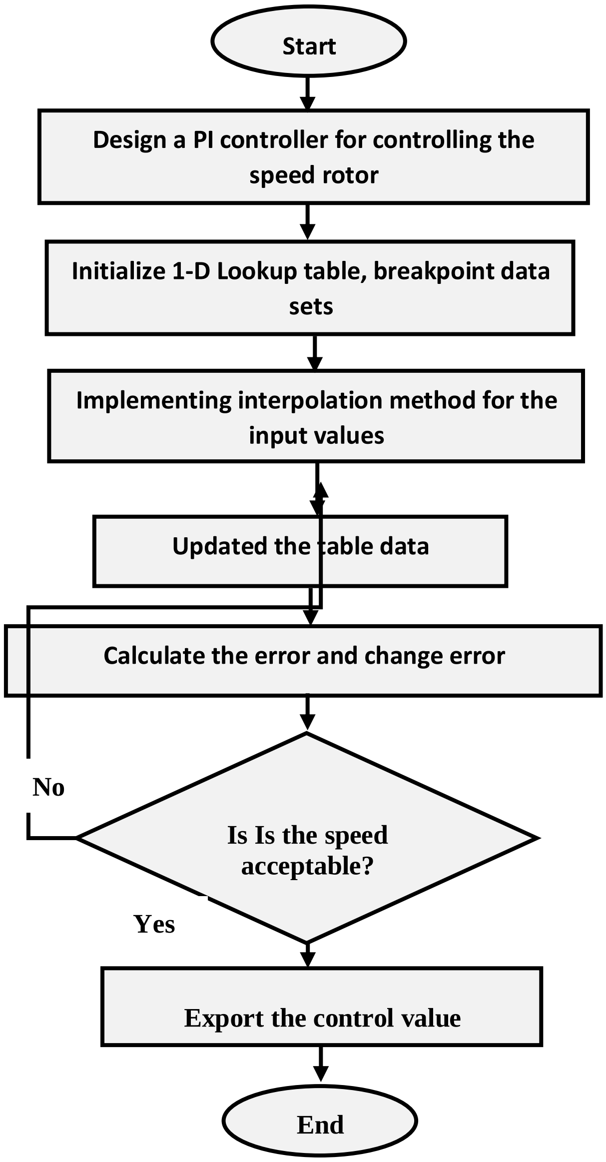


Figure 6: Flow chart of proposed power system based 1-D lookup controller

4. Results and discussion

This paper presents several simulations to illustrate the performance of the suggested LFC based on the 1-DLuT controller. To reduce system frequency oscillation, the 1-D Lookup Table (1-DLuT) controller, ANN controller, and PI controller are compared.

Case 1: Single Area Model

A step load disturbance of ΔPL increased 2pu and 4pu, respectively, is applied at t = 5 s, as shown in Figures 7, 8, and 9. The performance of the 1-DLuT controller on load disturbance was investigated. A clear comparison with the conventional PI controller, ANN- controller (NARMA-L2 model) controller under the consideration of the performance measures such as settling time, overshoots, undershoot, and the Integral of Time Absolute Error (ITAE) performance index is computed as shown in Table 2.

Table 2: Δf $parameters\ using\ PI, ANN, and\ 1-D\ LuT$ for single area

Controllers	Settling time (s)	Over-shoot (Hz)	Under- shoot (Hz)	ITAE
PI	19.72	0.0060	-0.0209	4.266
ANN	13.32	0.0042	-0.0121	1.924
LuT	9	0.00057	-0.0128	0.118

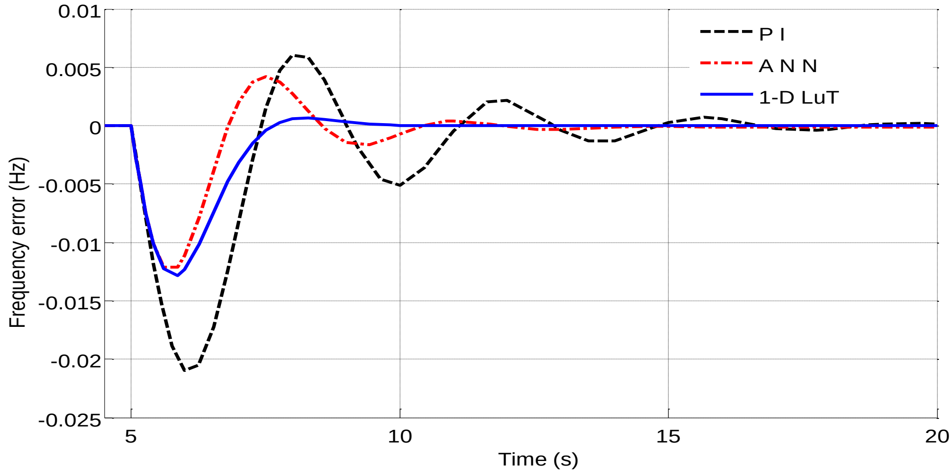


Figure 7: Comparative frequency response of a single area power system

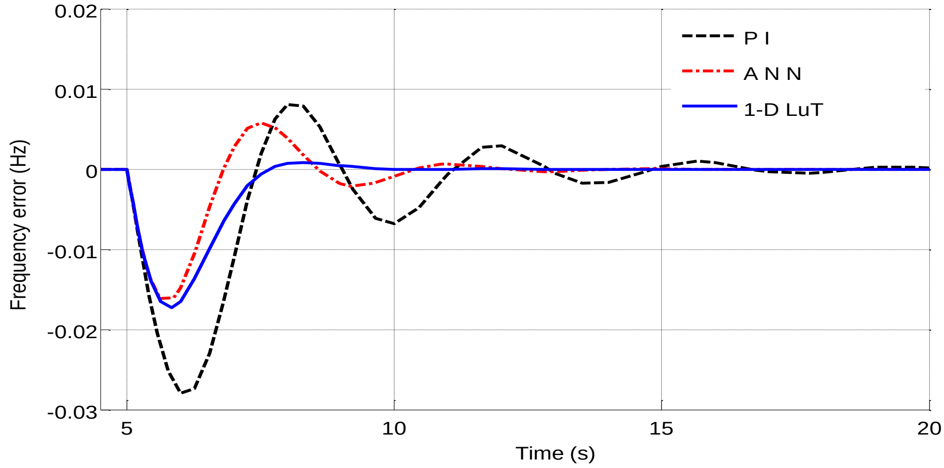


Figure 8: Δf $using\ PI, ANN, and\ 1 - D\ LuT$ for the single area with step load 2 pu

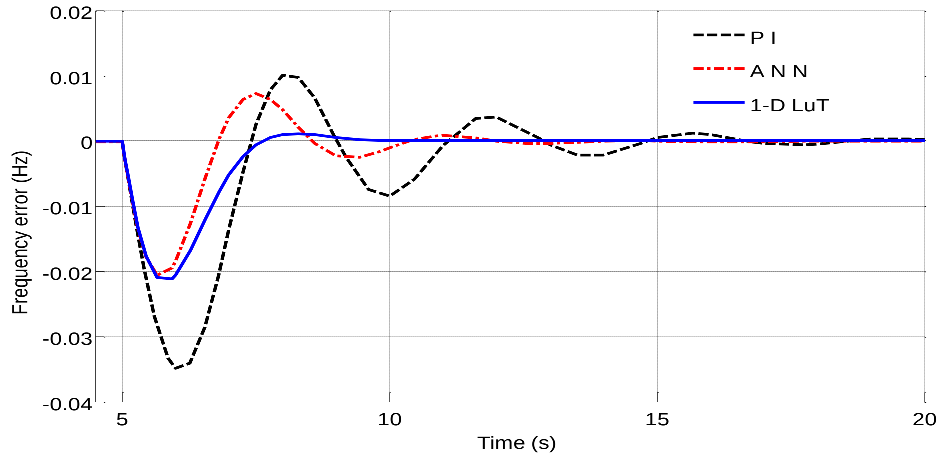


Figure 9: Δf $using\ PI, ANN, and\ 1 - D\ LuT$ for the single area with step load 4 pu

The overshoot and undershoot in the first swing have been greatly reduced, as shown by the comparison of Table 2 and Figure 9. The suggested 1-D LuT controller has also rapidly dampened the system frequency oscillation, and the settling time is also significantly shorter, which is superior to that of the PI and ANN controllers. Figure 9 shows that the 1-DLuT controller achieves steady output power faster and with fewer adjustments.

Case 2: Two Area Model

In this case, the 1-D LuT is designed using the circuit-based controller design shown in Figure 10. The system may reduce frequency oscillation under load disturbance, as shown in Figures 11 and 12.

The 1-D LuT controller continues to offer superior decreasing performance over the ANN and PI controllers. Figures 11 and 12 (a and b) demonstrate that the system can reduce frequency oscillation under load disturbance, with the 1-D LuT controller continuing to offer superior decreasing performance compared to the ANN and PI controllers. In contrast, the Integral of Time Absolute Error (ITAE) performance index varies from one another, as indicated in Table 3. Figure 13 (a and b) illustrates how the 1-D LuT controller outperformed the PI and ANN controllers in terms of the frequency response of the two areas with step load, increasing twice (in 5s).

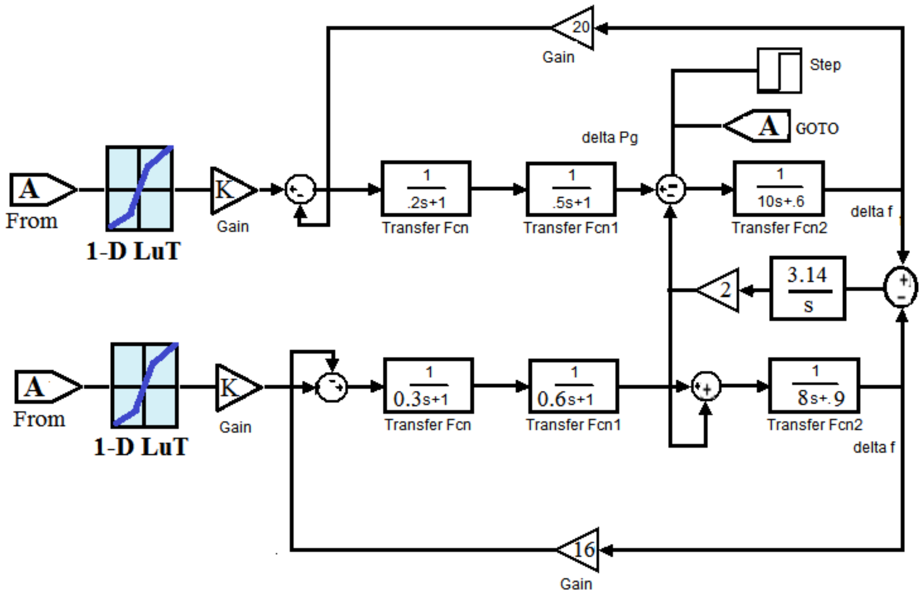
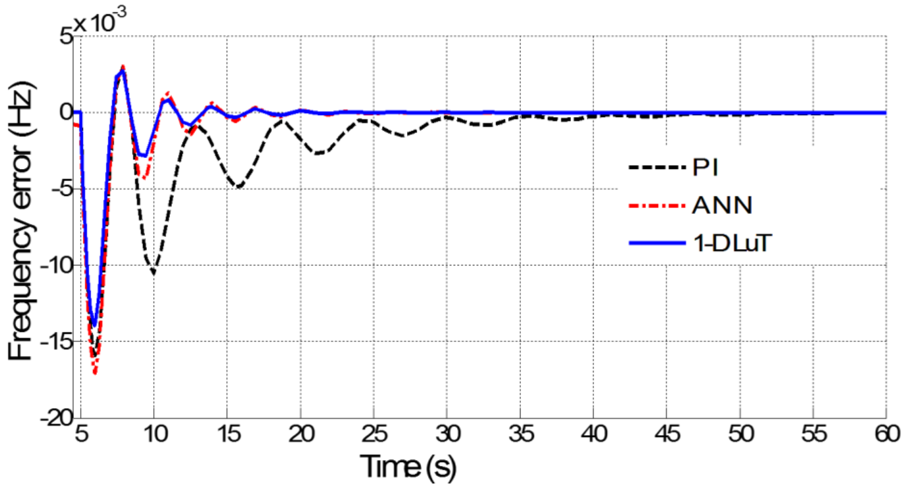
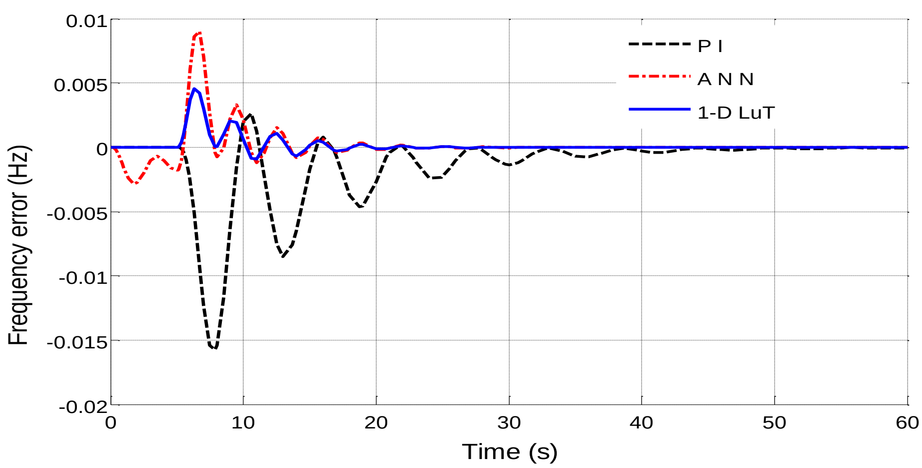


Figure 10: 1-D LuT Control in a two-area power system

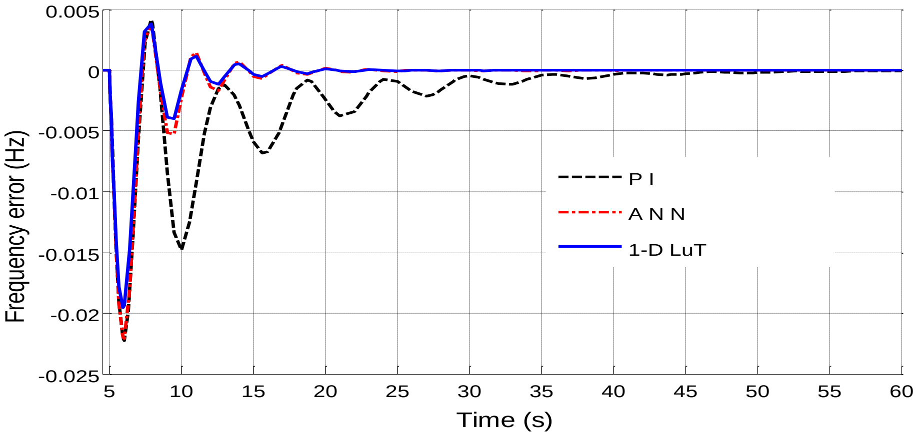


(a)

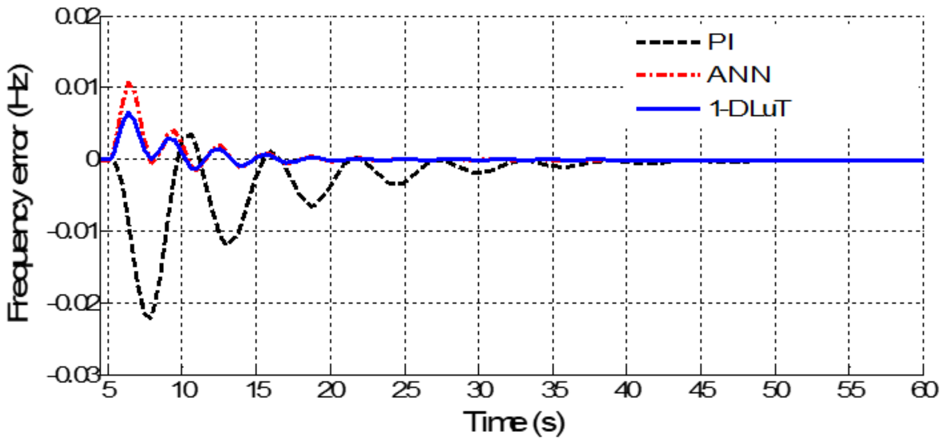


(b)

Figure 11: Comparative frequency response of the two areas with three control methods: (a) Area 1 and (b) Area 2



(a)

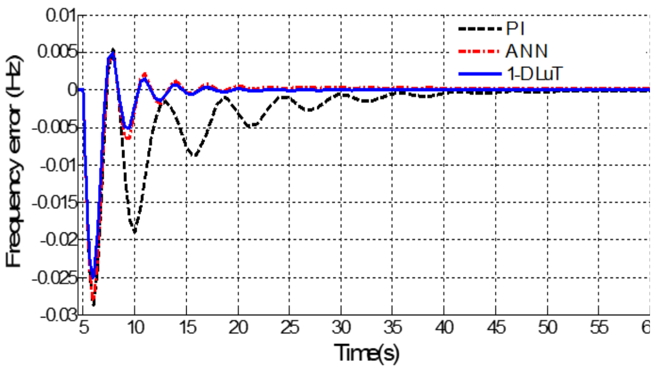


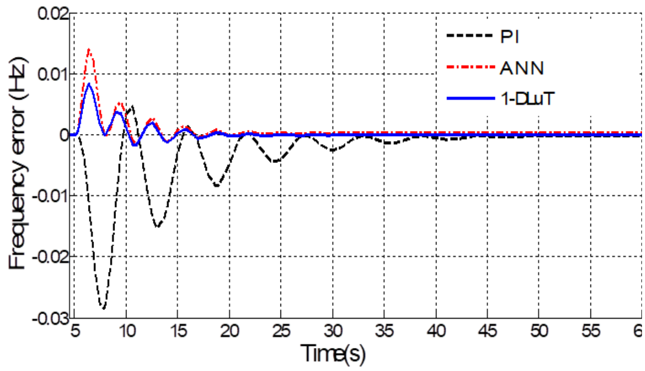
(b)

Figure 12: Comparative frequency response of the two areas with step load increased 2pu (a) Area 1 (b) Area 2

Table 3: The response parameters values of PI, ANN, and the proposed control for the two area power system

Controllers	Settling time (s)	Over-shoot (Hz)	Under- shoot (Hz)	ITAE
PI	53	0.0046	-0.0284	2.487
ANN	29	0.0139	-0.0016	1.631
1-D LuT	28	0.0083	-0.0015	0.366





(a) **(b)**

Figure 13: Comparative frequency response of the two areas with step load increased 4pu (a) Area 1 (b) Area

5. Conclusion

In this paper, a 1-DLuT control has been used to compare the behavior and transient performance of the area power system with the ANN and PI controller. The proposed technique proved to be quite powerful tool in the resolution of problems related to electrical power systems, particularly in load frequency control. Through the simulations carried out on MATLAB/Simulink, the proposed controller is found more effectively to eliminate the oscillations and provide smooth operation. The1-DLuT control, based on the lookup table, is capable of controlling frequency and power whose support is lost due to the discontinuity of the power system. 1-DLuT control adopts three cases of load change as input and generates an output control signal that is required to reduce frequency errors. Additionally, it is seen that the suggested proposed controller gives better responses regarding overshooting and faster response than both the ANN and PI controls.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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