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A Critical Review on Smart Control Techniques for Load Frequency Control in an Interconnected Power System

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ABSTRACT

Load Frequency Control (LFC) is a critical aspect of power system control that ensures the balance between the generation and load demand. The demand for efficient LFC has increased because to the growing integration of dispersed power and renewable energy sources. Smart control techniques have emerged as a promising solution to enhance the performance of LFC in an interconnected power system. Despite the fact that various studies and approaches on load frequency control have been presented previously, no research concentrated on reviewing the approaches and limitations in the control techniques for load frequency control. Hence, this review paper presents a comprehensive overview of the recent developments in smart control techniques for LFC, focusing on Energy Storage Systems (ESS), conventional controllers, filters, optimization techniques, Machine Learning (ML)/Deep Learning (DL) techniques, and Deep Reinforcement Learning (DRL). The advantages and limitations of each technique are discussed, and a comparison of their performance is presented. The review also highlights the future research directions and challenges in implementing smart control techniques for LFC in an interconnected power system and provides some suggestions for further improvements to be done in the future for better load frequency control in an interconnected power system.

1. INTRODUCTION

Load–frequency control (LFC) is. more crucial to the functioning and design of electric power systems. In an interconnected power system, the LFC's goal is to maintain each area's frequency within set bounds and tie-line power flows within a set of pre-specified tolerances by modifying the generators' MW outputs to account for changing load requirements [1]. A properly-designed and operated power system must be able to adapt to changes in the load as well as system disruptions. In addition, it must be able to maintain the voltage and frequency within tolerance limits and provide a respectably high level of power quality [2]. In the event of a disturbance, a power system's nominal operating point departs from its predetermined value. As a result, there is an unfavorable divergence from the operational point, such as the nominal system frequency or the scheduled power exchange to other places [3]. Using transmission-line interconnections or tie-lines, each part of an interconnected power system can import and/or export a specified quantity of electricity. The reactance of the transmission line has an inverse relationship with the tie-line power exchange of a power system [4]. The dynamic model can be enhanced by adding a net gain to the stability power system. The additional gain amount will be adjusted so that only the generator closest to the disturbance will respond to the associated disturbances, while the other generators will not respond at all. As a consequence, the system will be able to continue working without experiencing any blackouts [5]. When renewable resources like wind farms and solar plants become more ingrained in power networks and cause frequency swings, the uncertainty around active power generation grows significantly [6]. This increase in active power fluctuation would result in significant frequency fluctuations in the power system in addition to the demand stochasticity. Thus, in order to address these problems, future power systems will need to implement more dependable and optimal LFC approaches [7]. A promising way to get around these restrictions and enable the grid to run steadily is through the incorporation of an Energy storage system (ESS). By integrating ESS and Renewable Energy Storage (RES) into the microgrid, power fluctuations can be avoided, power quality can be improved, frequency regulation can be improved, and more ancillary services may be made available. As a result, numerous ESS technologies including those for electrical, electrochemical, chemical, and mechanical storage systems have developed recently [8]. Supercapacitors (SC), Superconducting magnetic energy storage systems (SMES), flywheels, pumped hydro storage, batteries, and hydrogen tanks are some of the commonly utilized ESS. Batteries are considered one of the most important and potential ESS for preserving the stability of power system networks among these technologies. Additionally, the off-grid system's ESS is essential for controlling power quality and transient power fluctuations [9]. On the other hand, when the power system model is nonlinear, the efficiency of a basic energy system would decline. Therefore, LFC issues are treated using sophisticated control strategies.

In a multi-area power system with HVDC transmission lines, an improved LFC technique with better performance is introduced. Because not all system states may be known and measurements may not be noise-free, the LQR approach is employed in conjunction with the Kalman Filter. The best LQR gain for frequency control is incorporated into the Kalman Filter, which estimates unmeasurable states. the significance of a traditional control technique, such as integral control, in the LFC issue [10]. PID controller settings have been tuned using optimization approaches including fuzzy logic, particle swarm optimization (PSO), and genetic algorithms (GA) to increase power system performance. When compared to the traditional PI controller, which yields subpar outcomes in the form of significant overshoots and dynamic performance, these strategies immediately enhance system performance. These control methods, which ensure not only the system frequency but also zero elimination of steady-state error, are based on smooth computing for LFC parameters [11]. An artificially intelligent approach of the fuzzy and neural-based control system is used to construct the adaptive PI controller described in using area-control error and its adjustment. The controller was effectively designed and its performance was improved using evolutionary techniques like the genetic algorithm and particle swarm optimization. Since these methods are fundamentally stochastic, it is difficult to theoretically guarantee their efficacy. It has been necessary to construct and analyze a unique PI-derivative (PID) controller for a hybrid energy storage system integrated into a multi-area linked power system [12,13]. Planning and running the grid in effective ways is necessary to address these issues.

The physical flows of power as well as economic transactions are made more uncertain and complex as a result of the grids' continual evolution. Moreover, decision-making challenges are more challenging today than they were in the past due to the proliferation of information and the fluctuation of data [14]. A machine learning technique called reinforcement learning was developed from neutral stimuli and responses. Due to its effectiveness in addressing difficult sequential decision-making situations, it has grown in popularity. Deep reinforcement learning, which it creates in conjunction with deep learning, has shown considerable success in the fields of gaming, robots, natural language processing (NLP), finance, and business management [15]. Numerous scholars have presented diverse methods for controlling load frequency in a networked power system; however, the analysis of these methods has hardly been condensed. The main contribution of the review paper is to study load frequency control which is given below:

- In order to minimize overshooting, undershooting,

and settling times in load frequency management within an interconnected power system, this article examines smart control strategies, outlining their value and constraints.

- Various smart control techniques such as energy storage systems, convolutional controllers, filters, ML/DL techniques, optimization techniques, and deep reinforcement learning are used to control the load frequency, and these techniques are analyzed with their significance and limitations.

The paper's content is arranged as follows: The literature review of various methods for load frequency regulation in an interconnected power system is presented in Section 2, comparative analysis is provided in Section 3, the result is discussed in Section 4, the article is concluded in Section 5, and the future viewpoint is provided in Section 6.

2. LITERATURE SURVEY

The review of several technologies for load frequency management in an interconnected power system has been presented in this part. Also, the significance and limitations of these techniques are described. The directions for load frequency control techniques are shown in Figure 1.

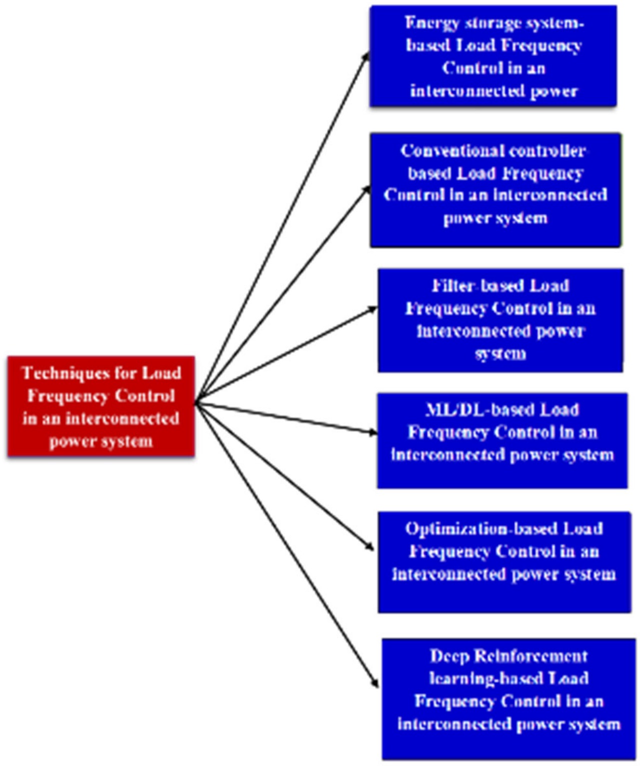

Figure 1. The directions for load frequency control techniques

This review has been made in five different phases of load frequency control in an interconnected power system namely, energy storage system-based techniques, conventional controller-based techniques, filter-based techniques, ML/DL-based techniques, optimization-based techniques, and deep reinforcement learning-based techniques.

2.1. Review on Energy Storage System-based Load Frequency Control in an Interconnected Power System

Pandey et al [16] introduced a linked power system with wind power that operated in a sliding mode with flexibility using supercapacitors, BESS, and LFC. This approach maximized the frequency modulation capabilities of the energy storage system and the supercapacitors, increased the system stability concurrently, and lowered the capacity requirements for energy storage systems taking part in secondary frequency regulation. However, the storage system has a poor compensating capacity

Lin et al [17] presented the battery energy systems used in the load frequency regulation of connected power networks. By the established parameters, LFC supports sustaining the scheduled system frequency and tie-line power exchange with the other locations. An outside Battery Energy Storage (BES) system was implemented to correct this power imbalance. Frequency oscillations caused by a large load disturbance were effectively muted by employing fast-responding energy storage technologies, such as battery energy storage systems. As a result, the BES system proved to be extremely effective, and the other controllers' settling times were reduced. However, the power imbalance still needs to be corrected.

Nosratabadi et al [18] outlined the frequency management of a multi-area, multi-source power system, taking into account the importance of the LFC in preserving the system's stability. The power system consisted of a range of generation units operating in a reorganized setting, including wind, hydropower, natural gas, diesel, and thermal. It was suggested that the Redox Flow Battery (RFB) energy storage technology be used to improve the functionality of the system that was being studied. For a wide variety of system parameters including frequency adjustment, tracking load changes, and disturbance damping, had greatly improved. However, this mathematical strategy has not suitable right away to address the optimization problem.

Zhu et al [19] presented that load frequency control systems' performance was enhanced by the use of a hybrid energy storage system made up of a battery and a supercapacitor. To gather online data on the interval boundaries of the system state in each region, the multi-area interconnected power system's load frequency management model was used to establish the interval observers for each area. According to the proposed control technique, the HESS efficiently participated in frequency modulation, ensuring grid stability and limiting system frequency and tie-line power fluctuations. However, technical improvements to the control method are require to combat some significant nonlinearities, such as generating rate constraints and dead bands.

Oshnoei et al [20] proposed a reliable control strategy to integrate distributed Battery Energy Storage Systems into LFC via BESS aggregators with sparse communication networks. To improve BESS responsiveness and boost their contribution to the LFC in order to address operational uncertainties, a two-layer model predictive control was developed. With the suggested controller, the distributed BESSs produce power more quickly and at a higher level, ensuring a greater improvement in frequency regulation. However, the time delay makes a negative impact on the performance .

Jalilian et al [21] presented an LFC system in power plants to enhance the dynamic performance of power networks and frequency control. Superconducting magnetic energy storage was employed to lessen the frequency fluctuation's effect from the uncertainty of PV and PW sources. The performance of LFC and the stability of the system was improved as a result of SMES quick dynamic reaction and advantageous inertia characteristics. The proposed system has a maximum overshoot value and settling time when SMES were present. However, due to its poor compensating capacity, it has been unable to make up for the overshoot.

Dong et al [22] introduced a combined LFC approach based on Fractional-order (FO) PID controllers (FOPID) for pumped storage stations (PSS) and battery energy storage. A FOPID controller was created using a two-area reheat steam turbine unit's LFC model with nonlinear factors. When utilized to control a system with nonlinear linkages, it produced better control effects and exhibits stronger robustness. It was practical and efficient to include battery energy storage in PSS's LFC. However, the frequency oscillation's amplitude is diminished.

Zhou et al [23] investigated the load frequency regulation of the linked power system and used a hybrid energy storage device to reduce frequency fluctuations brought on by electric vehicles and other new energy sources connected to the grid. The estimated value and sliding mode technology are used to construct the sliding mode observer and provide fault-tolerant control of connected power systems. It improved the system's stability and robustness. The Fault-tolerant control (FTC) algorithm was presented in this study. The superior frequency stabilization impact and early warning function than the conventional LFC control. However, some faults still lead to system instability or degraded control performance.

Singh et al [24] presented load frequency regulation of two components of traditional thermal-based power systems combined with energy storage systems and an efficient imperialist competitive algorithm (ICA) optimized tilted integral derivative (TID) controller was recommended. The RFB was integrated with the system under consideration to complete the exploration, which improved frequency management and boosted frequency response. A straightforward and intelligible structure akin to other traditional controllers in PSs was necessary for the TID controller to be practical. Processing significant benefits shows it as a positive resolution to LFC-related problems. It does, however, need strengthening the power systems' use of the suggested control approach.

Gupta et al [25] suggested using Particle Swarm Optimization to investigate how a battery energy storage system affects a multi-source thermal-gas-hydro linked power system's ability to regulate frequency. Integrated power systems consist of gas, hydropower, and thermal reheat turbines. It was shown how well BESS worked when an integral square error was used as the objective function for three connected power systems with increasing load disturbances in each area. There was a noticeable improvement in the system response characteristics for peak amplitude, peak time, and settling time. Nonetheless, it necessitates enhancing the system's dynamic reaction and compensatory capacity.

Table 1. Review On Energy Storage System-Based Load Frequency Control in an Interconnected Power System

Ref no	Techniques/method	Significance	Limitations
[16]	BESS	Maximize the frequency modulation capabilities and increase system stability.	It has a poor compensating capacity.
[17]	Battery Energy Storage System	Settling time is reduced compared with other controllers.	The power imbalance still needs to be corrected.
[18]	RFB energy storage technology	System parameters including frequency adjustment, tracking load changes, and disturbance damping, have greatly improved.	This mathematical approach was immediately applied to resolve the optimization issue.
[19]	Hybrid energy storage system	The HESS efficiently participates in frequency modulation, ensuring grid stability and limiting system frequency.	Technical improvements to the control method are required to combat some significant nonlinearities.
[20]	Distributed Battery Energy Storage Systems	Larger improvement in frequency regulation.	The time delay makes a negative impact on performance.

[21]	Superconducting magnetic energy storage system	The proposed system has a maximum overshoot value and settling time when SMES are present.	It has a poor compensating capacity.
[22]	Battery energy storage system and pumped storage station	It produces better control effects and exhibits stronger robustness.	The frequency oscillation's amplitude is diminished.
[23]	Hybrid energy storage device	It improves the system's stability and robustness.	Some faults may still lead to system instability or degraded control performance.
[24]	Hybrid power system with an energy storage system	It improves frequency management and boosts frequency response.	There is a need to improve the implementation of the proposed control strategy.
[25]	Battery energy storage system	There is an improvement in peak amplitude, peak time, and settling time.	There is a need to improve the dynamic response of the system.

The load frequency control utilizing different energy storage devices is shown in Table 1. The chart shows that the benefits and drawbacks of the various energy storage methods are assessed, together with the load frequency management in an interconnected power system. An interconnected power system uses a variety of energy storage systems, including distributed battery energy storage systems, redox flow batteries, pumped storage stations, superconducting magnetic energy storage systems, and battery energy storage systems, for load frequency control. However, all these approaches have some limitations such as, the power imbalance still needs to be corrected, the dynamic response of the system needs to be improved, and time delay. Hence, there is a need to develop energy storage systems techniques for effectively controlling the load frequency in an interconnected power system.

2.2. Review on conventional controller-based Load Frequency Control in an Interconnected Power System

Ahmed et al [26] described how the construction of a modified TID controller structure solved the load frequency management challenge of a multi-area connected multisource power system. The Archimedes optimization algorithm (AOA), a novel optimization method, was also used to modify the suggested integral derivative-tilted (ID-T) controller settings. The performance of the suggested IDT controller based on AOA was evaluated using a two-area connected power system with a range of conventional and renewable energy sources in each region. The ID-T controller based on the AOA significantly increased the system frequency stability under a number of conditions, including different load disruptions, system uncertainties, physical restrictions, communication time delays, and high renewables penetration. Still, there has been a need to increase the ID-T controller's efficacy.

Sharma et al [27] provided an optimal design for a fractional-order proportional-integral (FOPI) controller using the LA algorithm for linear frequency control (LFC) on two-area multi-source connected power systems (henceforth referred to as LFOPI controller). The proposed controlling approach was the LFOPI controller, which was nothing more than the FOPI controller that used the LA to get the best gain. In terms of convergent behavior, controller gain optimization, transient profile, and steady-state responsiveness, this strategy performed better. Better controlling performance was provided by the minimal Integral Square Error (ISE) value. However, a perfect implementation of a FOPID controller is available, with the reality that FOPID controllers are often not equal to high-order integer-order controllers.

Fathy et al [28] suggested using a modified version of the Hunger Games search optimizer (MHGS) to create LFC. FOPID was selected to represent LFC because it was more accurate than other typical controllers. The suggested MHGS was utilized to ascertain the ideal values for the five FOPID parameters in order to reduce the ITAE values of frequencies and tie-line powers' violations. Because it had the quickest settling time, the MHGS-based system stabilized the fastest after overshooting early on and having the lowest peak and best construction. However, in the event of system modifications and load variations, it leads to subpar dynamic performance.

Chen et al [29] introduced the LFC of multi-area power systems and created an enhanced ant colony optimization (IACO) method for the FPID controller using a new objective function. FPID controllers, which combine FLC with PID, are used to handle nonlinearity and uncertainty in LFC in an efficient manner. The enhancement of the pheromone increment updating technique and the nonlinear incremental evaporation rate are offered to enhance the algorithm's ability to explore at a later stage. All of the simulations' results demonstrated that the suggested method and revised objective function produce better results and lower objective values. Nonetheless, there has been a need to improve the controller's performance.

Prakash et al [30] suggested a load frequency control, which was a special use of a linear quadratic regulator with a proportional-integral linear quadratic regulator with PI (LQR-PI) controller. A networked multi-source power system was employed to evaluate the suggested techniques. In terms of overshoots, undershoots, and settling time, the suggested controller performed better than the LQR-based controller. Given the minimal variance in the system parameters, sensitivity analysis demonstrated that the controller was reliable enough and the LQR gain does not need to be altered. However, there is a need to include optimal Kalman filtering in combination with the LQR-PI controller to make the system more robust and stable.

Kalyan et al [31] provided a 3-Degree-of-Freedom (DOF) Proportional-Integral-Derivative (3DOFPID) controller for load frequency management of multi-area interconnected power systems, based on the seagull optimization method. To show how MIPS affected the effectiveness of load frequency management, it was dynamically analyzed both with and without the nonlinear realistic restriction of communication time delays. Further, with 3DOFPID the ISE index was improved. However, there is a need to prevent power system instability brought on by unintentional delays, to adopt CTDs with IPS models in the LFC research. However, in the real-time study, all system states' measurement is not possible or expensive to measure.

Kumari et al [32] proposed load frequency control to deliver consumers with high-quality electrical power within the parameters of frequency and scheduled tie-line power variation. LFC required a very effective and intelligent control system to accomplish this goal. The LFC analysis of a pair of interconnected thermal-hydro-nuclear generating units was proposed here, using a unique integral-tilt-derivative (I-TD) controller that was optimized using a potent heuristic optimization technique. It was thought that the suggested I-TD controller is dependable and offers a superior transient response in a variety of operating scenarios. However, it fails to eliminate steady-state error.

Barakat et al [33] suggested using a fractional-order (FO) proportional-integral-derivative-FO proportional-integral (FOPID-FOPI) controller to calculate an integral time multiplied absolute error performance function. Using the suggested CGO-based FOPID-FOPI controller, a two-area, two-source model of a non-reheat unit was first evaluated, both with and without the governor dead band nonlinearity taken into account. The superiority of the proposed plan was in lowering the settling time, frequency, and tie-line power deviations. However, the proposed method must be challenging real-world applications.

Doan et al [34] proposed a type of fuzzy logic controller built on the PID principle that has 49 rules and was suited for fully resolving the load frequency control issue in a two-area thermal power system. Such a novel PID-like fuzzy logic controller with modified scaling factors used in a variety of real-world scenarios involving an interconnected power system, including changing load change conditions, changing system parameters by up to 50%, and considering the governor dead band (GDB) along with nonlinearities of the generation rate constraint (GRC) and time delay. The fuzzy-PID controller achieved significantly improved dynamic performance, with the smallest IATE value, smallest overshoots, and smallest settling times of the area frequency oscillations. However, it has sensitive to noise and measurement errors.

Jalali et al [35] suggested networked multi-area power systems with external disturbances and parametric uncertainty, and a unique fuzzy PID controller was added to LFC. The modal parameters and scaling factors of the input and output membership functions, as well as the weights of the fuzzy PID controller rule values, were altered by the suggested algorithm. To further enhance the response's quality, the Tribe-DE method was employed to optimize the modal parameters and scaling factors of the fuzzy PID controllers' input and output membership functions. The proposed control approach benefits from having good transient behavior to changes in parameters and load disturbances. However, it has been need to enhance the performance of the controller.

Table 2. Review On Conventional Controller-Based Load Frequency Control in an Interconnected Power System

Ref no	Techniques/method	Significance	Limitations
[26]	Tilted Integral Derivative controller	Increase in the system frequency stability	There is a need to improve the ID-T controller's effectiveness.
[27]	LFOPI controller	Better controlling performance is provided by the minimal ISE value and LA to get the best gain.	A perfect implementation of a FOPID controller is needed.
[28]	FOPID controller	It has the lowest peak, overshoots at early periods, and then stabilizes the fastest because it has the shortest settling time.	It results in poor dynamic performance in case of system changes and load fluctuations.
[29]	Fuzzy PID controller	The updated objective function achieves better outcomes and minimum objective values.	There is a need to enhance the performance of the controller.
[30]	LQR-PI controller	Minimal variance in the system parameters	There is a need to include optimal Kalman filtering in combination with the LQR-PI controller.
[31]	DOFPID controller	ISE index is improved	All system states' measurement is not possible or expensive to measure
[33]	I-TD controller	I-TD controller is reliable and provides a better transient response.	It fails to eliminate steady-state error.
[33]	FOPID-FOPI controller	Lowering settling time, frequency, and tie-line power deviations	The proposed method must be tested with challenging real-world applications.
[34]	Fuzzy-PID controller	Significantly improved dynamic performance, with the smallest IATE value, smallest overshoots, and smallest settling times of the area frequency oscillations	It is sensitive to noise and measurement errors
[35]	Fuzzy PID controller	Having a good transient behavior and being less sensitive to changes in parameters and load disturbances.	There is a need to enhance the performance of the controller.

Table 2 gives the load frequency control using various convolutional controllers in an interconnected power system. From the table, it is observed that the load frequency control in an interconnected power system is reviewed and the advantages as well as the disadvantages of using various convolutional controllers are also reviewed. Many controllers are used in load frequency control such as Fuzzy PID controller, FOPID-FOPI controller, DOFPID controller, I-TD controller, LQR-PI controller, LFOPI controller, FOPID controller, and Tilted Integral Derivative controller. However, there were some limitations such as testing is a challenge for real-time applications and it fails to eliminate steady-state error. Therefore, controllers must be developed to properly manage the load frequency in an interconnected power system.

2.3. Review on Filtering based Load Frequency Control in an Interconnected Power System

Hu et al [36] presented a load frequency control of uncertain non-linear power systems with cyber-physical threats proposed using a new distributed filtering method. The model for the nonlinear power system was an IT2 T-S fuzzy system. The parametric coupling issue in the required filter gain matrices was dealt with while developing distributed filters using artistic matrix transformation approaches. The proposed filtering algorithm's robustness against system parametric uncertainties and its tolerance to both physical and cyberattacks were confirmed by simulation results based on a more realistic smart grid with internal uncertainties. However, it requires improving the design of filters and extending their applications.

Shahalami et al [37] discussed the technical features of the hydroelectric and thermal turbines, using the AC and HVDC transmission lines, with a focus on the LQR-KF controller in particular. These factors were taken into account in order to solve the LFC problem in a reorganized multi-area power system. To monitor and regulate all system conditions, the LQR controller was utilized.The primary benefit of the LQR-KF controller was that it got input from every projected state. But not all of the system states were accessible or noise-free, necessitating the employment of a tertiary controller, energy management, specific contracts, or load needs, therefore the KF was deployed as an observer of the system's states.

Arya et al [38] provided an early method for the LFC of linked systems: an ICA-based cascade fuzzy fractional order integral derivative with filter (CF-FOIDF) controller. The suggested CF-FOIDF controller outperformed the other controllers in terms of rapid reaction time and minimal oscillations. The proposed strategy was reliable and effective for providing end consumers with reliable, high-quality electricity. However, the limits of the CF-FOIDF controller tuning problem are exposed by the constrained optimization problem.

Kumari et al [39] proposed a new intelligent control method for the Load Frequency Control of a three-area power system. The Kalman filter (KF) and the LQR-based state feedback gain controller were both jointly executed in the proposed controller, which was called the enhanced linear quadratic regulator (ELQR). The results show that ELQR-based controllers perform better in terms of fewer oscillations, reduced frequency deviation, and faster settling times. However, time investment has needed in the state space and robust controllers using the trial-and-error method.

Ahmed et al [40] offered a novel method for utilizing three degrees of freedom to manage the load frequency in two-area connected power systems. The suggested control employed the tilt integrator differential with filter (TIDF) for the tie-line power loop feedforward compensation and an enhanced hybrid fractional order control approach to carry out the suggested LFC methodology. The suggested LFC technique effectively reduced the effects of ongoing variations in renewable energy sources' production and power system uncertainty. But in order to raise the frequency deviation.

Saxena et al [41] offered a simple solution employing internal model control technology to the LFC problem in power systems. To create a reliable controller, the proposed approach applied the CRONE principle, model-order reduction, and fractional-order-based filter (FO filter) concepts inside the IMC framework. The idea was first used to a single-area power system before being extended to a two-area linked system. This result will also motivate the researchers to investigate efficient reducedorder modeling strategies for enhanced power systems dynamic performance. Nonetheless, this approach's control system was quickly implemented.

Shakibjoo et al [42] a novel type-2 fuzzy control (T2FLC) technique was provided and load frequency control (LFC) in power systems with various locations, demand response (DR), battery energy storage systems, and wind farms were discussed. DR was utilized to improve network stability caused by sudden changes in demand, while BESS was used to reduce frequency fluctuations caused by wind energy. An online tuning was conducted to improve the LFC accuracy in the coordination of wind farms, BESS, and DR using the extended Kalman filter-based suggested T2FLC. With the aid of the DR, BESS, and wind farms, LFC enhanced the frequency changes of the regions and increased network stability. However, there are a few limitations, such as BESS, demand response delays, governor dead bands, and GRC.

Elmelegi et al [43] proposed a novel optimized fractional-order (FO) LFC based on the slime mold algorithm (SMA) for a multi-area interconnected power system. The hybrid fractional-order controller and the tilt-derivative controller with filter (TDF) are two FO controllers that are combined in the newly created controller. Future electric vehicle (EV) installations are also anticipated to take part in the LFC. By doing numerous comparative assessments with featured controllers in the literature under various step load disturbances and major interruptions of renewable energy sources (RESs), it was confirmed that the SMA-tuned controller is superior and more effective. It enhanced the system response capability of the proposed controller. However, the stability of the filters needs to be improved.

Dekaraja et al [44] introduced, three unequal zones with multiple sources and an integrated SMES made up the proposed system. In the hybrid three-area systems, a new fractional order controller known as FOI-FOPDF was effectively applied. Artificial flora algorithm (AFA), a new optimization method, was used to simultaneously optimize the gain and other controller parameters. The frequency variation in terms of peak overshoot, undershoot, and settling time at the location was greatly reduced by the usage of SMES. The controller parameters don't require constant value resets. However, the design of the filter design needs to be improved.

Khan et al [45] presented a marine microgrid system with renewable energy sources, a unique controller and optimization approach was created for LFCs. To establish the dynamics of the system and compare them with various case studies, a modified PIDF controller known as the I-PDF controller was used in this work. Another unique feature of this work was the use of a recently created serval optimization algorithm (SOA) to tune the modified PID controller using real-time wind data at the time of tuning. Proposed I-PDF controllers showed better performance than PIDF controllers in terms of settling time and undershooting. However, it does not work well with energy storage technologies or renewable sources of energy.

Table 3. Review On Filtering-Based Load Frequency Control in an Interconnected Power System

Ref no	Techniques/method	Significance	Limitations
[36]	Distributed filtering method	Artful matrix transformation techniques are used to tackle the parametric coupling issue in the desired filter gain matrices.	There is a need to improve the design of filters and extends their applications.
[37]	Kalman filter	It received feedback from all the estimated states.	A tertiary controller, energy management, or certain contracts or load demands may be necessary
[38]	Cascade fuzzy-fractional order integral derivative with filter.	It is reliable and effective for providing end consumers with reliable, high-quality electricity.	The limits of the CF-FOIDF controller tuning problem are exposed by the constrained optimization problem.
[39]	Kalman filter	Perform better in terms of fewer oscillations, reduced frequency deviation, and faster settling times.	Time investment is needed in the state space and robust controllers.
[40]	Tilt integrator differentiator with filter	Effectively reduce the effects of power system uncertainty and continuous variations in renewable generation power outputs.	There is a need to improve the frequency deviation.
[41]	FO filter	It improved the dynamic performance of power systems.	The control method of this approach was immediately adopted.
[42]	Kalman filter	LFC improves the frequency changes in the areas and boosts network stability.	There are some restrictions, including GRC, governor dead bands, demand response delays, and BESS.
[43]	tilt-derivative controller with filter (TDF)	It enhanced the system response capability of the proposed controller.	There is a need to improve the stability of the filters.
[44]	FOI-FOPDF	Peak overshoot, undershoot, and settling time at the location have been greatly reduced by the usage of SMES.	There is a need to improve the design of the filter design.
[45]	Modified proportional integral derivative with the low-pass filter	Proposed I-PDF controllers showed better performance than PIDF controllers in terms of settling time and undershooting.	It does not work well with energy storage technologies or renewable sources of energy.

The different filters in an interconnected power system that use load frequency control are listed in Table 3. It is noted that the advantages and disadvantages of the various filters used for load frequency management in an interconnected power system are also discussed. In an interconnected power system, different filters are used for controlling the frequency of the load. These filters include the Kalman filter, the distributed filtering method, the tilt-derivative controller with filter (TDF), the cascade fuzzy-fractional order integral derivative with filter, and the tilt integrator differentiator with filter FO filter. However, some limitations are the time investment required in the state space and the requirement for robust controllers to increase the stability of the filters. To effectively control the load frequency in a connected power system, the filters' performance must be improved.

2.4. Review on ML/DL-based Load Frequency Control in an Interconnected Power System

Ramachandran et al [46] a novel self-adaptive proportional integral-derivative (PID) controller-based generalized Hopfield neural network (GHNN) was constructed, and a two-area linked power system with nonlinearities of generator rate constraint and regulator dead band was suggested. The results demonstrated the robustness of the suggested GHNN-based self-adaptive PID controller against large perturbations, such as changes in the load, inertia constant, and synchronizing power coefficient. In order to minimize system dynamics, it expedites system settlement with zero or low overshoots and is also relevant to multi-area power systems. It is challenging to theoretically ensure its efficacy, nevertheless.

Lone et al [47] presented the load frequency control of two areas of connected thermal and reheat systems that incorporate a static synchronous series compensator to regulate the tie-line power transmission. Using fuzzy logic and controllers built on neural networks, the system dynamics were further enhanced. Utilizing a self-tuned PID controller with a static synchronous series compensator (SSSC), the steady-state error was reduced to zero and the system overshoot was also reduced. Compared to PID and fuzzy controllers, the NN controller has reduced overshoot. However, the performance of fuzzy controllers needs to be improved.

Devaraj et al [48] suggested the SCSO-SNN approach to improve the existing connected power system's wind and solar energy system LFC's energy output, efficiency, and error reduction. Wind power fluctuation has a negative impact on power imbalance and frequency deviation. A hybrid approach that combined Sand Cat Swarm Optimisation, Spiking Neural Network (SCSO-SNN), and other techniques to solve this problem. The SCSO-SNN approach aims to reduce error and boost productivity. When compared to other existing methods, the proposed method's battery error value was lower. However, the performance of the load frequency needs to be improved.

Ramachandran et al [49] suggested utilizing a hybrid moth flame optimization generalized Hopfield neural network (MFO-GHNN) to create a hybrid self-adaptive fractional order proportional integral derivative (FOPID) controller for automated load frequency regulation of multi-area hybrid power systems. With the least amount of steady-state error, the dynamics were swiftly calmed down, and the suggested FOPID controller works better than traditional controllers. Additionally, it enhanced the settling time and peak overshoot transient performance indices. However, in the presence of FACTS and HVDC devices, ALFC has to be improved by using a GHNNbased controller architecture.

Adamu et al [50] introduced the regulation of load frequency of Two Area Interconnected Power System using an Artificial Neural Network and Conventional PID. The basic goal of load frequency control was to ensure that the frequency and tie-line power deviations' steady-state errors were zero while also minimizing their transient changes. This study used an ANN-based nonlinear auto-regressive moving average controller to dynamically model and simulate a two-area connected hydro-thermal power system for ALFC. In comparison to a typical PID controller, it minimized a peak error and decreased settling time, steady state error of frequency deviation, and tie-line power deviation. However, a turbine generator unit's speed control issue is directly converted into a frequency control issue.

Dokht et al [51] demonstrated the load frequency of a two-area power system with the use of error back-propagation and descending gradient training, and an adaptive type-2 fuzzy controller was created. The behavior of the system was completely unexpected.The multilayer perceptron (MLP) artificial neural network structure was used for Jacobian extraction and system model estimation. The system's robustness and stability were increased by adding a proportional-derivative (PD) controller to the type-2 fuzzy controller. But the dynamic properties of the system have no bearing on the controller.

Shakibjoo et al [52] offered a novel fuzzy approach for the load frequency control (LFC) of a multi-area power system. The primary control system was constructed using fractional-order calculus and interval type-2 fuzzy inference techniques.

Since the system dynamics were not necessary for developing the controller, a multilayer perceptron neural network was used to determine the system Jacobian. Using LMA, which compared to similar methods offered higher efficiency and performance in terms of speed and resilience. The proposed control system's biggest drawback in real-world scenarios was its complexity when compared to more straightforward controllers like PID.

Yin et al [53] suggested the creation of an integrated frequency control framework to reduce the frequency deviation of a multi-area, multi-microgrid system, in place of generating command dispatch (GCD) and load frequency management. A technique known as adaptive deep dynamic programming (ADDP) was then used to the integrated frequency control. The ADDP contained three deep neural networks: the deep action neural network, the deep criticism neural network, and the deep prediction neural network. The ADDP effectively accomplished a high control performance of the frequency control in a multi-area multimicrogrid system because of the DNNs' representation learning. On the other hand, the load frequency's performance needs to be enhanced.

Veerasamy et al [54] suggested a novel self-adaptive PID controller based on recurrent HNN for the automated load frequency management of linked hybrid power systems (HPS). The control problem was formulated as an optimization problem and addressed using a heuristic optimization approach in order to minimize the Lyapunov function. In comparison to conventional controllers, the recommended cascade controller required significantly less control effort. The proposed controller was better suited for the efficient and reliable operation of a modern power network using PEVs and green energy technologies. However, it is ineffective for dynamic operation.

Prasad et al [55] Recently, a sliding mode control method based on an artificial neural network observer was used to solve the issue of load frequency management in a multi-area power system. In this work, mismatched disturbances were estimated and rejected using the ANN observer. The ANN observer was trained using a recently developed adaptive training process, and it was thought of as a three-layer feed-forward neural network. The adjustment of the state feedback gains led to the appropriate damping ratio and overall plant performance enhancement. An ANN controller and an adaptive learning rule will replace the switching surface technique, although performance still has to be increased.

Table 4. Review On Ml/Dl-Based Load Frequency Control in an Interconnected Power System

Ref no	Techniques/method	Significance	Limitations
[46]	Generalized Hopfield neural network	It is also applicable to multi-area power systems and accelerates system settlement with zero or minimal overshoots.	It is difficult to guarantee its effectiveness in a theoretical way.
[47]	Neural networks	The steady-state error is reduced to zero and the system overshoot is reduced.	There is a need to improve the performance of fuzzy controllers.
[48]	Spiking Neural Network	The proposed method's battery error value is lower.	There is a need to improve the performance of the load frequency.

[49]	MFO-GH Neural Network	Improves the transient performance indices of peak overshoot and settling time.	ALFC must be enhanced by utilizing a GHNN-based controller design
[50]	Artificial Neural Network	It minimizes peak error and decreases settling time, and steady-state error.	A turbine generator unit's speed control issue is directly converted into a frequency control issue.
[51]	Artificial neural network	Improves the system's stability and resilience.	The controller is independent of the system's dynamic characteristics.
[52]	Multilayer perceptron neural network	This method offers higher efficiency and performance in terms of speed and resilience.	In real-world scenarios is its complexity when compared to more straightforward controllers like PID.
[53]	Deep neural networks	The ADDP successfully achieves high control performance of the frequency control.	There is a need to improve the performance of the load frequency.
[54]	Hopfield neural networks	It is better suited for the efficient and reliable operation of a modern power network.	It is ineffective for dynamic operation.
[55]	Artificial neural network	The damping ratio was achieved by the optimization of the state feedback gains, which also increased plant performance.	To improve the performance, a switching surface scheme will be replaced with an ANN controller.

The several ML/DL methods in an interconnected power system that use load frequency control are listed in Table 4. It is noted that the benefits and drawbacks of adopting different ML/DL strategies for load frequency management in an interconnected power system are evaluated. In an interconnected power system, a variety of ML/DL techniques, including Generalized Hopfield neural networks, Artificial neural networks, Hopfield neural networks, Deep neural networks, Multilayer perceptron neural networks, MFO-GH neural networks, and Spiking neural networks, are used for load frequency control. Each technique has some drawbacks such as difficulty to guarantee their effectiveness in a theoretical way, in real-world scenarios complexity when compared to more straightforward controllers like PID, and ineffective for dynamic operation. Therefore, it is necessary to create advanced ML/DL methods for efficiently controlling the load frequency in an interconnected power system.

2.5. Review on Optimization based Load Frequency Control in an Interconnected Power System

Lu et al [56] offered a robust proportional-integral (PI) controller whose parameters were created using limited population extremal optimization (CPEO) as a solution to the load frequency management problem of several linked regions. Another restriction was the taking error performance requirement, such as integral time absolute error, and the robust performance index served as the fitness function. The H∞ constraint was described using the linear matrix inequality technique. Improved control performance in load disturbance scenarios with uncertainties in parameters. The CPEO algorithm outperforms the CPSO method in terms of convergence speed and global search capability. However, the control behavior of the system needs to be improved.

Sahani et al [57] presented a two-area hydro-thermal integrated power system that combined LFC and AVR. For the LFC-AVR control of the system, a PID controller using the Firefly algorithm was used. For the proposed control algorithm, the FA-based PID controller operated well and efficiently. A connected power system that uses an FA-based PID controller operated effectively and lower frequency and tie-line power flow deviation. However, there is a need for studies on stability.

Cam et al [58] presented a two-region multi-source interconnected power system, and a novel GA-FLC controller was put presented to address frequency stability issues. The thermal, reheated thermal, and PV units made up the power system that needed to be managed. Along with the proposed controller, traditional PID, FL, and GA-based PID controllers were also created. Using the MATLAB-Simulink program, all systems and controllers were created and tested. Solar energy sources' impact on the frequency stability of the associated power systems was eliminated. However, the operating lifespans, operating costs, and grid efficiencies are directly impacted by the overshoot values and the settling time values.

Sun et al [59] presented power systems utilizing wind turbines, and a load frequency control (LFC) secondary frequency control method was proposed. To improve the adaptability of the standard PI controller, a backpropagation (BP)-trained neural network-based PI control technique was used. The initial neuron weights of the neural network were modified using the improved particle swarm optimization (IPSO) algorithm, which significantly increased the convergence of optimization. It showed greater integration of wind energy into conventional power systems by achieving higher control accuracy and robustness. However, there is a need to study LFC for power systems with the integration of multiple renewable energy resources.

Ali et al [60] proposed a realistic multi-area, multi-source, realistic interconnected power system with nonlinearities that were examined using a proportional-integral proportional-derivative (PI-PD) controller based on a dandelion optimizer (DO). The simulation results and thorough comparison of the various control systems unequivocally show that the proposed DO-based PI-PD was very successful for realistic, multi-area multi-source IPS with nonlinearities. In comparison, the LFC settling time response from the DO-based PI-PD was superior.

However, there is a need to decrease the overshoot and undershoot time.

Yousri et al [61] suggested a dependable method for determining the optimal PI controller settings for simulating load frequency regulation in a multi-interconnected system powered by renewable energy sources. This method is based on the Harris Hawks Optimizer (HHO). The optimization process employed the integral time absolute error (ITAE) of the tie-line power and frequency as the aim function. The HHO was chosen because it was simple to use and required fewer controlling settings. The proposed system has better reliability and superiority. However, there is a need to develop a more reliable HHO-LFC technique because the HHO algorithm still has certain flaws. The practical use of the proposed approach based on HHO should be taken into consideration for future development.

Rezk et al [62] Using a trustworthy technique based on the multi-verse optimization algorithm (MVO), the design of load frequency control for multi-interconnected power systems with wind and solar plants was presented. It was used to optimize the control parameters of the load frequency controller of the multi-source power system. The proposed technique has demonstrated resilient performance against the fluctuation of system parameters, step load perturbation size, and loading condition disturbance. Dynamic parameters and frequency overshoot were used to observe the system's performance. The use of MVO significantly improves transient reactions and increases frequency overshoot. However, there are structural uncertainties and communication delays.

Rai et al [63] suggested using a controller for load frequency control (LFC) in a two-area linked power system with nonlinearities and disturbances that was based on the Super-Twisting algorithm. The power system model took consideration of the nonlinearities of GDB and GRC. The results of the simulation demonstrated that the frequency error, tie-line power error, and ACE all converged to zero. The complexity, operational inefficiency, difficulty in high-order controllers, and practical implementation restrictions of these processes, despite their relative success, pose certain limitations.

Poulose et al [64] proposed the use of a controller that was based on the Super-Twisting algorithm for load frequency control (LFC) in a two-area interconnected power system with nonlinearities and disturbances. The nonlinearities of GDB and GRC were taken into account and included in the power system model. The simulation's output showed that the ACE, tie-line power error, and frequency error all converged to zero. The power system with the super-twisting controller has a faster response time than the system with the traditional integral controller. However, there are some issues like chattering effects and relative degree limits.

Vedik et al [65] presented the tuning effectiveness of a novel quasi-oppositional dragonfly algorithm (QODA) in comparison to a traditional tuning technique. It shown that the optimal proportional-integral-derivative controller settings for load frequency management could be found using the QODA method. As an extra control duty, the PID controller was employed, and its settings were adjusted using the QODA approach. Additional performance indicators were calculated utilizing the integral of time absolute error as the objective function following program execution in order to assess the efficacy of the intended QODA-based PID controller. The QODA algorithm's tuning effectiveness is more than both standard and unconventional GA methods of PID controller tuning. However, the RES capacity and instantaneous penetration need to be improved.

Raja et al [66] proposed an improved GA optimization approach used to tune the gains of the PID controller in order to dampen the change in frequency deviations of the isolated thermal power system. The GA-PID controller's performance was proved by comparing it to the performance of other controllers like PID, PSO-PID, and Cuckoo-PID. An isolated system with a GA-PID controller was shown, modeled, and simulated. According to simulation results, the suggested controller GA-PID provided improved dynamic responses of the power system. When compared to other controllers, the LFC problem with enhanced GA provided greater performance and a shorter settling time. However, the improved GA is computationally intensive.

Prasanth et al [67] utilized different optimization strategies to tune a PID controller, to reduce frequency deviations in an isolated nuclear power plant. A power system was subjected to several step perturbations, and the outcomes were compared with respect to steady-state error, peak undershoot, and settling time. The LFC problem with enhanced GA yielded better results when compared to other controllers. When compared to other PID controllers, the GA-PID controller has a faster settling time. However, optimal initial conditions have an impact on the overall performance of the PID controller tuning and may restrict the approach's efficacy.

Nair et al [68] provided a novel robust GA LFC for two areas of interconnected power in the system to quench the differences in frequencies and tie-line power owing to diverse disturbances. The connected power system dynamic model was created using state variables with integral and area control errors. A variety of load disturbances were applied to the two-area interconnected power system. The control system responses show that as load increased, frequency deviations in each region and tie-line power deviations increased. However, it was discovered that the responses were non-oscillatory only when new genetic algorithm controllers were inserted in both regions with load fluctuations, area 1 and area 2. The proposed controllers result in the lowest frequency deviations and tie-line power deviations, indicating improved stability within the interconnected power system. Although the system is stable, the genetic algorithm controller method causes longer settling periods and negative overshoots during load fluctuations.

Table 5. Review On Optimization-Based Load Frequency Control in an Interconnected Power System

Ref no	Techniques/ method	Significance	Limitations
[56]	CPEO method	Improves control performance in load disturbance scenarios with uncertainties in parameters.	There is a need to improve the control behavior of the system.
[57]	Firefly optimization	FA-based PID controller operates effectively and lower frequency and tie-line power flow deviation.	There is a need to improve stability.
[58]	Genetic Algorithm	The impact on the frequency stability of the associated power systems was eliminated	The operating lifespans, operating costs, and grid

			efficiencies are directly impacted by the overshoot values and the settling time values
[59]	IPSO algorithm	Greater integration of wind energy into conventional power systems by achieving higher control accuracy and robustness.	There is a need to study LFC for power systems with the integration of multiple renewable energy resources.
[60]	Dandelion optimizer	DO-based PI-PD is very successful for realistic and better settling times.	There is a need to decrease the overshoot and undershoot time
[61]	Harris Hawks Optimizer	It has better reliability and superiority.	The HHO algorithm still has some shortcomings exploration phase.
[62]	Multi-verse Optimization Algorithm	MVO significantly improves transient reactions and increases frequency overshoot.	There are structural uncertainties and communication delays.
[63]	Class Topper Optimization technique	The CTO-based PID controller solves problems better than other controllers.	Difficulty in high-order controllers, and practical implementation restrictions of these processes.
[64]	Super-Twisting algorithm	Super-twisting controller has a faster response time than the system with the traditional integral controller.	There are some issues like chattering effects and relative degree limits.
[65]	Quasi-Oppositional Dragonfly Algorithm	The QODA algorithm's tuning effectiveness is more than both standard and unconventional GA methods.	There is a need to increase the RES capacity and instantaneous penetration.
[66]	Improved GA optimization	GA-PID provided improved dynamic responses of the power system.	The improved GA is computationally intensive.
[67]	Improved GA optimization	GA-PID controller has a faster settling time.	There is an impact on the overall performance of the PID controller tuning and restricts the approach's efficacy
[68]	Robust GA	It results lowest frequency deviations which indicates improved stability within the interconnected power system.	It causes longer settling periods and negative overshoots during load fluctuations.

Table 5 gives the various optimization techniques using load frequency control in an interconnected power system. It is observed that the load frequency control in an interconnected power system using various optimization techniques is reviewed and the advantages as well as the disadvantages are also provided. Many optimization techniques are used for load frequency control in an interconnected power system such as the Quasi-Oppositional Dragonfly Algorithm, Super-Twisting algorithm, Harris Hawks Optimizer, Multi-verse Optimization Algorithm, Class Topper Optimization technique, IPSO algorithm, Dandelion optimizer, CPEO method, and Improved GA optimization. However, there are some limitations to the operating lifespans, operating costs, and grid efficiency are cause a direct impact on overshoot values and the settling time values, and the stability of the system needs to be improved. Therefore, it is necessary to improve optimization techniques for efficiently controlling the load frequency in an interconnected power system

2.6. Review on Deep Reinforcement Learning based Load Frequency Control in an Interconnected Power System

Yan et al [69] suggested a data-driven, cooperative multi-agent deep reinforcement learning (MA-DRL) solution for the multi-area power system's load frequency control (LFC). In order to tackle the MADRL problem, multi-agent deep deterministic policy gradients, or DDPGs, were created to change the settings of the control agents while taking the nonlinear generating behaviors into account. The suggested technique effectively decreased control errors while dealing with stochastic frequency changes caused by fluctuations in renewable power and demand. However, deep Q networks may not be sufficient to appropriately change generator power because of discretized generating command and somewhat strict control measures.

Li et al [70] proposed a unified performance-based frequency regulation market mechanism and a data-driven grid-area coordinated load frequency control (GAC-LFC) technique. The framework algorithm was an efficient multi-agent deep reinforcement learning technique based on exploration. It was shown that the proposed strategy simultaneously called for more high-performing units, enhanced multi-area LFC control performance, and decreased frequency regulation. However, the proposed algorithm was tested on the actual power system because it survives unexpected outcomes.

Gorostiza et al [71] presented a deep reinforcement learning (DRL)-based controller to control the state of charge (SOC) of a Multi-EESS that offered frequency response services to the power grid. The Deep Deterministic Policy Gradients actor-critic technique was used to train the proposed DRL agent, enabling continuous action and more seamless SOC control of the M-EESS. The time required to achieve a specified performance threshold was reduced. However, it is necessary to study the way a long short-term memory network works in extracting features from frequency time series.

Khalid et al [72] suggested an automated load frequency control solution for hybrid power systems based on deep reinforcement learning. For a more realistic approach, the linked power system's complexity was raised by adding electric vehicles, intermittent renewable energy sources, and changing demands. Several deep reinforcement learning agents were employed to train the provided two-area linked system. Each agent minimized the frequency and tie-line power deviations by utilizing the local area control error information. Compared to traditional control techniques, the suggested approach significantly reduces the steady-state error and increases system stability under continuous load generation changes. But the system's dependability has to be raised.

Li et al [73] presented a controller and dispatch that work together as a multi-objective integrated automatic generation control. In a power system with several continuous power disturbances, this help to improve both control performance and the economy. The two-area load frequency control (LFC) model was put through simulation verification, and the results reveal that the suggested algorithm has improved control performance and financial advantages. It was capable of achieving regional optimum control and lowering mileage payment frequency. However, optimum-seeking and exploration processes are not well-optimized.

Li et al [74] presented an adaptive load frequency control (ALFC) strategy that was provided for an isolated microgrid to lower frequency deviation and unit generation costs. By adaptively altering the controller's parameters to output the regulation command, the method used a PID adaptive controller to achieve adaptive control. A deep actor-critic (DAC) technique was added to achieve adaptive regulation of the control parameters. It efficiently lowered generation costs and frequency variation. However, the average frequency deviation of the DAC must be reduced.

Xie et al. [75] Firstly, a multi-agent deep reinforcement learning (DRL) approach was used to develop the frequency controllers for the multi-microgrids. An LFC multi-microgrid model was developed for a single microgrid. Furthermore, based on the Centralized Training and Decentralized Execution multiagent RL framework, the Multi-Agent Soft Actor-Critic method was created and implemented to the multiple microgrid mode. The controller provided frequency stability when the system frequency modulation power source was lowered and the local power imbalance surpassed the capacity of a single microgrid. But there is now a reward maximization issue.

Li et al [76] The coordination control problem between the controller and power distributor of the system was addressed with a data-driven cooperative load frequency control (LFC) method in order to reduce the overall cost of power generation and improve the frequency stability of an island microgrid integrating renewable energy generation sources. The effective exploration distributed multi-agent twin delayed DDPG algorithm was a brand-new algorithm that has also been put forth. It lowered the cost of power generation overall and the frequency variation. However, due to the poor adaptability of traditional algorithms, the microgrid regulation performance under its control is seriously degraded and the robustness is low.

Rozada et al [77] presented a method for delivering an agent-based solution for load frequency management without the requirement for a centralized authority: multi-agent reinforcement learning. The basic and secondary layers of frequency control were approximated using a multi-agent deep deterministic policy gradient. Each generation unit was represented by a recurrent neural network-modeled agent. The advantage of the suggested strategy was that it presented a decentralized solution to the frequency control issue. However, the scalability of these techniques has more complex.

Xie et al [78] presented the frequency control was approached as an MDP problem and resolved using a cutting-edge distributional deep reinforcement learning technique. The suggested DSAC technique estimated the distribution of value function over returns and, in comparison to previous DRL methods, results in a significantly faster and more reliable agent learning process. The agent got additional insight and knowledge as a result of this development, which also improved frequency control performance and allowed for a lot faster and more stable learning process. However, more practical problems with generator frequency relays.

Table 6. Review On Deep Reinforcement Learning Based Load Frequency Control In An Interconnected Power System

Ref no	Techniques/method	Significance	Limitations
[69]	Multi-agent deep reinforcement learning	Successfully reduce control errors in the face of stochastic frequency variations.	Deep Q networks struggle with generator power adjustments due to discretized commands.
[70]	Multi-agent deep reinforcement learning	High-performing units, enhance multi-area LFC control performance and decrease frequency regulation.	The proposed algorithm was tested on the actual power system.
[71]	Deep reinforcement learning	The time required to achieve a specified performance threshold is reduced.	It is necessary to study the way a long short-term memory network works.
[72]	Deep reinforcement learning	Compensates the steady-state error and increases the system stability under continuous load.	The reliability of the system needs to be increased.
[73]	Deep Reinforcement Learning	Optimum-seeking and exploration processes are not well-optimized.	Achieving regional optimum control and lowering mileage payment frequency.
[74]	Deep actor-critic technique	It efficiently lowers generation costs and frequency variation.	The average frequency deviation of the DAC must be reduced.

[75]	Multi-agent deep reinforcement learning technique	The system frequency modulation power source is reduced, and the controller ensures frequency stability.	The reward maximization problem has occurred.
[76]	Multi-agent deep reinforcement learning	It lowers the cost of power generation overall and the frequency variation.	Robustness is low
[77]	A multi-agent reinforcement learning approach	It presents a totally decentralized solution to the frequency control issue.	The scalability of these techniques is more complex.
[78]	Cutting-edge distributional deep reinforcement learning technique.	It improves frequency control performance and allows for a lot faster and more stable learning process.	More practical problems with generator frequency relays.

Table 6 lists the several approaches to deep reinforcement learning in an interconnected power system with load frequency regulation. It is noted that the benefits and drawbacks of applying several deep reinforcement learning techniques for load frequency management in an interconnected power system are discussed. Many deep reinforcement learning approaches, including state-of-the-art distributional deep reinforcement learning techniques, deep actor-critic techniques, multi-agent deep reinforcement learning, and deep reinforcement learning, are utilized for load frequency management in an interconnected power system. Each approach has some drawbacks, including less robustness and more difficult scalability. Additionally, because Deep Q networks use discretized instructions, they may have trouble adjusting generator power. For an integrated power system to effectively regulate the load frequency, deep reinforcement learning must be established.

3. COMPARISON OF PERFORMANCE OF VARIOUS SMART CONTROL TECHNIQUES FOR LOAD FREQUENCY CONTROL IN AN INTERCONNECTED POWER SYSTEM

The comparison analysis of various smart control techniques using load frequency control in an interconnected power system is discussed in this section.

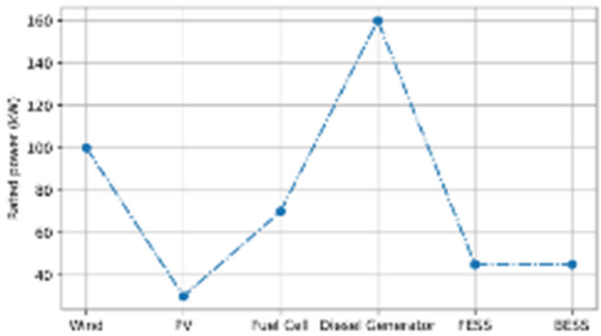

Figure 2. Comparison of rated power (kW) with various energy storage systems

Figure 2 shows the comparison of the rated power of the various existing energy storage systems such as Wind [79], Photovoltaic (PV) [79], Fuel cell, Diesel Generator [79], flywheel energy storage system (FESS) [79], battery energy storage system (BESS) [79]. The existing energy storage systems wind, PV, fuel cell, diesel generator, FESS, and BESS have a rated power value of 100, 35, 70, 160, 45, and 45 kW respectively. Compared with all the existing energy storage systems diesel generator has a high-rated power of 160kW.

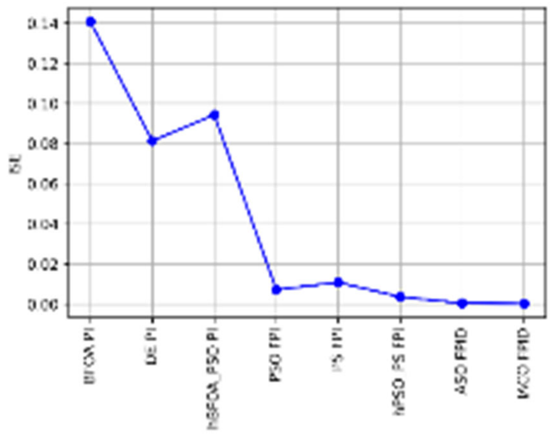

Figure 3. Comparison of ISE with various controllers

Figure 3 shows the comparison of ISE with various existing techniques such as the Bacterial Foraging Optimization Algorithm (BFOA PI) [41], Differential Evolution algorithm based Proportional–Integral (DE PI) [41], hybrid bacteria foraging optimization algorithm, and particle swarm optimization (hBFOA–PSO PI) algorithm[41], particle swarm optimization algorithm based FPI (PSO FPI) [41], Pattern Search optimized fuzzy PI controller (PS FPI) [41], hybrid Particle Swarm Optimization and Pattern Search optimized fuzzy PI controller (hPSO_PS FPI) [41], Ant Colony Optimization algorithm optimized fuzzy PID (ACO FPID) [41], Improved Ant Colony Optimization algorithm optimized fuzzy PID (IACO FPID) controller [41]. From the comparison, it is observed that BFOA PI attains a maximum ISE value of 0.14 and IACO FPID attains a minimum ISE value of 0.003.

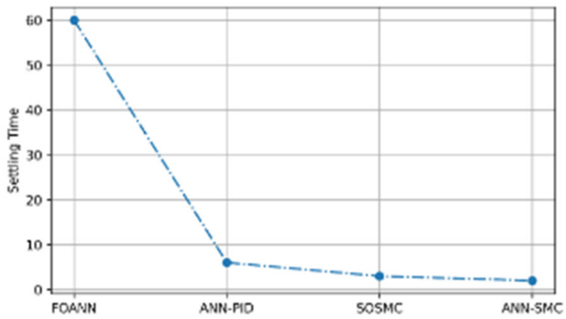

Figure 4. Comparison of settling time with various DL/ML techniques

Figure 4 shows the comparison of settling time with various existing techniques such as Fractional Order Artificial Neural Networks (FOANN) [80], ANN-PID [80], SOSMC [80], and ANN-SMC [80]. The existing techniques such as FOANN, ANN-PID, SOSMC, and ANN-SMC have a settling time value of 60, 7, 3, and 2 respectively. FOANN has a high settling time value of 60 and ANN-SMC has a low settling time value of 2.

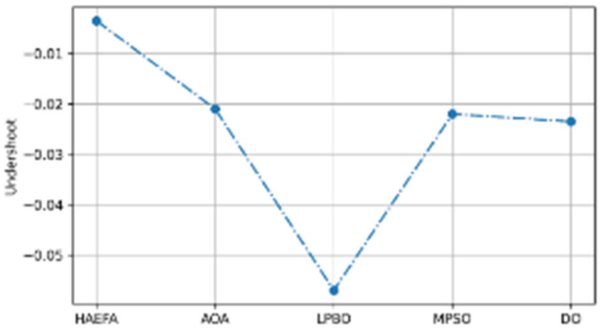

Figure 5. Comparison of Undershoot with various optimization techniques

Figure 5 shows the comparison of undershooting with various existing optimization techniques such as Hybridized Approach of the Artificial Electric Field Algorithm (HAEFA) [60], Archimedes Optimization Algorithm (AOA) [60], Learner Performance-Based Behavior Optimization (LPBO) [60], Modified Particle Swarm Optimization (MPSO) [60], Dandelion Optimizer (DO) [60]. The existing optimization techniques such as HAEFA, AOA, LPBO, MPSO, and DO have an undershooting value of -0.009%, -0.02%, -0.057%, -0.022%, and -0.024%. Compared with all the existing optimization techniques LPBO has a low undershooting value of -0.057 %.

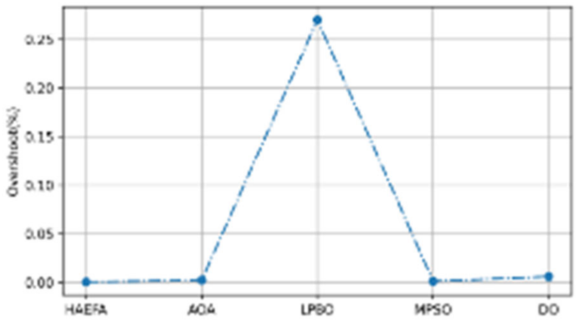

Figure 6. Comparison of Overshooting with various optimization techniques

Figure 6 shows the comparison of overshooting with various existing optimization techniques such as Hybridized Approach of the Artificial Electric Field Algorithm (HAEFA) [60], Archimedes Optimization Algorithm (AOA) [60], Learner Performance-Based Behavior Optimization (LPBO) [60], Modified Particle Swarm Optimization (MPSO) [60], and Dandelion Optimizer (DO) [60]. The existing optimization techniques such as HAEFA, AOA, LPBO, MPSO, and DO have an overshooting value of 0.01%, 0.02%, 0.27%, 0.01%, and 0.03%. Compared with all the existing optimization techniques LPBO has a high overshooting value of 0.27 %.

Figure 7 shows the comparison of the frequency deviation of various deep reinforcement learning techniques such as exploration-based multi-agent deep deterministic policy gradient (EE-MADDPG), Ape-MADDPG, single-agent DDPG, and Multi-agent DDPG. The existing techniques such as EE-MADDPG, Ape-MADDPG, single-agent DDPG, and Multi-agent DDPG have a frequency deviation value of 0.009, 0.013, and 0.0145, and 0.0153 respectively. Compared with all the existing techniques has a low-frequency deviation value of 0.009.

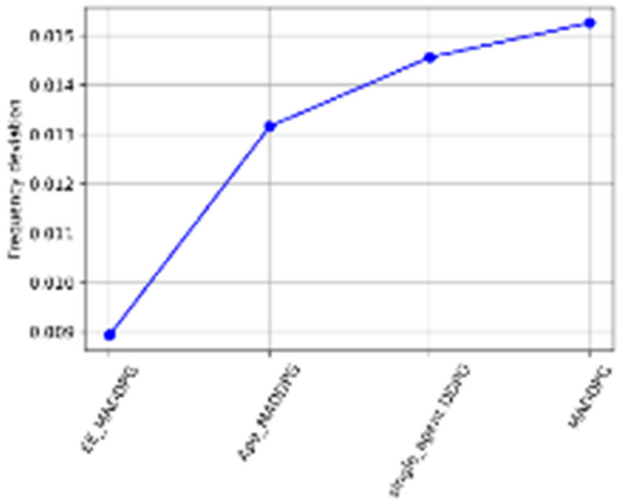

Figure 7. Comparison of frequency deviation with various deep reinforced learning

Overall, the comparison analysis of various smart control techniques for load frequency control in an interconnected power system is presented however there were some errors occurring while navigating a complicated frequency control in an interconnected power system. Hence these techniques require further improvement to perform efficient load frequency control without errors, less settling time, and undershooting value.

4. DISCUSSION

The Smart control techniques for load frequency control in an interconnected power system have been analyzed in various directions such as energy storage system based Load Frequency Control, conventional controller-based Load Frequency Control in an interconnected power system, filtering based Load Frequency Control in an interconnected power system, optimization based Load Frequency Control in an interconnected power system, ML/DL based Load Frequency Control in an interconnected power system and Deep reinforcement learning based Load Frequency Control in an interconnected power system. The analyzed summary is given as follows:

- Fast-acting energy storage devices effectively dampen sudden changes in the load's power requirement. Examples of energy storage systems that have been found to be useful and effective in load frequency control and large load disturbance include pumped storage stations, Redox Flow batteries, Superconducting magnetic energy storage systems, and battery energy storage systems. These methods did, however, have several drawbacks, including power imbalance, a poor dynamic responsiveness of the system, and a time delay.
- The conventional controllers such as the Fuzzy PID controller, FOPID-FOPI controller, DOFPID controller, I-TD controller, LQR-PI controller, LFOPI controller, and FOPID controller were useful to provide better-controlling performance and reduce the ISE value of load frequency control. But, there were some limitations such as testing is a challenge for real-time applications and it fails to eliminate steady-state error
- The filters such as distributed filtering method, a Kalman filter, a cascade fuzzy-fractional order integral derivative with filter, a tilt integrator differentiator with filter FO filter, and a tilt-derivative controller with filter (TDF) were helpful to reduce the uncertainties and improve the dynamic performance of the load frequency control in an interconnected power system. However, some drawbacks such as the time investment required in the state space and the requirement for robust controllers, and the poor stability of the filters.
- Various ML/DL techniques such as Generalized Hopfield neural networks, Artificial neural networks, Hopfield neural networks, Deep neural networks, Multilayer perceptron neural networks, MFO-GH Neural Networks, and Spiking Neural Networks were found to be efficient and reliable operations of the modern power network. But, these strategies had some limitations such as difficulty to guarantee their effectiveness in a theoretical way, in real-world scenarios complexity when compared to more straightforward controllers like PID, and ineffective for dynamic operation.
- The optimization techniques such as Quasi-Oppositional Dragonfly Algorithm, Super-Twisting Algorithm, Harris Hawks Optimizer, Multi-verse Optimization Algorithm, Class Topper Optimization technique, IPSO Algorithm, Dandelion Optimizer, CPEO method, and Improved Genetic Algorithm were studied to be helpful for the load frequency control effectively increases the performance. However, these approaches have some drawbacks, the operating lifespans, operating costs, and grid efficiencies are directly impacted by the overshoot values and the settling time values, and the stability of the system needs to be improved.
- The various deep reinforcement learning approaches such as cutting-edge distributional deep reinforcement learning, deep actor-critic learning, and multi-agent deep reinforcement learning were studied to be helpful for load frequency control and effectively provide better accuracy. However, some drawbacks such as low resilience, and more complex scalability. Due to discretized commands, Deep Q networks also experience issues while adjusting generator power.

5. CONCLUSION

This review paper presented a comprehensive overview of the recent developments in smart control techniques for LFC, including Energy Storage Systems (ESS), conventional controllers, filters, optimization techniques, Machine Learning (ML)/Deep Learning (DL) techniques, and Deep Reinforcement Learning (DRL). The review highlighted that smart control techniques can significantly improve the performance of LFC in an interconnected power system. All things considered, this review article offers insightful information on the most current advancements in LFC smart control methods. For load frequency control in an interconnected power system, a comparison of the performance of several smart control strategies has been given in terms of ISE, settling time, overshoot, undershoot, rated power, and mean absolute error. The inclusion of smart control approaches can improve LFC performance and guarantee the stability and dependability of an interconnected power system, according to the paper's conclusion. Future study will focus on overcoming implementation barriers for smart control strategies and investigating novel approaches to boost LFC efficiency in networked power systems.

6. FUTURE PERSPECTIVE

From the above-mentioned limitations, the research can be developed in the future by analyzing each direction. Future research can be done based on the following suggestions

- Power imbalance and poor dynamic response of the system and time delay found in various approaches of the energy storage system using load frequency control have to be considered and eliminated by utilizing a feedback control loop for the energy storage system and Adaptive Control techniques like Model Reference Adaptive Control (MRAC). As a result, power imbalances will have a smaller effect and frequency abnormalities will be responded to more quickly.
- Testing is a challenge for real-time applications and it fails to eliminate the steady-state error found in load frequency control using various controllers to be overcome by using robust control techniques such as H-Infinity Control, μ Synthesis can be used to improve the controller's capacity and disturbances, and lowering steady-state errors.
- In order to reduce the analysis time in the state space and to enhance the stability of the filters in filter-based load frequency control, robust control techniques, and an H-infinity control approach are utilized which significantly reduce the analysis time thereby considering the parameter's uncertainties.
- In load frequency control using ML/Dl techniques difficult to guarantee their effectiveness in a theoretical way and ineffective for dynamic operation. Choose appropriate ML/DL techniques i.e. Recurrent Neural Networks, Model Predictive Control with Neural Networks, and Adaptive Control with Neural Networks that can handle dynamic changes and provide stability guarantees.
- In optimization-based load frequency control, the operating lifespans and operating cost cause a direct impact on overshoot and undershoot values that can be overcome by using PID control and sophisticated machine learning-based optimization algorithms, which increase load frequency stability and decrease overshoot and settling time.
- Due to discretized commands, Deep Q networks experienced difficulties limiting generator power and low resilience in load frequency control using deep reinforced learning and these are minimized by algorithms like Deep Deterministic Policy Gradients (DDPG) and Twin Delayed Deep Deterministic Policy Gradients (TD3) which are the extensions of DQN designed for continuous action spaces and

can provide more stable and accurate control.

REFERENCE

[1]. Alhelou, H.H., Hamedani-Golshan, M.E., Zamani, R., Heydarian-Forushani, E., Siano, P. (2018). Challenges and opportunities of load frequency control in conventional, modern and future smart power systems: A comprehensive review. Energies, 11(10): 2497. doi:10.3390/en11102497

[2]. Rahman, M.M., Chowdhury, A.H., Hossain, M.A., (2017). Improved load frequency control using a fast-acting active disturbance rejection controller. Energies,10(11): 1718. doi:10.3390/en10111718

[3]. Ismail, M.M., Bendary. A.F., (2018). Load frequency control for multi area smart grid based on advanced control techniques. Alexandria engineering journal, 57(4): 4021-4032. https://doi.org/10.1016/j.aej.2018.11.004

[4]. Pandey, S.K., Mohanty, S.R., Kishor, N., (2013). A literature survey on load–frequency control for conventional and distribution generation power systems. Renewable and Sustainable Energy Reviews, 25: 318-334. http://dx.doi.org/10.1016/j.rser.2013.04.029

[5]. Fernández-Guillamón A, Gómez-Lázaro E, Muljadi E and Molina-García A 2019 Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. *Renewable and Sustainable Energy Reviews* 115: 109369. https://doi.org/10.1016/j.rser.2019.109369

[6]. Tan K.M., Babu, T.S., Ramachandaramurthy, V.K., Kasinathan. P., Solanki, S.G., Raveendran, S.K., (2021). Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration. Journal of Energy Storage 39: 102591. https://doi.org/10.1016/j.est.2021.102591

[7]. Hannan, M.A., Wali, S.B., Ker, P.J., Abd Rahman, M.S., Mansor, M., Ramachandaramurthy, V.K., (2021). Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues. Journal of Energy Storage 42: 103023. https://doi.org/10.1016/j.est.2021.103023

[8]. Tian, E., Peng, C., (2020). Memory-based event-triggering H∞ load frequency control for power systems under deception attacks. IEEE transactions on cybernetics 50(11): 4610-4618. doi: 10.1109/TCYB.2020.2972384

[9]. Ramesh, M., Yadav, A.K., Pathak, P.K., (2021). An extensive review on load frequency control of solar-wind based hybrid renewable energy systems. Energy sources, part A: Recovery, utilization, and environmental effects 1-25. https://doi.org/10.1080/15567036.2021.1931564

[10]. Mohan, A.M., Meskin, N., Mehrjerdi, H., (2020). A comprehensive review of the cyber-attacks and cyber-security on load frequency control of power systems. Energies 13(15): 3860. doi:10.3390/en13153860

[11]. Zhang, Y., Shi, X., Zhang, H., Cao, Y., Terzija, V., (2022). Review on deep learning applications in frequency analysis and control of modern power system. International Journal of Electrical Power & Energy Systems 136: 107744. https://doi.org/10.1016/j.ijepes.2021.107744

[12]. Liu, J., Yao, Q., Hu, Y., (2019). Model predictive control for load frequency of hybrid power system with wind power and thermal power. Energy 172: 555-565. https://doi.org/10.1016/j.energy.2019.01.071

[13]. Hu, J., Shan, Y., Guerrero, J.M., Ioinovici, A., Chan, K.W., Rodriguez, J., (2021). Model predictive control of microgrids–An overview. Renewable and Sustainable Energy Reviews, 136: 110422. https://doi.org/10.1016/j.rser.2020.110422

[14]. Neupane, D., Seok, J., (2020). Bearing fault detection and diagnosis using case western reserve university dataset with deep learning approaches: A review. IEEE Access 8: 93155-93178. doi: 10.1109/ACCESS.2020.2990528

[15]. Hossain. E., Khan, I., Un-Noor, F., Sikander, S.S., Sunny MSH (2019). Application of big data and machine learning in smart grid, and associated security concerns: A review. Ieee Access 7: 13960-13988. doi:10.1109/ACCESS.2019.2894819

[16]. Xu, Y., Ma, Y., Han, Y., Hu, T., Lun, X., Mi, Y., (2020). August Load Frequency Control for Renewable Energy Power System Based on Sliding Mode control with Hybrid Energy Storage. In 2020 Chinese Control and Decision Conference (CCDC) 1340-1345. IEEE. doi: 10.1109/CCDC49329.2020.9163995

[17]. Lin, C.H., Wu, Y.K., (2023). Coordinated frequency control strategy for VSC-HVDC-connected wind farm and battery energy Storage system. IEEE Transactions on Industry Applications. doi: 10.1109/TIA.2023.3289939

[18]. Nosratabadi, S.M., Bornapour, M., Gharaei, M.A., (2019). Grasshopper optimization algorithm for optimal load frequency control considering predictive functional modified PID controller in restructured multi-resource multi-area power system with redox flow battery units. Control Engineering Practice 89: 204-227. https://doi.org/10.1016/j.conengprac.2019.06.002

[19]. Zhu, F., Zhou, X., Zhang, Y., Xu, D., Fu, J., (2021). A load frequency control strategy based on disturbance reconstruction for multi-area interconnected power system with hybrid energy storage system. Energy Reports 7: 8849-8857. https://doi.org/10.1016/j.egyr.2021.09.029

[20]. Oshnoei, A., Kheradmandi, M., Muyeen, S.M., (2020). Robust control scheme for distributed battery energy storage systems in load frequency control. IEEE Transactions on Power Systems 35(6): 4781-4791. doi: 10.1109/TPWRS.2020.2997950

[21]. Jalilian, M., Rastgou, A., Kharrati, S., Hosseini-Hemati, S., (2023). Frequency stability of hybrid power system in the presence of superconducting magnetic energy storage and uncertainties. Journal of Operation and Automation in Power Engineering 11(4): 230-239. doi: 10.22098/JOAPE.2023.9829.1686

[22]. Dong, M., Liu, K., He, J., Li, X., Qiao, L., Zhao, X., (2023). Power grid load frequency control based on Fractional Order PID combined with pumped storage and battery energy storage. Energy Reports 9: 1402-1411. https://doi.org/10.1016/j.egyr.2023.05.117

[23]. Zhou, X., Wang, Y., Zhang, W., Yang, W., Zhang, Y., Xu, D., (2020). Actuator fault-tolerant load frequency

control for interconnected power systems with hybrid energy storage system. Energy Reports 6: 1312-1317. https://doi.org/10.1016/j.egyr.2020.11.028

[24]. Singh, K., Dahiya, M., Grover, A., Adlakha, R., Amir, M., (2023). An effective cascade control strategy for frequency regulation of renewable energy based hybrid power system with energy storage system. Journal of Energy Storage 68: 107804. https://doi.org/10.1016/j.est.2023.107804

[25]. Gupta, N., Kumar, N., (2018). Particle swarm optimization based automatic generation control of interconnected power system incorporating battery energy storage system. Procedia computer science 132: 1562-1569. doi: 10.1016/j.procs.2018.05.120

[26]. Ahmed, M., Magdy, G., Khamies, M., Kamel, S., (2022). Modified TID controller for load frequency control of a two-area interconnected diverse-unit power system. International Journal of Electrical Power & Energy Systems 135: 107528. https://doi.org/10.1016/j.ijepes.2021.107528

[27]. Sharma, D., Yadav, N.K., (2020). LFOPI controller: a fractional order PI controller based load frequency control in two area multi-source interconnected power system. Data Technologies and Applications 54(3): 323-342. doi: 10.1108/DTA-08-2019-0126

[28]. Fathy, A., Yousri, D., Rezk, H., Thanikanti, S.B., Hasanien, H.M., (2022). A robust fractional-order PID controller based load frequency control using modified hunger games search optimizer. Energies 15(1): 361. https://doi.org/10.3390/en15010361

[29]. Chen, G., Li, Z., Zhang, Z., Li, S., (2019). An improved ACO algorithm optimized fuzzy PID controller for load frequency control in multi area interconnected power systems. IEEE Access 8: 6429-6447. DOI:10.1109/ACCESS.2019.2960380

[30]. Prakash, A., Parida, S.K., (2020). December LQR based PI controller for load frequency control with distributed generations. In 2020 21st National Power Systems Conference (NPSC), 1-5. IEEE. doi: 10.1109/NPSC49263.2020.9331761

[31]. Kalyan, C.N.S., Suresh, C.V., (2022). Higher order degree of freedom controller for load frequency control of multi area interconnected power system with time delays. Global Transitions Proceedings 3(1): 332-337. https://doi.org/10.1016/j.gltp.2022.03.020

[32]. Kumari, S., Shankar, G., Das, B., (2021). Integral-Tilt-Derivative Controller Based Performance Evaluation of Load Frequency Control of Deregulated Power System. In Modeling, Simulation and Optimization: Proceedings of CoMSO, 189-200. Springer Singapore. DOI:10.1007/978-981-15-9829-6_15

[33]. Barakat, M., (2022). Novel chaos game optimization tuned-fractional-order PID fractional-order PI controller for load–frequency control of interconnected power systems. Protection and Control of Modern Power Systems 7(1): 16. (2022) 7:16 https://doi.org/10.1186/s41601-022-00238

[34]. Doan DV, Nguyen K and Thai QV 2021 A novel fuzzy logic based load frequency control for multi-area interconnected power systems. Engineering, Technology & Applied Science Research 11(4): 7522-7529. DOI:10.48084/etasr.4320

[35]. Jalali, N., Razmi, H., Doagou-Mojarrad, H., (2020). Optimized fuzzy self-tuning PID controller design based on Tribe-DE optimization algorithm and rule weight adjustment method for load frequency control of interconnected multi-area power systems. Applied Soft Computing 93: 106424. https://doi.org/10.1016/j.asoc.2020.106424

[36]. Hu, Z., Liu, S., Yang, L., Wu, L., (2020). Distributed fuzzy filtering for load frequency control of non-linear interconnected power systems under cyber-physical attacks. IET Control Theory & Applications 14(4): 527-538. doi: 10.1049/iet-cta.2019.0268

[37]. Shahalami, S.H., Farsi, D., (2018). Analysis of load frequency control in a restructured multi-area power system with the Kalman filter and the LQR controller. AEU-International Journal of Electronics and Communications 86: 25-46. https://doi.org/10.1016/j.aeue.2018.01.011

[38]. Arya, Y., (2020). Effect of electric vehicles on load frequency control in interconnected thermal and hydrothermal power systems utilising CF-FOIDF controller. IET Generation, Transmission & Distribution 14(14): 2666-2675. doi: 10.1049/iet-gtd.2019.1217

[39]. Kumari, N., Malik, N., Jha, A.N., (2019). Multi-area interconnected power system load frequency control using ELQR based state feedback gain controller. Evolving Systems 10: 635-647. DOI:10.1007/s12530-018-9252

[40]. Ahmed Emad, M., Emad, A., Mohamed, Ali Selim, Mokhtar Aly, Abdurhman Alsadi, Waleed Alhosaini, Hammad Alnuman, (2023). Improving load frequency control performance in interconnected power systems with a new optimal high degree of freedom cascaded FOTPID-TIDF controller. Ain Shams Engineering Journal 14(10): 102207. https://doi.org/10.1016/j.asej.2023.102207

[41]. Saxena, S., (2019). Load frequency control strategy via fractional-order controller and reduced-order modeling. International Journal of Electrical Power & Energy Systems 104: 603-614. https://doi.org/10.1016/j.ijepes.2018.07.005

[42]. Shakibjoo, A.D., Moradzadeh, M., Din, S.U., Mohammadzadeh, A., Mosavi, A.H., Vandevelde, L., (2021). Optimized type-2 fuzzy frequency control for multi-area power systems. IEEE access 10: 6989-7002. DOI:10.1109/ACCESS.2021.3139259

[43]. Elmelegi, A., Mohamed, E.A., Aly, M., Ahmed, E.M., (2021, December). an enhanced slime mould algorithm optimized LFC scheme for interconnected power systems. In 2021 22nd international middle east power systems conference (MEPCON) 613-618. IEEE. DOI: 10.1109/MEPCON50283.2021.9686245

[44]. Dekaraja, Biswanath, Lalit Chandra Saikia, Satish Kumar Ramoji, Naladi Ram Babu, Sanjeev Kumar Bhagat (2020). Coordinated control of voltage and frequency in a three-area multisource system integrated with SMES using FOI-FOPDF controller. In 2020 IEEE 17th India Council International Conference (INDICON), 1-7. IEEE, 2020. DOI: 10.1109/INDICON49873.2020.9342562

[45]. Khan, I.A., Mokhlis, H., Mansor, N.N., Illias, H.A., Usama, M., Daraz, A., et al. (2023). Load Frequency

Control using Golden Eagle Optimization for Multi-Area Power System Connected Through AC/HVDC Transmission and Supported with Hybrid Energy Storage Devices. IEEE Access. DOI:10.1109/ACCESS.2023.3272836

[46]. Ramachandran, R., Madasamy, B., Veerasamy, V., Saravanan, L., (2018). Load frequency control of a dynamic interconnected power system using generalised Hopfield neural network based self-adaptive PID controller. IET Generation, Transmission & Distribution 12(21): 5713-5722. DOI:10.1049/iet-gtd.2018.5622

[47]. Lone, A.H., Yousuf, V., Prakash, S., Bazaz, M.A., (2018, October). Load frequency control of two area interconnected power system using SSSC with PID, Fuzzy and Neural Network Based Controllers. In 2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES) 108-113. IEEE. DOI: 10.1109/ICPEICES.2018.8897468

[48]. Devaraj, V., Kumaresan, M., (2023). Load Frequency Control of Modern Interconnected Power System Using SCSO-SNN Approach. International Journal of Intelligent Systems and Applications in Engineering 11(7s): 466-479. https://doi.org/10.1016/j.est.2024.113609

[49]. Ramachandran, R., Satheesh Kumar, J., Madasamy, B., Veerasamy, V., (2021). A hybrid MFO-GHNN tuned self-adaptive FOPID controller for ALFC of renewable energy integrated hybrid power system. IET Renewable Power Generation 15(7): 1582-1595. DOI: 10.1049/rpg2.12134

[50]. Adamu, M., Jiya, J.D., Haruna, Y.S., Isa AI and Abdullahi ZM (2022) Automatic Load Frequency Control of Two Area Interconnected Power System With Diverse Source In Nigeria. Journal of Multidisciplinary Engineering Science Studies (JMESS) 7(12): 1-6. DOI:10.1504/IJAAC.2018.10008724

[51]. Dokht Shakibjoo, A., Moradzadeh, M., Moussavi, S.Z., Vandevelde, L., (2020). A novel technique for load frequency control of multi-area power systems. Energies 13(9): 2125. doi:10.3390/en13 092125

[52]. Shakibjoo, A.D., Moradzadeh, M., Moussavi, S.Z., Mohammadzadeh, A., Vandevelde, L., (2022). Load frequency control for multi-area power systems: A new type-2 fuzzy approach based on Levenberg–Marquardt algorithm. ISA transactions 121: 40-52. https://doi.org/10.1016/j.isatra.2021.03.044

[53]. Yin L, Yu T, Yang B and Zhang X 2019 Adaptive deep dynamic programming for integrated frequency control of multi-area multi-microgrid systems. Neurocomputing 344: 49-60. https://doi.org/10.1016/j.neucom.2018.06.092

[54]. Veerasamy V, Wahab NIA, Ramachandran R, Othman ML, Hizam H, Kumar JS 2022 Design of single-and multi-loop self-adaptive PID controller using heuristic based recurrent neural network for ALFC of hybrid power system. Expert Systems with Applications 192: 116402. https://doi.org/10.1016/j.eswa.2021.116402

[55]. Prasad, S., Ansari, M.R., (2020). Frequency regulation using neural network observer based controller in power system. Control Engineering Practice 102: 104571. https://doi.org/10.1016/j.conengprac.2020.104571

[56]. Lu, K., Zhou, W., Zeng, G., Zheng, Y., (2019). Constrained population extremal optimization-based robust load frequency control of multi-area interconnected power system. International Journal of Electrical Power & Energy Systems 105: 249-271. https://doi.org/10.1016/j.ijepes.2018.08.043

[57]. Sahani, A.K., Raj, U., Shankar, R., Mandal, R.K., (2019). Firefly optimization based control strategies for combined load frequency control and automatic voltage regulation for two-area interconnected power system. International Journal on Electrical Engineering and Informatics 11(4): 747-758. DOI: 10.15676/ijeei.2019.11.4.8

[58]. Cam. E., Gorel, G., Mamur, H., (2017). Use of the genetic algorithm-based fuzzy logic controller for load-frequency control in a two area interconnected power system. Applied Sciences 7(3): 308. doi:10.3390/app7030308

[59]. Sun, J., Chen, M., Kong, L., Hu, Z., Veerasamy, V., (2023). Regional load frequency control of BP-PI wind power generation based on particle swarm optimization. Energies 16(4): 2015. https://doi.org/10.3390/en16042015

[60]. Ali, T., Malik, S.A., Daraz, A., Aslam, S., Alkhalifah, T., (2022). Dandelion optimizer-based combined automatic voltage regulation and load frequency control in a multi-area, multi-source interconnected power system with nonlinearities. Energies 15(22): 8499. https://doi.org/10.3390/en15228499

[61]. Yousri, D., Babu, T.S., Fathy, A., (2020). Recent methodology based Harris Hawks optimizer for designing load frequency control incorporated in multi-interconnected renewable energy plants. Sustainable Energy, Grids and Networks 22: 100352. DOI: 10.1016/j.segan.2020.100352

[62]. Rezk, H., Mohamed, M.A., Diab, A.Z., Kanagaraj, N., (2021). Load frequency control of multi-interconnected renewable energy plants using multi-verse optimizer. Comput. Syst. Sci. Eng, 37(2): 219-231. DOI:10.32604/csse.2021.015543

[63]. Rai, A., Das, D.K., (2020, October). Class topper optimization (cto) algorithm based load frequency control of multi-area interconnected power system with non-linearity. In 2020 IEEE International Conference on Computing, Power and Communication Technologies (GUCON), 45-50. IEEE. DOI: 10.1109/GUCON48875.2020.9231245

[64]. Poulose, A., (2019, December). Super-twisting algorithm based load frequency control of a two area interconnected power system. In 2019 20th International Conference on Intelligent System Application to Power Systems (ISAP), 1-5. IEEE. DOI:10.1109/ISAP48318.2019.9065992

[65]. Vedik, B., Kumar, R., Deshmukh, R., Verma, S., Shiva, C.K., (2021). Renewable energy-based load frequency stabilization of interconnected power systems using quasi-oppositional dragonfly algorithm. Journal of Control, Automation and Electrical Systems 32(1): 227-243. https://doi.org/10.1007/s40313-020-00643-3

[66]. Raja, S.K., Badathala, V.P., Ss, K., (2018). LFC problem by using improved genetic algorithm tuning PID

controller. Int. J. Pure Appl. Math 120(6): 7899-7908. https://acadpubl.eu/hub/2018-120-6/6/546.pdf
[67]. Prasanth, B.V., (2018). Tuning of PID controller by improved GA technique for an Isolated Nuclear Power System. Int J Pure Appl Math 120: 8011-8020. doi: 10.1038/s41598-023-41024-5
[68]. Nair, M.M.S., Kumar, R.S., Prasanth, B.V., (2013). New Control Strategy for Improvement Of Transient Behaviour In Multi Area Interconnected Power System With Emphasis On Robust Genetic Algorithm. International Journal of Engineering Research & Technology (IJERT) 2(10): 3989-3993. DOI:10.1201/9781032708348-60
[69]. Yan, Z., Xu, Y., (2020). A multi-agent deep reinforcement learning method for cooperative load frequency control of a multi-area power system. IEEE Transactions on Power Systems 35(6): 4599-4608. DOI:10.1109/TPWRS.2020.2999890
[70]. Li, J., Geng, J., Yu, T., (2022). Grid-area coordinated load frequency control strategy using large-scale multi-agent deep reinforcement learning. Energy Reports 8: 255-274. https://doi.org/10.1016/j.egyr.2021.11.260
[71]. Gorostiza, F.S., Gonzalez-Longatt, F.M., (2020). Deep reinforcement learning-based controller for SOC management of multi-electrical energy storage system. IEEE Transactions on Smart Grid 11(6): 5039-5050. DOI: 10.1109/TSG.2020.2996274
[72]. Khalid, J., Ramli, M.A., Khan, M.S., Hidayat, T., (2022). Efficient load frequency control of renewable integrated power system: A twin delayed DDPG-based deep reinforcement learning approach. IEEE Access 10: 51561-51574. DOI:10.1109/ACCESS.2022.3174625
[73]. Li, J., Yu, T., (2020). Deep reinforcement learning based multi-objective integrated automatic generation control for multiple continuous power disturbances. IEEE Access 8: 156839-156850. DOI:10.1109/ACCESS.2020.3019535
[74]. Li, J., Zhou, T., Deep reinforcement learning based adaptive energy management for islanded microgrids considering multi-objective optimization. https://doi.org/10.46855/energy-proceedings-10523
[75]. Xie, L., Li, Y., Fan, P., Wan, L., Zhang, K., (2022). Research on load frequency control of multi-microgrids in an isolated system based on the multi-agent soft actor-critic algorithm. DOI: 10.1049/rpg2.12782
[76]. Li, J., Yang, S., Yu, T., (2022). Data-driven cooperative load frequency control method for microgrids using effective exploration-distributed multi-agent deep reinforcement learning. IET Renewable Power Generation 16(4): 655-670. DOI: 10.1049/rpg2.12323
[77]. Rozada, S., Apostolopoulou, D., Alonso, E., (2020, August). Load frequency control: A deep multi-agent reinforcement learning approach. In 2020 IEEE Power & Energy Society General Meeting (PESGM), 1-5. IEEE. doi: 10.1109/PESGM41954.2020.9281614
[78]. Xie, J., Sun, W., (2021). Distributional deep reinforcement learning-based emergency frequency control. IEEE Transactions on Power Systems 37(4): 2720-2730. https://doi.org/10.1109/tpwrs.2021.3130413
[79]. Abazari, A., Monsef, H., Wu, B., (2019). Coordination strategies of distributed energy resources including FESS, DEG, FC and WTG in load frequency control (LFC) scheme of hybrid isolated micro-grid. International Journal of Electrical Power & Energy Systems 109: 535-547. https://doi.org/10.1016/j.ijepes.2019.02.029
[80]. 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