Frequency Stabilization of Two Area Power Systems using TID Controller

Vikash Kumar[1], Pooja Jha[2]

[1]PG Scholar, Electrical Engineering, Sandip University
[2]Assistant Professor (H.O.D), Electrical Engineering, Sandip University

Abstract

This review paper presents a comprehensive analysis of frequency stabilization in two area interconnected power systems with special emphasis on the Tilt Integral Derivative (TID) controller. Load Frequency Control is essential for maintaining system stability, especially under increasing penetration of renewable energy sources, deregulated environments, and uncertain load conditions. The paper systematically reviews classical, modern, and intelligent control strategies used for LFC, and highlights the advantages of fractional and tilt based controllers. Comparative analysis using reported performance indices shows that the TID based controllers, particularly TID ABCO, provide better settling time and reduced frequency and tie line power deviations compared to conventional and several optimized controllers. The study confirms that TID controllers offer a robust and efficient solution for frequency regulation in modern interconnected power systems.

Keywords: Load Frequency Control, Two Area Power System, TID Controller, Frequency Stabilization, Tie Line Power, Renewable Integration, Automatic Generation Control.

1. Introduction

In today's globe, electricity is undeniably seen as a crucial and perhaps environmentally friendly energy source. Loads, transmission, distribution, and generation are the four legs of an interdependent power system. An expanded interconnected power system uses a tie-line to link many service areas that are located in different parts of the country. So, if there was an unforeseen load disruption in one area, it would cause unwelcome changes to the tie-line power and frequency in other areas [1,2].Each area's generation has to be controlled in order to keep the planned power exchange with other regions running. Automatic generation control (AGC) relies on load frequency control (LFC) as a key operator because of its superior power control capabilities [3]. There is concern about the availability of non-renewable resources for both present and future generations because of its unequal distribution and non-renewability [4]. Commercially available equipment and energy storage research are both seeing an increase in the use of lithium-ion batteries, or LiBs.

Energy security is one of the main reasons why microgrid applications are growing and being adopted. As a function of active power needs, power system frequency and its fluctuation are connected. The system frequency fluctuates and fails to meet the goal value when the active power used exceeds the active power produced. To address this issue, LFC is used to control the output power while keeping the nominal frequency constant at a predetermined value [2]. Maintaining the system's frequency and limiting tie-line power fluctuation to predetermined limits are two of LFC's primary objectives as an important part of the power system.

As a stability criteria in systems involving two or more regions, frequency is crucial. Consequently, for optimal stability, the frequency must be consistently maintained in relation to the active power balance [3]. On top of that, LFC prevents disturbances from causing grid instability [2]. The control aim of LFC is to keep the total tie-line flow deviation and frequency variation among the control zones as low as feasible. Specifically, resonance assaults, model parameter inaccuracies, and system nonlinearities should not destabilize the LFC. These issues may occur in actual power systems.

New systems including autonomous grids, micro-grids, nano-grids, and smart grid technologies, as well as the integration of different renewable energy sources, are causing modern power systems to undergo a fast change [5]. It is difficult to predict the generation of active power due to the interconnection of many renewable energy sources (e.g., wind turbines, tidal turbines, geothermal plants, biomass plants, hydro power plants, photovoltaic cells, etc.) (Figure 1 [6]). The potential of solar energy has been the subject of much study. Solar energy is seen as a convenient substitute for hydro energy systems because to its cheaper construction cost and mobility, which makes it an easy alternative to the traditional most environmentally friendly energy source. However, hydro energy systems do come with a big initial cost and lengthy building timeframe [7]. Therefore, an unstable power system functioning is caused by frequency variations. Modern electricity grids are deregulated and need the separation of horizontal and vertical components, rather than being vertically integrated. Under these conditions, it is crucial to study and build better frequency controller devices. “The design of load frequency controllers has been the subject of much study for the purpose of development and enhancement [8].” Automatic generation management of multi-area power plants using a PID controller was the subject of Krishan et al.'s study in [9]. There was successful implementation of “generating rate constraint-aware multivariable predictive-based load frequency control in [10].” Nevertheless, the controllers that were created fail to provide exceptional values for the settling time, peak overshoot, and peak undershoot. Load Frequency Controllers primarily aim to swiftly stabilize themselves by adjusting their settings in response to external factors [11,12]. “There has been a lot of study into finding the perfect load frequency controller, but most of them suffer from slow settling times. Newer studies are looking at using intelligent design techniques to LFC designs.” An LFC design that relied on Artificial Neural Networks was aimed at the deregulated power market in [13,14]. As such, it exemplifies the characteristics of an intelligent controller that can learn from its environment.

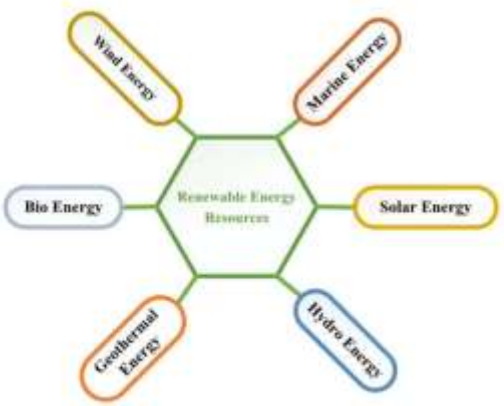


Figure 1: Renewable Energy Systems [13].

A. Overview of load frequency control

Figure 2 shows the two primary components of AGC, the AVR function and the LFC function. Maintaining the stipulated values for power interchanges and frequency variations in connected power systems, as well as ensuring a steady-state error (SSE) of zero, are the responsibilities of LFC in monitoring load demands and controlling frequency variations [14–16]. In response to changes in the load, AVR regulates the excitation voltage, which in turn controls the generator's power output, ensuring steady, reliable power [17, 18].

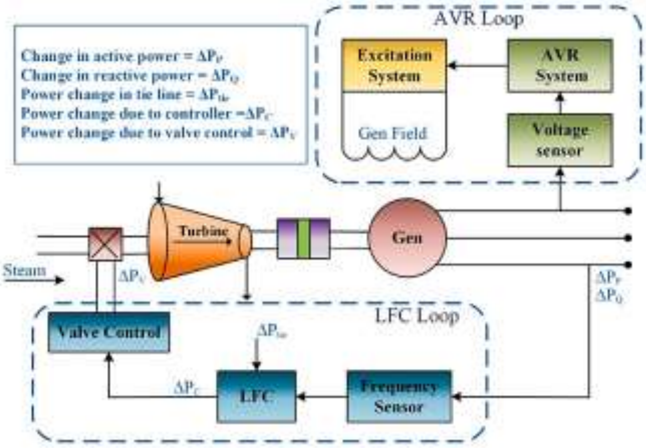


Figure 2: LFC and AVR control mechanisms [15].

Hierarchical structure of frequency management, safeguards, and restrictions on equipment damage is what frequency coordination is all about. For example, AGC, time correction, governor response set points, generation and load trip set points, and other devices responsible for controlling frequency will need to be adjusted and synchronized in order to permit normal frequency fluctuations to occur within wider boundaries, as is done in certain other power systems. Although it's within the realm of possibility, the necessary engineering and manpower to execute this activity system-wide may drive up the cost significantly. Primary, secondary, and tertiary control systems make up LFC. Total generation and demand are kept in equilibrium by the basic process. One of the main ways to manage the turbine is via the governor [19]. Once the primary control system is unable to counteract frequency fluctuation, the next step is to set the frequency to the desired value. The output of individual unit turbines is applied via the secondary control system in order to keep power flowing throughout linked regions [20]. The operator has the option to manually engage tertiary control, also known as manually frequency restoration reserve, when it becomes required [21]. Whenever there is a significant decrease in either generation or load, it is used to restock the secondary reserve. The main control transients have a time scale of seconds, whereas the secondary and tertiary controls have a time range of minutes (Fig. 3). In each area, a gas unit, a hydropower plant, and a power plant are all optimized using the TID controller shown in Figure 3. The rated power in each area is 2000 MW.

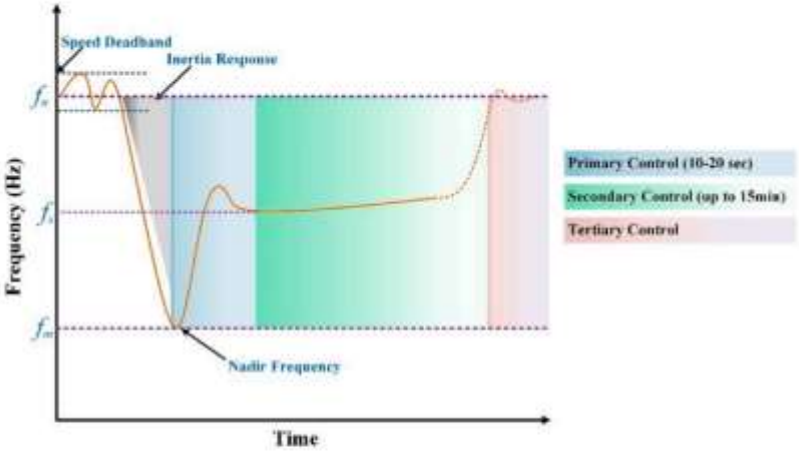


Figure 3: Deviation in frequency and their control levels [15].

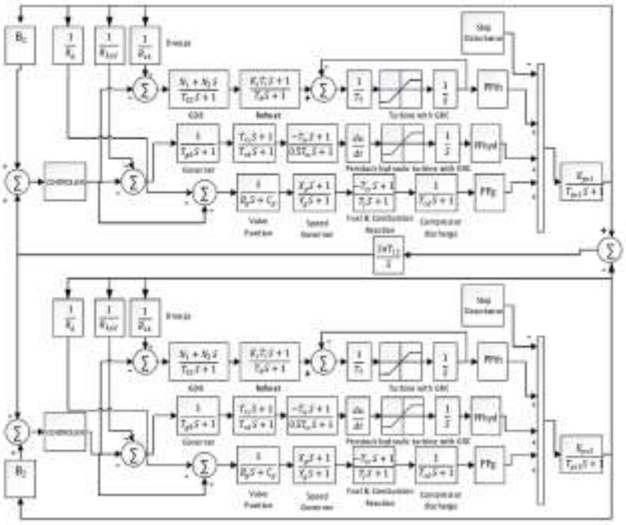


Figure 4: Dynamic representation of a multi-area power network [24]

B. PID and TID Controller

PID Controller

Electronic product performance and operational lifetime may be optimized and extended with proper management of the Load Frequency Control (LFC) process. The proportional-integral-derivative (PID) controller measures the difference between the output and the target set point to determine how to operate. This controller has a simple design, flexible tuning techniques, and simple electrical circuits, which make it popular in the process industry [22]. When you tune the controller, you use various optimization strategies to minimize the performance function, which is a measure generated from the error over time. The PID controller improves system stability by including separate integral, proportional, and derivative elements, which assist reduce dynamic response damping and steady-state inaccuracy. Equation following expresses the transfer function of the PID controller that was used in this research and was incorporated into the LFC linear model that was discussed before.

$$U_{PID} = K_P + \frac{K_i}{S} + K_d S$$

TID Controller

The innovative TID controller is presented in this publication. It consists of three gain terms, “tilt gain, integral gain, and derivative gain,” that are coupled in parallel. The TID controller, which is based on fractional-order calculus, is designed as a fractional-order controller (FOC). Figure 5 shows the controller's architecture. It should be noted that a slanted component, defined by a transfer function of s^-(1/n), is used in place of the proportional component. Figure 5 shows that for any non-zero real number 'n,' there are proportional, integral, and derivative gains denoted by Kt, Ki, and Kd, respectively. The TID controller's mathematical model may be found in Equation below.

$$u(t) = U_{TID} = \frac{K_t}{S^{\left(\frac{1}{n}\right)}} + \frac{K_i}{S} + K_d S$$

Here are the configured error inputs for the controller:

$$e(t) = B\,\Delta\,F$$

Starting with the required requirements and restrictions, the objective function is defined in order to formulate a modern heuristic optimization method that is integrated with the controller. “The Integral of Time multiplied Absolute Error (ITAE) is the selected performance metric for control design. Using the ITAE criteria is driven by its ability to minimize settling time, which cannot be achieved when tuning using the Integral of Absolute Error (IAE) or Integral of Squared Error (ISE) metrics.” Overshoot and undershoot are both helped by the ITAE criteria. According to previous research, “when it comes to Load Frequency Control (LFC) investigations, ITAE is the way to go for an objective function.” Therefore, in order to optimize the gain of the TID controller, this research uses ITAE as the objective function [23]. You may find the ITAE objective function's expression in the following equation.

$$J = \text{ITAE} = \int_0^{T_{sim}} \left|\left(\Delta F\right)\right| t \; .dt$$

The above equation uses ΔF to indicate the incremental change in the area's frequency and Tsim to designate the simulation's time span. Problem restrictions are related to the limits of the TID controller settings. Thus, the following optimization problem statement best describes the design issue:

$$\text{Minimize} = \int_0^{T_{sim}} \left|\left(\Delta F\right)\right| t \; .dt$$

With the following limitations in mind, In this case, J stands for the goal function, while KTID min and KTID max are the upper and lower bounds of the TID control parameters, respectively.

“Kt min ≤ Kt ≤ Kt max, Ki min ≤ Ki ≤ Ki max, Kd min ≤ Kd ≤ Kd max,, n min ≤ n ≤ n max”

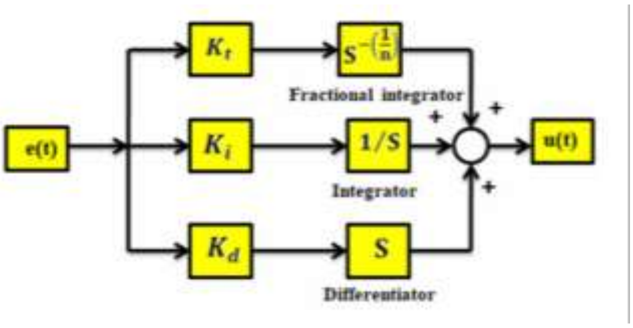
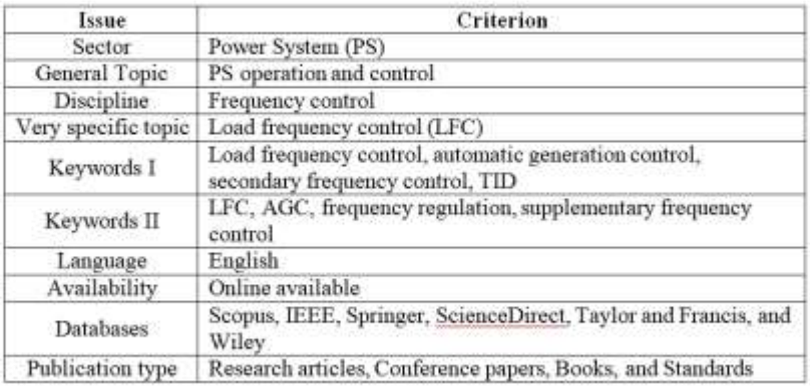


Figure 5: Illustrates the configuration of the TID controller [22]

2. Methods

In order to carry out this extensive study, publications published in the area of LFC are sought for using particular keywords in the most prominent and renowned databases, including Scopus, IEEE discover, Science Direct, and Springer. Figure 6 provides an overview of the search approach, including the full list of terms utilized in the search. After eliminating duplicates, 513 articles remained from the first search that used the aforementioned methods, which generated 748 papers. After that, 203 articles were eliminated after their abstracts, contributions, and titles were reviewed according to the criteria and purpose of this study. Our experienced staff thoroughly reviews the final paper listings on the subject of LFC. This review study has also been peer-reviewed by two other experts in the field of LFC before it was submitted to Energies Journal, thus that should be mentioned. The review procedure utilized to conduct this review article is shown in Figure 7, which is a flow diagram.



Issue	Criterion
Sector	Power System (PS)
General Topic	PS operation and control
Discipline	Frequency control
Very specific topic	Load frequency control (LFC)
Keywords I	Load frequency control, automatic generation control, secondary frequency control, TID
Keywords II	LFC, AGC, frequency regulation, supplementary frequency control
Language	English
Availability	Online available
Databases	Scopus, IEEE, Springer, ScienceDirect, Taylor and Francis, and Wiley
Publication type	Research articles, Conference papers, Books, and Standards

Figure 6: Description of the used review methodology.

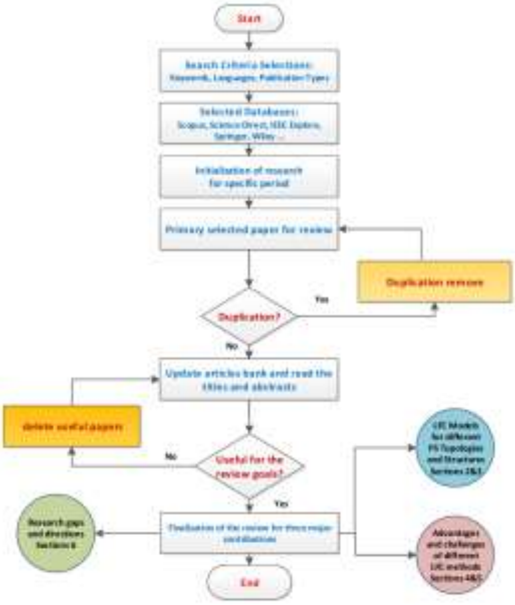


Figure 7: Flowchart of the used review methodology.

3. Load Frequency Control (LFC)

Several other types of renewable energy power systems exist; however, for the sake of this study, we will refer to them as either single-area or multi-area power systems. Typically, the latter is a linked power system, while the former is an isolated one. The connectivity of renewable energy sources causes transients and frequency variations [25], and environmental non-linearity disrupts the regular functioning of the power system. Figure 8 shows the use of LFC and optimization strategies in different sectors. To optimize the LFC and enhance its transient responsiveness and settling time, several methods are used.

Figure 8: LFC in Different Environments

Intelligent tuning of LFC controllers in contemporary power systems makes use of several soft computing technologies. Using the multi-objective extremal optimization approach, a FOFPID controller has been created for islanded microgrids. “To optimize the PI-PD cascade controller for controlling the AGC in MAPS, the Flower Pollination algorithm was used.” A hydrothermal power system's load frequency management and dynamic fuzzy valve position modeling were the inspiration for the distributed model predictive control. It made the power system more responsive in both transient and stable states. A multi-source linked power system was equipped with “an optimum fuzzy PID controller and automated generation control was implemented utilizing the hybrid differential evolution-grey wolf optimization technique.” In order to improve “the cascaded architecture of a PD-fuzzy-PID controller, fuzzy logic methods were used [26].”

A. Single-Area Power System

Renewable energy sources such as wind, solar, biomass, hydro, and tidal power can all be found in single-area power systems, but only one. The technology is straightforward, making both electricity production and consumption a breeze. See Figure 9 for an illustration of a single-area power system that utilizes wind turbines. Here, a controller is housed in the feedback loop; it monitors the output signal and modifies the system's settings to keep the power output quality constant.

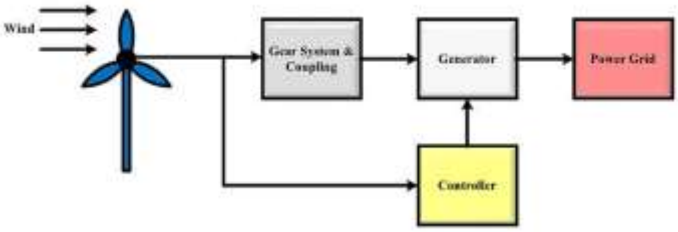


Figure 9: Wind Turbine-Based Single-Area Power System [13].

The settling time, overshoot, and undershoot in the output signal have been reduced via the evolution of LFC's design for a single-area power system. Disruptions impose on power system variables, leading to operational mistakes, in contemporary power systems that include several generating sources. It is time to create a method to reject disturbances. In order to fine-tune the PID controller, “the Microgrid System described by Qi et al. [27] use an improved linear active disturbance rejection control algorithm (ILADRC).” Compared to traditional PI controllers, “Fuzzy PI, and LADRC, the findings indicated that it performed better.” When put through its paces in a variety of test scenarios, the power system consistently outperformed expectations.

B. Multi-Area Power System

Power grids nowadays are more adaptable, allowing for the integration of renewable energy sources like solar and wind with more traditional power plants. Because of the increased instability caused by the connectivity of diverse generating sources, load frequency regulation becomes a challenging issue in multi-area power systems. A multi-area power system's LFC design takes into account the amount of frequency variation in each control region. Problems with transients and power system instability may arise from the tie line power variation, which is a major concern in linked systems. The output power of renewable energy sources is quite unstable and may be caused by sudden changes in both demand and power. The power exchange between different regions is shown in Figure 10. Each area is made up of conventional units with dispersed generation and is linked to different sub-systems. Issues like transients and harmonics arise from the interaction of several sectors. Because power imbalances cause problems with power flow on linked lines, measuring power flow on linked lines is an integral part of frequency regulation. Reliability in operation is dependent on the frequency regulation, which is a defining feature of the whole power system. Active power consumption and total active power generation must be equal at all times for the power system frequency to remain constant.

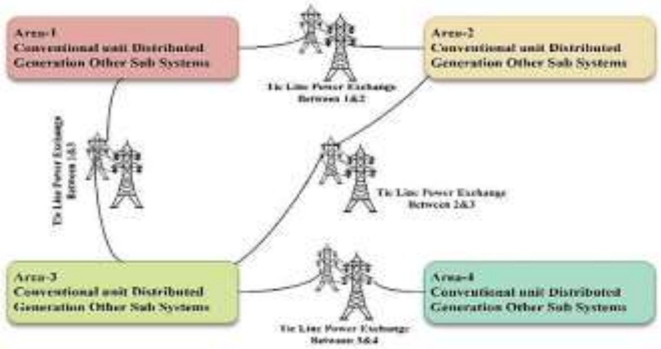


Figure 10: Power Exchange between Different Areas [13].

The Tie Line Interconnection of several GENCOs is seen in Figure 11. The system is separated into different regions here. The tie lines allow for connectivity between the various areas, “which are home to generating companies (GENCOs) and distribution businesses (DISCOs).” A more manageable power system may be achieved by configuring the number of regions in this way. In each section, electricity travels from GENCO to DISCO, and vice versa, thanks to the tie lines that connect the various sections. The GENCOs and DISCOs are connected in a two-way power flow.

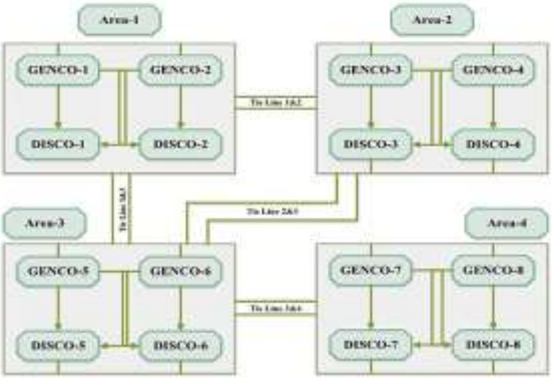


Figure 11: Tie Line Interconnection of GENCO [13].

4. Strategies

A. Classical Control Method

Most often, PI and PID are thought of while discussing classical control approaches. The controller is designed using the tie-line power deviation and frequency deviation in LFC using PI or PID control techniques. On the basis of the signal transmission ΔPtie and Δfi, the area control error ACEi is summarized. Here we have the PI controller:

$$u_i = K_p ACE_i + K_i \int ACE_i$$

“in where Kp and Ki stand for the controller's gain. You may express the controller as yi(t) = [ACEi, ACEi].”

$$u_i = K_{pi} y_i(t)$$

“where Kpi = [Kp,Ki], Kpi will be designed. The PID controller can be designed as follows:”

$$K_i(s) = K_p + \frac{K_i}{s} + sK_d$$

$$u_i = K_i(s) y_i(t)$$

For the delayed LFC system, the frequency-domain method was used to describe a fractional-order PID controller cascading with a first-order filter [28]. It was suggested to stabilize the system using a “PID-based secondary controller, which would use an enhanced form of particle swarm optimization [16].” Authors in [28] compared “GSD-PID and GSD-GSD controllers, which are based on the gain-scheduling decentralized (GSD) method.” In order to get stabilizing sets of PID or PI controllers while reducing computational cost and overcoming uncertainties, a new numerical technique was developed in [29]. In [30], a PID control approach was devised that does not need tweaking.

B. Modern Control Method

The LFC problem has prompted the development of several control systems, including as adaptive control, digital control, intelligent procedures, variable structure, and robust control. Statistical method control (SMC) is a common example in this field. In addition to being easy to execute, SMC is also impervious to disturbances and changes in parameters [31]. The useful sliding mode surface must have s(t) = 0 and ˙s(t) = 0, which is of utmost importance. Many efforts have been made by researchers to develop an appropriate SMC. An LFC power system was equipped with a specific sort of PI-type SMC in [13].

$$s(t) = G_i x_i(t) - \int_0^t G_i(A_i - B_i K_i)$$

“where Gi and Ki are a constant matrix and Gi is chosen to ensure that GiBi is non-singular.”

The SMC design is mostly affected by the system state. Unfortunately, there are many of situations when we can just get the system's output. This happens when we're dealing with system states that are either too complicated or expensive to measure in their whole. As a result, designers of output sliding mode controllers have their pick of two approaches: one uses a state observer to make educated guesses about the system's states, while the other starts with the output data itself. A sliding mode surface for the output [33] is created according to the current condition of the system and its output.

$$s(t) = G_i y_i(t) - \int_0^t C_i x_i(\vartheta) d\vartheta$$

“where yi(t) is the system output and Gi is selected to ensure that GiCiBi is non-singular.”

The output feedback SMC does a good job of fixing the issues caused by partially utilized system states. It is also possible to estimate the states of a renewable power system using a full-order observer, which takes into account any uncertainty or disruption in the system [34]. The design of an output-dependent SMC was as follows:

$$s(t) = G_i(y_i(t) - y_i(0)) - \int_0^t L_i(q) dq$$

$$L_i(t) = -K_i(x_i(t) - e_i(t))$$

C. Intelligent Control

The efficiency of LFC power systems may be enhanced with the use of intelligent control. The intelligent control system processes the power system's important data using algorithms or logic. One may wonder whether data-driven control techniques are still a viable option for achieving frequency balance in power systems in light of the ever-increasing data and system sizes. Using particle swarm optimization (PSO), the authors of [35] were able to create a fuzzy-PSO-PIDLFC. A data-driven cooperative LFC approach for a power system was described in [36], which is “based on multi-agent deep reinforcement learning with continuous action domain.” It is necessary to reduce area control mistakes in order to implement the LFC method. “Unscheduled tie-line power flow interchange and the squared sum of frequency variations [36] are the definitions of goal Q,” which is supplied as

$$Q^{\mu}(s, \alpha) = -\sum_{t=1}^{T} [\Delta t \sum_{i=1}^{n} [(\beta_i \Delta f_i)^2 + (\Delta P_{tie})^2]]$$

The simulated total time is represented by T, the step size is denoted by Δt, and the state information is represented by s. The data-driven strategy's system frequency is adequate for all circumstances after investigation. The controller settings are adjusted using coordinates during centralized learning using a multi-agent deep deterministic policy gradient, with the goal of improving the performance of load frequency control. “One way to speed up multi-agent deep reinforcement learning is to use an initialization method for agent settings.”

There are a plethora of control strategies that “work very well when it comes to fixing LFC issues, not just the ones listed above.” The authors of [37] sought to use the idea of a grid-forming (GFM) converter “to make renewable energy sources a reality in contemporary power systems.” To improve the virtual inertia control loop, researchers in [38] used a whale optimization method to optimize the settings of a virtual inertia controller. “This approach took into account the uncertainties of the system's inertia while using renewable energy sources. The parameter regulator of a WTG that relies on direct heuristic dynamic programming was given virtual inertia control in [39].” For an isolated MG taking high-level RES penetration into account, a novel controller based on robust virtual inertia control and the coefficient diagram approach was suggested in [40] to improve system validity and resilience against disturbances and parametric uncertainties.

5. Tilt Integral Derivative Controller

When it comes to system dynamics and load disturbances, TID controllers outperform traditional PID controllers.

Table 1: “Performance Indices of TID Controller in an Inter connected Power System.”

Performance Indices	[41] MPSOGA	[42] FOTID	[43] CC-TI-TD	[44] TID-ABCO	[45] TLBO-PID
Δf_1 ST (s)	25	23.59	13.29	9.5654	5.82
Δf_1 US (Hz)	0	0.0117	0.01	0	0.253
Δf_1 OS (Hz)	0.04	0.0026	0.00	0.0241	0.045
Δf_2 ST (s)	0	18.77	32.10	11.104	0.2312
Δf_2 US (Hz)	16	0.0068	0.00	0	0.0336
Δf_2 OS (Hz)	0.03	0.0228	0.00	0.0291	0
ΔP_{tie} ST (s)	9	23.25	30.70	18.7992	2.53
ΔP_{tie} US (Hz)	0	0.0044	0.00	0	0.0064
ΔP_{tie} OS (Hz)	0.023	0.0245	0.00	0.0048	0.05

Table 1 presents a comparative evaluation of different controllers based on key performance indices for an interconnected power system. From Table 1, it is clearly observed that the TID ABCO controller shows significantly improved dynamic performance when compared with MPSOGA [41], FOTID [42], CC TI TD [43] and TLBO PID [45]. In terms of frequency deviation of area one, the settling time using TID ABCO is 9.5654 s, which is much lower than 25 s for MPSOGA [41], 23.59 s for FOTID [42] and 13.29 s for CC TI TD [43], although TLBO PID [45] gives the minimum value of 5.82 s.

For undershoot and overshoot of frequency deviations, TID ABCO maintains zero or very small values in both areas, showing better damping of oscillations compared to other methods. For tie line power deviation, TID ABCO achieves a settling time of 18.7992 s, which is lower than FOTID [42] and CC TI TD [43], and much better than MPSOGA [41]. Table 1 confirms that the TID ABCO controller provides a balanced improvement in settling time, overshoot and undershoot, demonstrating superior frequency stabilization performance among the compared techniques.

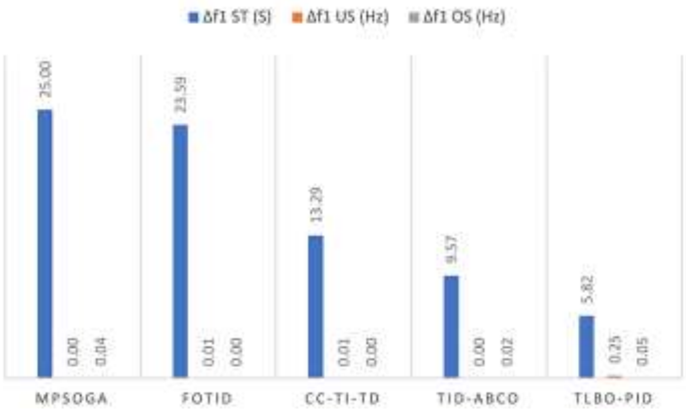


Figure 12: “Frequency Deviation for Interconnected Systems.”

Figure 12 illustrates the comparative frequency deviation performance of different controllers for interconnected systems in terms of settling time, undershoot and overshoot of area one frequency. From Figure 12, it is clear that MPSOGA and FOTID show high settling times of 25 s and 23.59 s respectively, indicating slower dynamic response. CC TI TD improves the response with a settling time of 13.29 s, while TID ABCO further reduces it to 9.57 s. The best settling time is achieved by TLBO PID at 5.82 s. In terms of undershoot and overshoot, TID ABCO maintains zero undershoot and very small overshoot, showing effective damping of oscillations. This confirms that TID ABCO provides a good balance between fast settling and low oscillations.

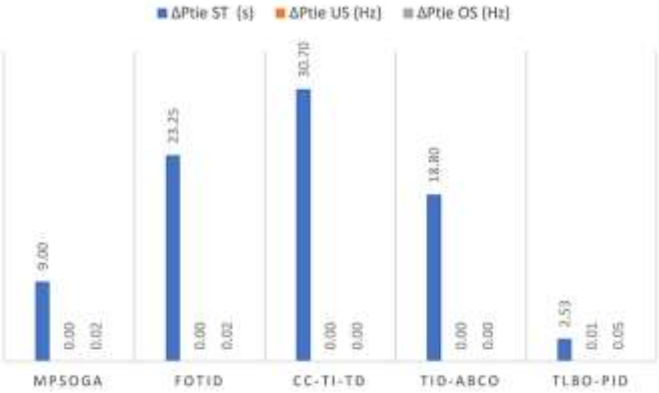


Figure 13: "Frequency Deviation for Interconnected Systems."

Figure 13 presents the comparative performance of different controllers in terms of tie line power deviation for interconnected systems, considering settling time, undershoot and overshoot. From Figure 13, it is observed that CC TI TD shows the highest settling time of about 30.70 s, indicating a very slow dynamic response, followed by FOTID with 23.25 s. MPSOGA performs better with a settling time of 9 s, while TID ABCO further reduces it to about 18.80 s. The minimum settling time is achieved by TLBO PID at only 2.53 s, showing the fastest response. In terms of undershoot, most controllers maintain zero or very small values. Overshoot is lowest for CC TI TD and TID ABCO, indicating better damping of tie line oscillations.

6. Conclusion and Future Scope

This review has examined the evolution of load frequency control strategies for interconnected power systems, with particular focus on two area systems operating under modern challenges such as renewable energy integration, deregulation, and system uncertainties. Classical PI and PID controllers, although simple and widely used, show limitations in terms of settling time and oscillation damping. Modern and intelligent control techniques have significantly improved performance, but often at the cost of higher complexity. The Tilt Integral Derivative controller emerges as a strong alternative due to its fractional order structure and superior dynamic characteristics. Comparative results clearly show that TID based controllers, especially the TID ABCO approach, achieve faster settling time and lower overshoot and undershoot in both frequency and tie line power deviations. Therefore, TID controllers provide an effective and reliable solution for frequency stabilization in interconnected power systems. Their flexibility and robustness make them well suited for future power systems with high renewable energy penetration.

The current state of affairs regarding the stability and communication security issues in linked power systems powered by renewable energy is noteworthy. One of the biggest challenges for the energy sector going forward is figuring out how to integrate and optimize different renewable energy sources. The development of cutting-edge technology like cloud computing, big data, and artificial intelligence also holds enormous promise for addressing issues connected to LFC. Below, we will go over the present difficulties and potential avenues for further study.

(1) Some previously unusable renewable energy sources have been created for use in power systems as a result of increased study into renewable energy. Uncertainty and complexity in power production are exacerbated by the varying power output of renewable energy sources that are linked to the power system.

(2) In order for electricity systems to function properly, cyber-security issues are intrinsically linked. The effect of a hybrid cyberattack may be more significant than that of a single cyberattack type. And we must not ignore the emerging threat of cyberattacks on LFC power grids.

(3) Numerous intelligent algorithm-based control solutions for LFC power systems have been investigated in recent years. A lot of people are putting more effort and resources into developing intelligent control systems because of all the problems with renewable energy and cyberattacks.

7. References

1. Ameli, A., Hooshyar, A., El-Saadany, E. F., & Youssef, A. M. (2018). Attack detection and identification for automatic generation control systems. IEEE Transactions on Power Systems, 33(5), 4760–4774. https://doi.org/10.1109/tpwrs.2018.2810161
2. Mohammadikia, R., & Aliasghary, M. (2018). A fractional order fuzzy PID for load frequency control of four-area interconnected power system using biogeography-based optimization. International Transactions on Electrical Energy Systems, 29(2), e2735. https://doi.org/10.1002/etep.2735
3. Kumar, R., & Sharma, V. K. (2019). Whale Optimization Controller for load frequency control of a Two-Area multi-source deregulated power system. International Journal of Fuzzy Systems, 22(1), 122–137. https://doi.org/10.1007/s40815-019-00761-4
4. Shayeghi, H.; Rahnama, A.; Mohajery, R.; Bizon, N.; Mazare, A.G.; Ionescu, L.M. Multi-Area Microgrid Load-Frequency Control Using Combined Fractional and Integer Order Master–Slave Controller Considering Electric Vehicle Aggregator Effects. Electronics **2022**, 11, 3440.
5. Verma, Y.P.; Kumar, A. Load frequency control in deregulated power system with wind integrated system using fuzzy controller. Front. Energy 2013, 7, 245–254.
6. Hasanien, H.M. Whale optimisation algorithm for automatic generation control of interconnected modern power systems including renewable energy sources. IET Gener. Transm. Distrib. 2018, 12, 607–614.
7. Yousef, H.A.; Al-Kharusi, K.; Albadi, M.H.; Hosseinzadeh, N. Load frequency control of a multi-area power system: An adaptive fuzzy logic approach. IEEE Trans. Power Syst. 2014, 29, 1822–1830.
8. Shiva, C.K.; Mukherjee, V. A novel quasi-oppositional harmony search algorithm for automatic generation control of power system. Appl. Soft Comput. J. 2015, 35, 749–765.
9. Snehal, G.; Krishan, A. Automatic generation control of multi area power plants with the help of advanced controller. Int. J. Eng. Res. 2015, V4, 470–474.

10. Shiroei, M.; Toulabi, M.R.; Ranjbar, A.M. Robust multivariable predictive based load frequency control considering generation rate constraint. Int. J. Electr. Power Energy Syst. 2013, 46, 405–413.
11. Haes Alhelou, H.; Hamedani Golshan, M.E.; Hajiakbari Fini, M. Wind Driven Optimization Algorithm Application to Load Frequency Control in Interconnected Power Systems Considering GRC and GDB Non Linearitirs. Electr. Power Compon. Syst. 2018, 46, 1223–1238.
12. Jagatheesan, K.; Anand, B.; Samanta, S.; Dey, N.; Santhi, V.; Ashour, A.S.; Balas, V.E. Application of flower pollination algorithm in load frequency control of multi-area interconnected power system with nonlinearity. Neural Comput. Appl. 2017, 28, 475–488.
13. Gulzar, M. M., Iqbal, M., Shahzad, S., Muqeet, H. A., Shahzad, M., & Hussain, M. M. (2022). Load Frequency Control (LFC) Strategies in Renewable Energy-Based Hybrid Power Systems: A review. Energies, 15(10), 3488. https://doi.org/10.3390/en15103488
14. Masiala, M., Ghribi, M., & Kaddouri, A. (2012). A Two-Layered load and frequency controller of a power system. In InTech eBooks. https://doi.org/10.5772/48404
15. Gulzar, M. M., Sibtain, D., Alqahtani, M., Alismail, F., & Khalid, M. (2024). Load frequency control progress: A comprehensive review on recent development and challenges of modern power systems. Energy Strategy Reviews, 57, 101604. https://doi.org/10.1016/j.esr.2024.101604
16. Alshammari, B., Salah, R. B., Kahouli, O., & Kolsi, L. (2020). Design of Fuzzy TS-PDC Controller for electrical power System via rules Reduction approach. Symmetry, 12(12), 2068. https://doi.org/10.3390/sym12122068
17. Suid, M., & Ahmad, M. (2021). Optimal tuning of sigmoid PID controller using Nonlinear Sine Cosine Algorithm for the Automatic Voltage Regulator system. ISA Transactions, 128(Pt B), 265–286. https://doi.org/10.1016/j.isatra.2021.11.037
18. Izci, D., & Ekinci, S. (2022). An improved RUN optimizer based real PID plus second-order derivative controller design as a novel method to enhance transient response and robustness of an automatic voltage regulator. e-Prime - Advances in Electrical Engineering Electronics and Energy, 2, 100071. https://doi.org/10.1016/j.prime.2022.100071
19. Li, C., Feng, C., Li, J., Hu, D., & Zhu, X. (2022). Comprehensive frequency regulation control strategy of thermal power generating unit and ESS considering flexible load simultaneously participating in AGC. Journal of Energy Storage, 58, 106394. https://doi.org/10.1016/j.est.2022.106394
20. Yu, J., Liao, S., & Xu, J. (2022). Frequency control strategy for coordinated energy storage system and flexible load in isolated power system. Energy Reports, 8, 966–979. https://doi.org/10.1016/j.egyr.2022.02.133
21. Perninge, M., & Eriksson, R. (2017). Optimal Tertiary Frequency Control in Power Systems with Market-Based Regulation. IFAC-PapersOnLine, 50(1), 4374–4381. https://doi.org/10.1016/j.ifacol.2017.08.881
22. Murugesan, D., Jagatheesan, K., Shah, P., & Sekhar, R. (2024). Application of a TID controller for assessing frequency stability in a thermal power system with renewable energy sources. In Advances in civil and industrial engineering book series (pp. 158–178). https://doi.org/10.4018/979-8-3693-2003-7.ch007
23. Khan, I. A., Mokhlis, H., Mansor, N. N., Illias, H. A., Daraz, A., Ramasamy, A., Marsadek, M., & Afzal, A. R. (2024). Load frequency control in power systems with high renewable energy

penetration: A strategy employing P I λ (1+PDF) controller, hybrid energy storage, and IPFC-FACTS. Alexandria Engineering Journal, 106, 337–366. https://doi.org/10.1016/j.aej.2024.06.087

24. Kumar, A. (2025). Optimal tuning of tilted integral derivative (TID) controller parameters for multi-area power system and frequency regulation using pelican optimization algorithm (POA). journal.esrgroups.org. https://doi.org/10.52783/jes.8803
25. Sondhi, S.; Hote, Y.V. Fractional order PID controller for perturbed load frequency control using Kharitonov's theorem. Int. J. Electr. Power Energy Syst. 2016, 78, 884–896.
26. Javed, M.Y.; Murtaza, A.F.; Ling, Q.; Qamar, S.; Gulzar, M.M. A Novel MPPT design using Generalized Pattern Search for Partial Shading. Energy Build. 2016, 133, 59–69.
27. Qi, X.; Bai, Y. Improved linear active disturbance rejection control for microgrid frequency regulation. Energies 2017, 10, 1047.
28. Puviyarasi, B.; Murukesh, C.; Alagiri, M. Design and implementation of gain scheduling decentralized PI/PID controller for the f luid catalytic cracking unit. Biomed. Signal Process. Control 2022, 77, 103780.
29. Urrea-Quintero, J. H.; Fuhg, J. N.; Marino, M.; Fau, A. PI/PID controller stabilizing sets of uncertain nonlinear systems: An efficient surrogate model-based approach. Nonlinear Dyn. 2021, 105, 277–299.
30. Yerolla, R.; Bestha, C. S. PI/PID controller design for critically damped SOPTD system and experimental validation. In Pro ceedings of the 2021 5th International Conference on Intelligent Computing and Control Systems, Madurai, India, 6–8 May 2021; pp. 531–535.
31. Hou,H.;Yu, X.; Fu Z. Sliding mode control of networked control systems: An auxiliary matrices based approach. IEEE Trans. Autom. Control 2021, 67, 3574–3581.
32. Odgaard, P. F.; Stoustrup, J.; Kinnaert, M. Fault-tolerant control of wind turbines: A benchmark model. IEEE Trans. Control Syst. Technol. 2013, 21, 1168–1182.
33. Wang,C.; Li, R.; Su, X.; Shi, P. Output feedback sliding mode control of Markovian jump systems and its application to switched boost converter. IEEE Trans. Circuits Syst. I: Regul. Pap. 2021, 68, 5134–5144.
34. Azizi, A.; Nourisola, H.; Shoja-Majidabad, S. Fault tolerant control of wind turbines with an adaptive output feedback sliding modecontroller. Renew. Energy 2019, 135, 55–65.
35. Joshi, M.; Sharma, G.; Bokoro, P, N.; Krishnan, N. A fuzzy-PSO-PID with UPFC-RFB solution for an LFC of an interlinked hydro power system. Energies 2022, 15, 4847.
36. Yan, Z.; Xu, Y. A multi-agent deep reinforcement learning method for cooperative load frequency control of a multi-area power system. IEEE Trans. Power Syst. 2020, 35, 4599–4608.
37. Qi, X.; Zheng, J.; Mei, F. Model predictive control-based load-frequency regulation of grid-forming inverter-based power systems. Front. Energy Res. 2022, 10, 932788.
38. Faragalla, A.; Abdel-Rahim, O.; Orabi, M.; Abdelhameed, E. H. Enhanced virtual inertia control for microgrids with high penetration renewables based on whale optimization. Energies 2022, 15, 9254.
39. Zhang, J.; Li, F.; Chen, T.; Cao, Y.; Wang, D.; Gao, X. Virtual inertia control parameter regulator of doubly fed induction generator based on direct heuristic dynamic programming. Energy Rep. 2022, 8, 259–266.
40. Ali, H.; Magdy, G.; Li, B.; Shabib, G.; Elbaset, A. A; Xu, D.; Mitani, Y. A new frequency control strategy in an islanded microgrid using virtual inertia control-based coefficient diagram method. IEEE Access 2019, 7, 16979–16990.

41. Elmelegi, A.; Mohamed, E.A.; Aly, M.; Ahmed, E.M.; Mohamed, A.-A.A.; Elbaksawi, O. Optimizedtilt fractional order cooperative controllers for preserving frequency stability in renewable energy-based Power Systems. IEEE Access 2021, 9, 8261–8277.
42. Priyadarshani, S.; Subhashini, K.R.; Satapathy, J.K. Pathfinder algorithm OPTIMIZED fractional order tilt-integral-derivative (FOTID) controller for automatic generation control of multi-source power system. Microsyst. Technol. 2020, 27, 23–35.
43. Kumari, S.; Shankar, G. Maiden application of Cascade tilt-integral–tilt-derivative controller for performance analysis of load frequency control of interconnected multi-source power system. IET Gener. Transm. Distrib. 2019, 13, 5326–5338.
44. Oshnoei, A.; Khezri, R.; Muyeen, S.M.; Oshnoei, S.; Blaabjerg, F. Automatic Generation Control Incorporating Electric Vehicles. Electr. Power Compon. Syst. 2019, 47, 720–732.
45. Khamari, D.; Sahu, R.K.; Gorripotu, T.S.; Panda, S. Automatic Generation Control of power system in deregulated environment using hybrid TLBO and pattern search technique. Ain Shams Eng. J. 2020, 11, 553–573.