SCIENTIFIC CULTURE
www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 12, No. 4, (2026), pp. 4347-4359
Open Access. Online & Print

DOI: 10.5281/zenodo.12426482

LOAD FREQUENCY CONTROL FOR SUSTAINABLE REGIONAL ENERGY SYSTEMS: A CONTRACT PARTICIPATION FACTOR APPROACH UNDER GENERATOR RATE CONSTRAINTS

Devesh Raj M[1*], Rengaraj R[2], Venkatakrishnan G R[3]

[1]Department of Electrical and Electronics Engineering Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India, Email: deveshraj.m@gmail.com, ORCID iD: https://orcid.org/0000-0003-2148-5695
[2]Department of Electrical and Electronics Engineering Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India, Email: rengarajr@ssn.edu.in, ORCID iD: https://orcid.org/0000-0002-1617-1555
[3]Department of Electrical and Electronics Engineering Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India, Email: venkatakrishnangr@ssn.edu.in, ORCID iD: https://orcid.org/0000-0001-6538-930X

Received: 07/07/2025
Accepted: 12/03/2026

Corresponding Author: Devesh Raj M
(deveshraj.m@gmail.com)

ABSTRACT

The increase in use of renewable energy and the shift towards deregulated markets bring major challenges to the concept of the Load Frequency Control (LFC) in local power systems. To solve the intermittency and physical limitation, a Contract Participation Factor (CPF) based Automatic LFC scheme with Generator Rate Constraints (GRC) is proposed in this paper. The study models a single-area system comprised of integration of contractual allocation among generation companies (GENCOs), ramp-rate limits and wind/solar sources. Utilising dynamic models and pid controllers, the system is tested in centralised, deregulated and sustainability-oriented modes via frequency indices and parameters such as carbon emissions. Simulation results indicate that centralised control is plagued with large deviations and introducing the CPFs can provide an improvement in regulation through coordinated response. In addition, renewable integration increases the sustainability without reducing the stability, while the enforcement of GRC guarantees physically feasible operation. Finally, the results indicate that contractual distribution, physical constraints, and renewable involvement are a strong road to stable and sustainable regional energy systems.

KEYWORDS: Load Frequency Control; Contract Participation Factor; Generator Rate Constraint; Renewable Energy Integration; Regional Energy Systems.

1. INTRODUCTION

The shift towards sustainable and low-carbon energy systems has resulted in a dramatic growth in the penetration of renewable energy sources (RES) such as wind and solar power at the regional and national levels. While this transition is supportive to long term environmental and climate considerations, it has brought about some considerable operational challenges regarding power system stability, especially load frequency regulation. Frequency deviations resulting from renewable intermittency, the reduced system inertia, and the complex market-based operation are becoming of important concerns for the modern power systems (Amir and Singh, 2024; Asad et al., 2025; Rasolomampionona et al., 2024).

Load Frequency Control (LFC) has been one of the inherent means to stabilize the generative and demand balance and guarantee the adequate functioning of the system. However, conventional centralised LFC schemes have been designed for vertically integrated power systems dominated by synchronous thermal generation schemes and are increasingly inadequate in deregulated and renewable dominated power systems (Liu et al., 2023; Kumari and Pathak, 2024). In the case of deregulated power systems, electricity generation and load is spread across several independent entities, which need coordinated control strategies, keeping in mind the contractual agreements between generation companies (GENCOs) and distribution companies (DISCOs) (Arora et al., 2022; Kumar et al., 2022).

It is also more complicated by the fact that the integration of renewable energy sources makes it difficult to regulate the frequency because of their stochastic and non-dispatchable character. Numerous studies have explored advanced control methods such as robust control, model predictive control, reinforcement learning and data-driven control methods to reduce the frequency fluctuations caused by renewables (Fan et al., 2022; El-Hameed et al., 2025; Bu et al.; 2024; Ma et al., 2023). Reviews focused on wind-integrated and hybrid power systems emphasise the fact that frequency performance can be affected to a great extent when renewable penetration is increased without proper coordination and constraints (Asghar et al., 2023; Rouhanian et al., 2023).

Contract Participation Factors (CPF) have been extensively utilized in the deregulated setting to distribute the responsibility of generating to GENCOs based on bilateral contracts and participation in the market (Arora et al., 2022; Kumar and Prasad, 2024; Lalngaihawma et al., 2024). CPF-based LFC models enhance coordination and equity in load sharing, but most of the existing literature either ignores physical generation constraints or uses idealistic reactions of generators. Such disregards of practical constraints as the ramp-rate limits of generators may lead to overly optimistic control performance, which cannot be realised in reality (Sharma et al., 2023; Jiang and Zhao, 2025). Generator Rate Constraints (GRC) is a vital functional constraint, which is manifested by the limited ramping capacity of thermal units. Recent literature has focused on the necessity to include frequency and ramping limits in dispatch and control issues, especially in systems abundant in renewable energy that have lower inertia (Jiang et al., 2025; Wang et al., 2023; Zeng et al., 2025). Nevertheless, the combined effect of CPF-based coordination and explicit GRC enforcement in a sustainability-oriented LFC setting is still insufficiently investigated.

Simultaneously, the sustainability criteria, including the penetration of renewable sources, carbon emissions, and operational cost, are also becoming a fundamental performance indicator along with traditional frequency indicators. Emerging research has been conducted on the role of electric vehicles, energy storage and cyber-physical coordination to help with frequency regulation, reducing emissions (Kumar and Chopra, 2023; Ma, 2024; Ramesh et al., 2026). However, a large number of current LFC research works assess sustainability indicators independently from each other rather than incorporating them directly into coordinated control design. Driven by these loopholes, the paper suggests an introduction of Contract Participation Factor-based Load Frequency Control framework given Generator Rate Constraints to develop sustainable regional energy systems. The proposed approach combines CPF based coordination, explicit GRC modelling and renewable energy participation in a unified control structure. A single-area regional power system is analysed using centralised, deregulated and sustainability-oriented operating modes in order to systematically test frequency performance, operational realism and sustainability results.

The main contributions of this work are as follows:

- Development of a CPF-based automatic load frequency control (ALFC) framework explicitly accounting for generator rate constraints.
- Integration of wind and solar energy sources into a deregulated load frequency control environment.

- Quantitative assessment of frequency regulation performance together with sustainability metrics, including renewable penetration, CO_2 emissions, and operational cost.
- Comparative analysis highlighting the trade-offs between control performance and sustainability objectives in regional power systems.

2. MATERIALS AND METHODS

The methodology employed in this paper relies on the current developments in load frequency control (LFC) studies on the deregulated power systems that are integrated with renewable sources. The reviews of the contemporary world of LFC design emphasize that the design needs to be coordinated with the themes of renewable intermittency, contractual coordination, operational constraints, and sustainability goals (Kumari and Pathak, 2024; Rasolomampionona et al., 2024; Liu et al., 2023). This means that the single-layer control structures or the pure centralized formulations would not be adequate any longer to realistic regional energy systems.

Under deregulated settings, other studies have shown the efficiency of the Contract Participation Factor (CPF)-based coordination in assigning the responsibility of generation between GENCOs on a bilateral contract basis (Arora et al., 2022; Kumar et al., 2022; Kumar and Prasad, 2024). LFC frameworks based on CPF have also been applicable to renewable resources, electric vehicles, and heterogeneous regulation assets (Lalngaihawma et al., 2024; Kumar and Chopra, 2023; Ma, 2024). These articles underline that having contracts that allocate reasonably better but frequently assume idealistic responses by generators.

Recent work has thus changed into including physical and operational constraints within the frequency control design. It has been demonstrated that generator ramp-rate constraints, as well as frequency constraints, substantially affect the dynamics of a system, especially in systems with reduced inertia that are rich in renewable resources (Jiang et al., 2025; Jiang and Zhao, 2025; Wang et al., 2023). The literature on hybrid energy storage systems and virtual inertia also supports the fact that the disregard of these limitations may result in unfeasible or excessively optimistic control performance (Sharma et al., 2023; Zeng et al., 2025).

The concept of advanced controller designs has been highly developed, such as robust control, fuzzy control, fractional-order controllers, and reinforcement learning, to increase the LFC robustness during uncertainty and cyber-physical disturbances (Rouhanian et al., 2023; Ruan, 2023; Shangguan et al., 2025; Zheng et al., 2023; El-Hameed et al., 2025). Although they provide good performance, they are frequently computationally complex, need a lot of training, or lack transparency to be used in practical application in regional grids.

Simultaneously, metaheuristic-based optimization-based PID tuning methods including WOA, GSA-BPSO, and hybrid methods of evolutionary algorithm implementation have also shown better frequency control with a comparatively low implementation cost (Nayak et al., 2023; Kumar et al., 2022; Gbadega and Sun, 2023). These results indicate the applicability of PID-based ALFC with realistic constraints and tuning to date.

Regarding sustainability, recent research is more and more biased towards the necessity to measure LFC schemes with environmental and economic indicators on one hand and classical frequency measures on the other hand (Ma et al., 2023; Wang et al., 2023; Ramesh et al., 2026). Renewable penetration, CO 2 emissions, and operational cost are now considered to be the fundamental criteria of the evaluation of the long-term viability of frequency control in regional energy systems.

The current study is inspired by these advances and is based on a CPF-based ALFC framework and a clear rate limit on the generators, the integration of renewable resources, and the sustainability-based performance assessment. The structure used in the selected model is a tradeoff between control effectiveness and operational realism and computational simplicity and allows a clear and reproducible evaluation of sustainable frequency regulation in regional power systems.

2.1 System Configuration and Assumptions

This research takes into account the single area regional power system under three modes of regulation i.e. the Centralised, Deregulated and Sustainable Deregulated modes. The chosen framework is that of a regional grid, where a number of generation companies (GENCOs) feed power to a number of distribution companies (DISCOs), which is a realistic model of the operation of power systems in the market. In the centralised mode, generation and load are aggregated and there is a single control signal to control the overall generation to balance the system load. In case of deregulated mode, the contractual relations between GENCOs and DISCOs are explicitly modelled in a Contract Participation Factor (CPF) matrix. In the sustainable mode, renewable energy sources as well as sustainability-conscious CPF weighting are implemented in addition to the deregulated framework. This system functions at a nominal frequency of 60 Hz and a base power which is defined at 1000 MW.

It is decided to take the simulation horizon that is sufficient in representing transient and steady-state frequency behaviour after disturbances of load. Load variations are simulated in the form of step changes and small stochastic variations to mimic realistical regional fluctuation of demands. Thermal generation units are modelled as non-reheat turbines with governors and automatic load frequency controllers. Wind and solar generation are considered exogenous renewable power injections. Generator physical limitations are modelled by Generation Rate Constraints (GRCs) which limit the amount of ramped power production.

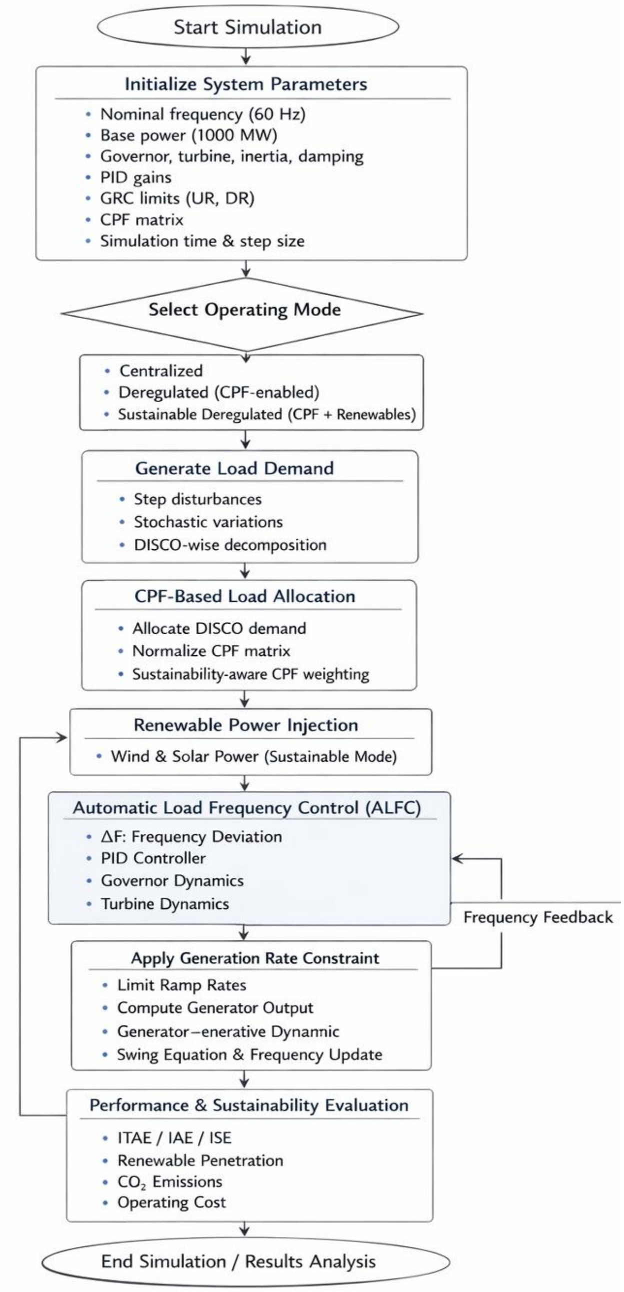

Figure 1: Flowchart of the proposed CPF-based ALFC framework under generator rate constraints and renewable integration.

2.2 *Mathematical Modeling of ALFC Components*

The Automatic Load Frequency Control (ALFC) system is modeled in terms of standard dynamic models of the governor, turbine and generator - load dynamics. The models are all in continuous time and are converted to discrete time for numeric simulation.

2.2.1 Governor Model

The governor controls the valve position of the turbine according to frequency deviations and control signals. The governor is modeled as a first order system with speed regulation:

$$G_g(s) = \frac{K_g}{1 + T_g s}$$

where $K_g$is the governor gain and $T_g$is the governor time constant. The input to the governor is the control signal P_c, adjusted by frequency deviation through the droop characteristic.

In the time domain, the governor dynamics are expressed as:

$$\frac{dY(t)}{dt} = \frac{K_g\left(P_c(t) - \frac{f(t)}{R}\right) - Y(t)}{T_g}$$

where $Y(t)$denotes the governor valve position, $f(t)$is the system frequency, and $R$is the speed regulation constant. Physical bounds are applied to limit the valve position within feasible operating limits.

2.2.2 Turbine Model

A model of a non-reheat turbine is employed to model the thermal generation units. The turbine, using the position of the governor valve, transforms the position into then mechanical power supplied to the generator.

The turbine transfer function is given by:

$$G_t(s) = \frac{1}{1 + T_t s}$$

where $T_t$is the turbine time constant. The corresponding time-domain representation is:

$$\frac{dP_m(t)}{dt} = \frac{Y(t) - P_m(t)}{T_t}$$

where $P_m(t)$denotes the mechanical power output of the turbine. This formulation captures the inherent delay between governor action and mechanical power response.

2.2.3 Generator–Load Model (Swing Equation)

The generator–load dynamics are described using the **swing equation**, expressed in terms of frequency deviation:

$$\frac{d\Delta f(t)}{dt} = \frac{f_0}{2H}(P_m(t) - P_d(t) - D\Delta f(t))$$

where f_0 is the nominal system frequency, H is the inertia constant, D is the load damping coefficient, and $P_d(t)$ represents load demand. The actual system frequency is obtained as:

$$f(t) = f_0 + \Delta f(t)$$

This expression allows one to examine directly frequency deviations after the disturbance of loads or generation.

2.3 Renewable Energy Modeling

Renewable generation is incorporated into the ALFC scheme as non-dispatchable generation sources to create an overall balance between generation.

2.3.1 Wind Power Model

The amount of mechanical power derived from the wind is proportional to the cubed wind speed. For the purpose of simulation, a simplified normalized model of wind power is taken:

$$P_{wind}(t) = P_{wind,rated}\left(\frac{v(t)}{v_{mean}}\right)^3$$

where $v(t)$ is the wind speed, v_{mean} is the mean wind speed, and $P_{wind,rated}$ is the rated wind power. Wind speed is modeled as a sinusoidal signal with superimposed stochastic variations to emulate natural intermittency.

2.3.2 Solar PV Model

Solar photovoltaic generation is modeled based on irradiance variation:

$$P_{solar}(t) = P_{solar,rated} \cdot G(t)$$

where $G(t)$ is a normalized solar irradiance profile following a diurnal cosine pattern. Cloud-induced fluctuations are incorporated as random perturbations. The total renewable generation is expressed as:

$$P_{ren}(t) = P_{wind}(t) + P_{solar}(t)$$

2.4 Contract Participation Factor (CPF) Formulation

In the deregulated framework, the allocation of load demand among GENCOs is governed by the Contract Participation Factor (CPF) matrix:

$$\mathbf{CPF} = \begin{bmatrix} cpf_{11} & \cdots & cpf_{1n} \\ \vdots & \ddots & \vdots \\ cpf_{m1} & \cdots & cpf_{mn} \end{bmatrix}$$

where m and n denote the number of GENCOs and DISCOs, respectively. Each column satisfies the constraint:

$$\sum_{i=1}^{m} cp\,f_{ij} = 1$$

The power allocated to each GENCO is computed as:

$$\mathbf{P}_{gen} = \mathbf{CPF} \cdot \mathbf{P}_{load}$$

The CPF matrix in sustainable mode is adjusted in a way that the sustainability weights are used that express economic cost, renewable contribution, and location proximity. This leads to a good CPF matrix that puts a priority to clean and regionally efficient generation.

2.5 Generator Rate Constraint (GRC) Modeling

Generator Rate Constraints represent physical ramp-rate limitations of thermal units. The GRC is mathematically expressed as:

$$-DR \le \frac{dP_g(t)}{dt} \le UR$$

where UR and DR denote the upward and downward ramp limits, respectively.

In discrete time, the constraint is implemented as:

$$P_g(k) = P_g(k-1) + \text{sat}\left(P_g^{des}(k) - P_g(k-1)\right)$$

Two enforcement strategies are considered:

- Hard limiting, which strictly clips the power change
- Soft limiting, which applies a smooth exponential transition near ramp limits

2.6 PID-Based ALFC Controller Design

Each GENCO is equipped with a PID-based ALFC controller. The continuous-time control law is defined as:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

where $e(t) = -\Delta f(t)$ is the frequency error signal. The controller is discretized using numerical integration. Anti-windup mechanisms are employed to prevent integrator saturation under GRC activation.

2.7 Simulation Framework

The system is simulated using a time-domain numerical integration framework implemented in MATLAB. The state equations are solved using explicit Euler integration:

$$x(k+1) = x(k) + \dot{x}(k)\Delta t$$

The simulation is performed in a serial fashion, that is load profile generation, CPF-based allocation and renewable power injection. This is followed by enforcement of generation rate constraint (GRC) and governor-turbine dynamics followed by updating the system frequency. In this paper, three different scenarios of a simulation are taken into account: a centralized automatic load frequency control (ALFC) structure, a deregulated ALFC structure with CPF, and a sustainable ALFC structure that combines both CPF and renewable energy sources.

2.8 Performance and Sustainability Metrics

On frequency performance, the frequency deviation has several standard indices, such as the maximum absolute frequency deviation (|human|>Frequency performance is measured in various standard indices, including the maximum absolute frequency deviation (|human|) and the Integral of Time-weighted Absolute Error (ITAE), the Integral Absolute Error (IAE), the Integral Square Error (ISE), and the settling time. Besides the dynamic performance, sustainability performance is measured in terms of renewable energy penetration, which is the ratio between the renewable energy generation and the total energy generation, carbon dioxide (CO 2) emissions as a result of the fuel-specific emission factor and operational cost as a result of the coefficient of generation cost. Together these measures give the overall assessment of the stability of the frequency and the sustainability performance.

3. RESULTS

Here, the simulation outcomes of the proposed ALFC framework are given over three operating conditions, namely centralised, deregulated and sustainable deregulated systems. The comparative analysis is based on the frequency regulation performance, the behavior of the generators during rate limitation and sustainability outcomes. All the findings are obtained at the same load disturbance profiles to make a fair comparison.

3.1 Centralised ALFC System Performance

The centralised ALFC model is taken to be the base case whereby, aggregated thermal generation is responsive to the overall load on the system without contractual distribution, renewable integration, and sustainability. The frequency response is also measured with a step load disturbance.

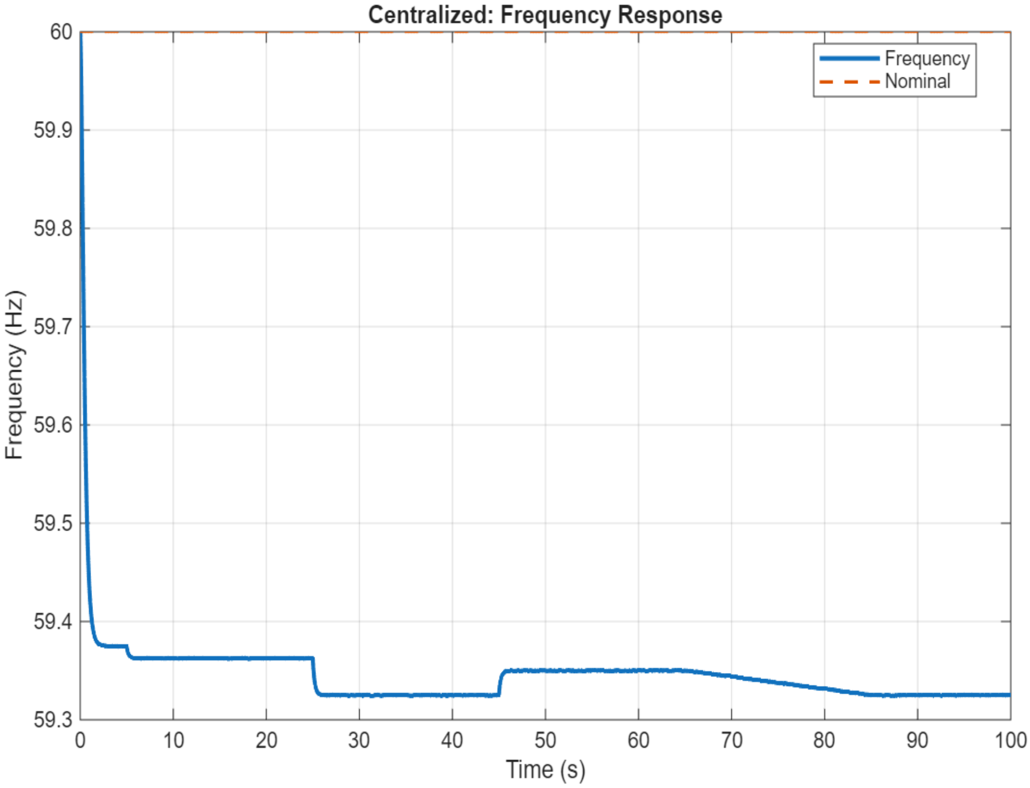

Figure 2: Centralised system frequency response following a step load disturbance.

Fig. 2 indicates that the initial drop in the system frequency is expressed literally at the original value of 60 Hz, then gradually increases. The response shows apparent undershoot and extended nontemporal deviation.

It is observed that despite the stabilisation of frequencies eventually, the amplitude and duration of deviation suggests the poor dynamic performance of centralised ALFC with the fluctuation of load in regional power systems.

3.2 Deregulated ALFC with Contract Participation Factors

In this phase the system is working under a deregulated environment where Contract Participation Factors (CPF) are introduced to apportion the load demand among several GENCOs. This configuration allows coordination of generation response according to predefined contractual agreements.

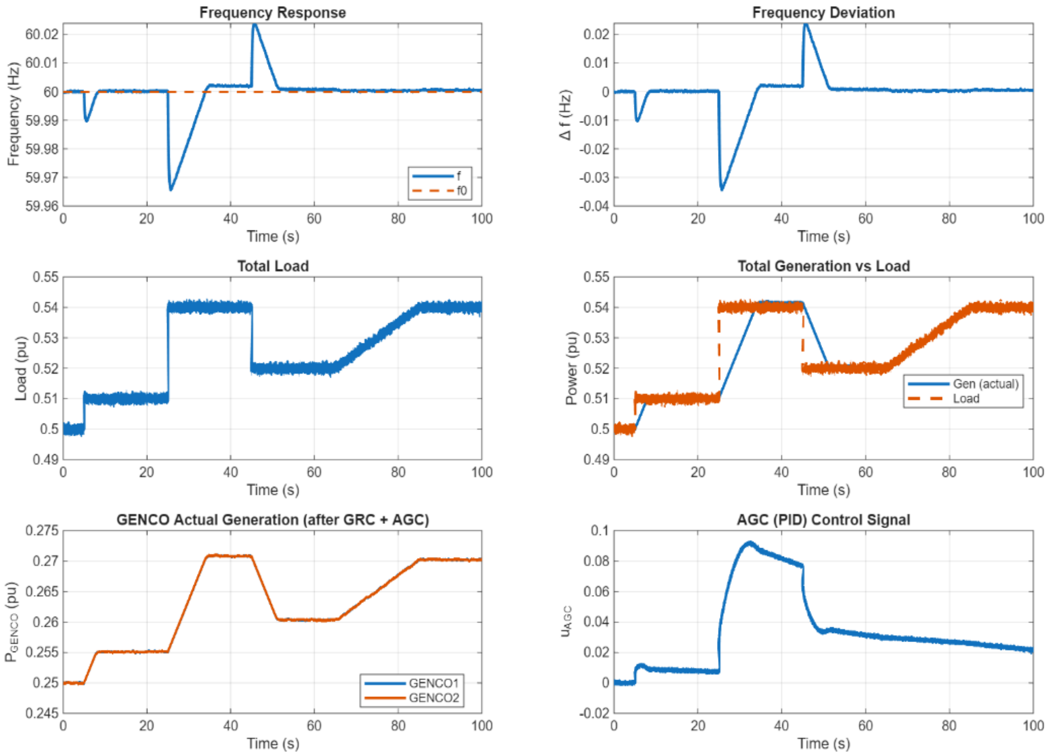

Figure 3: Frequency response and frequency deviation under CPF-based deregulated ALFC.

Figure 3 shows significant improvement of frequency deviation compared to the centralized case. Both the actual frequency and frequency deviation plots show faster correction and less oscillations.

The coordination that is done by CPF enhances better dynamic response by distributing generation responsibility between GENCOs, leading to more stable and smooth frequency response.

3.3 Deregulated ALFC with Renewable Integration

Next phase is an extension of the deregulated ALFC framework with the inclusion of renewable energy sources, namely wind and solar generation. The renewable power is added as a time varying source that is not dispatchable as a part of the total generation plant.

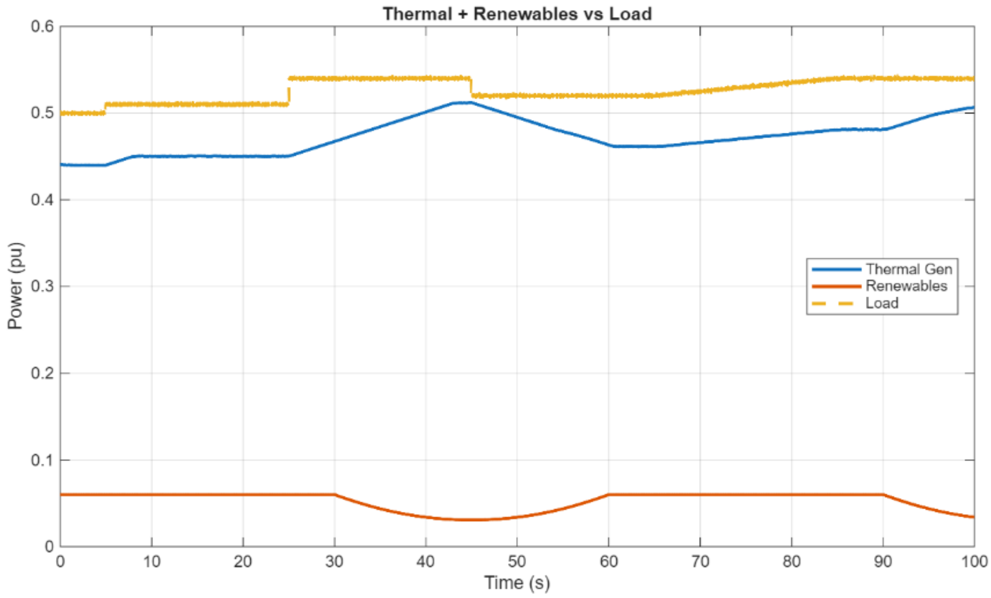

Figure 4: Thermal and renewable generation contributions compared with system load.

As shown in Fig. 4 the wind and solar generation have a time varying behaviour which contribute intermittently to the total power balance. Thermal generation changes accordingly to fill in the gaps in renewable generation.

Combined response also makes the total generation strongly correlated with the load profile, which shows that renewables are successfully integrated into the CPF-based ALFC framework.

3.4 Sustainability Performance Evaluation

Sustainability-related economic performance is assessed by studying the distribution of operational costs on thermal generation units and renewable resources. The breakdown of costs gives insight as to how renewable integration affects the overall cost of the system.

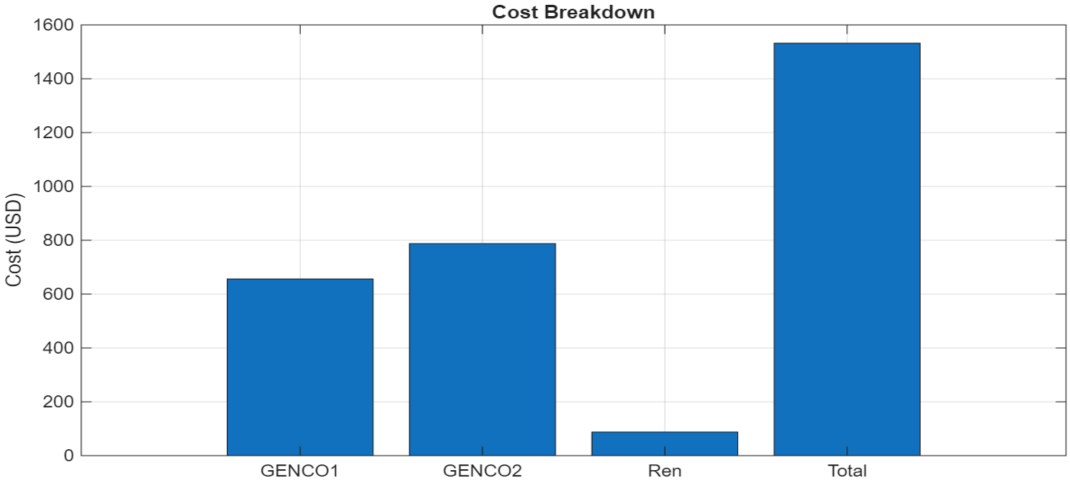

Figure 5: Operational cost breakdown among thermal generation units, renewable generation, and total system cost under the sustainable ALFC configuration.

Figure 5 illustrates the individual operational costs of GENCO1 and GENCO2, renewable generation and the total system cost. The renewable component has a fairly small share in the overall cost, and thermal generation continues to make up the largest cost share. The aggregated total cost is the sum of thermal dispatch and the participation of renewable in the sustainable operating framework. These results suggest that renewable integration provides low additional cost in addition to meeting system sustainability goals. The pricing scheme proves that the environmental advantages could be realized without unfair distribution of the overall operations cost.

3.5 Generator Rate Constraint and Operational Realism

The focus of this phase is operational realism in which Generator Rate Constraints (GRC) are enforced in addition to Automatic Generation Control (AGC). GRCs reduce the rate at which generator output changes (that represents physical ramp rate limitations).

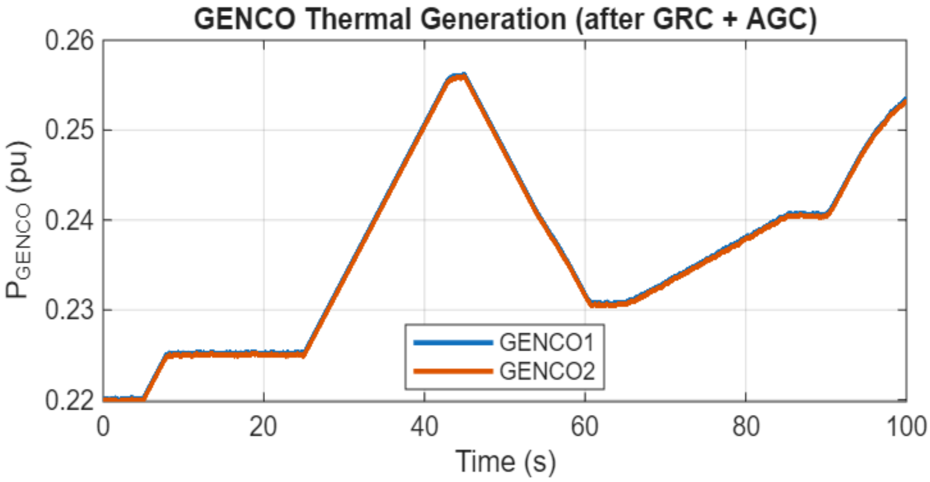

Figure 6: Thermal generator power output under AGC with generator rate constraints.

As we see in Fig. 6, the generator power output is following smooth trajectories when GRCs are applied. Abrupt changes in generation are effectively limited so as not to produce unrealistic ramping behavior.

The constrained response provides for physically feasible operation while providing acceptable frequency regulation performance.

3.6 Quantitative Performance Metrics Comparison

Table 1 shows a quantitative comparison of frequency-domain performance measures of different configurations. These metrics are calculated based on time domain simulations and include maximum frequency deviation, settling time, overshoot and control effort.

Table 1: Frequency regulation performance metrics for different ALFC configurations.

Configuration	Max $\lvert\Delta f\rvert$ (Hz)	Settling time (s)	Overshoot (%)	$\int\lvert u\rvert\,dt$
Centralized	0.6756	0.01	0.00	49.19
Phase 6 – Deregulated	0.0344	0.00	0.04	3.36
Phase 7 – Renewables	0.0342	0.00	0.04	5.94
Phase 9 – Optimised	0.0342	50.72	0.04	5.88

The within-table 1 results confirm that the use of CPF based deregulated control is a significant step in reducing frequency deviation and control effort compared to centralised ALFC, with optimised cases achieving the best overall frequency performance.

3.7 Final Sustainability and Cost Comparison

This phase provides a consolidated assessment of sustainability outcomes, including renewable penetration, CO_2 emissions, and operational cost.

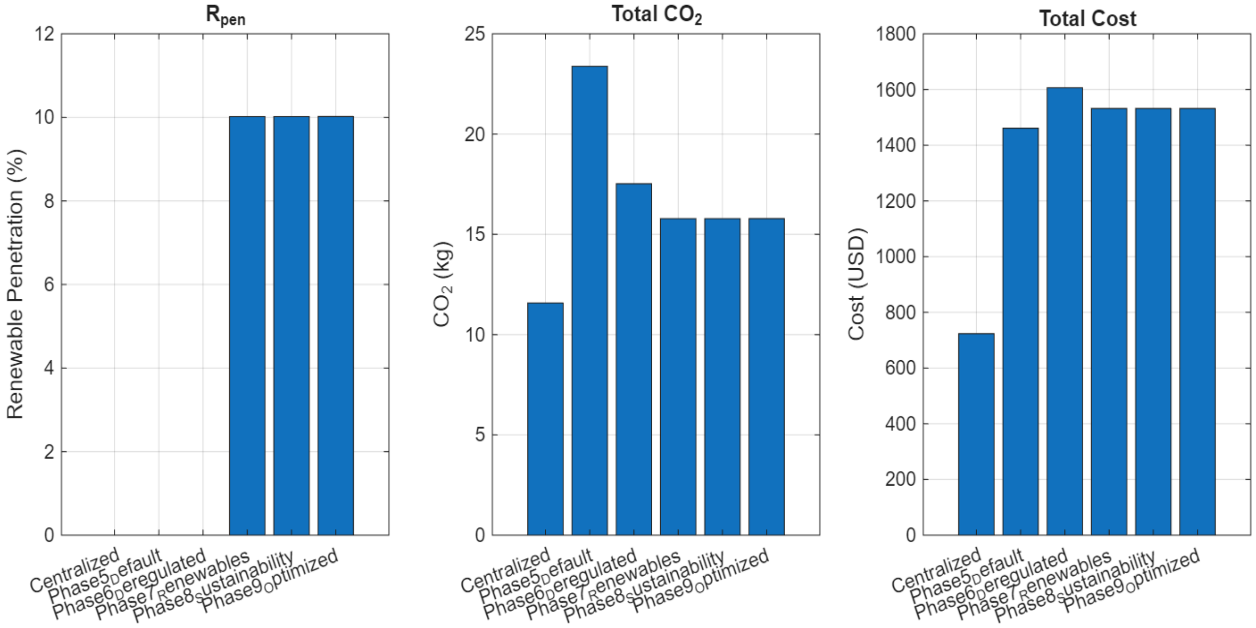

Figure 7: Comparison of renewable penetration, CO_2 emissions, and operational cost across operational phases.

As figure 7 shows, both the sustainable and optimised configurations have greater renewable penetration and reduced emissions as compared to purely thermal cases. Operational costs are also lowered as compared to previous deregulated setups.

Table 2: Sustainability and economic performance metrics for different ALFC configurations.

Configuration	Renewable penetration (%)	CO_2 emissions (kg)	Operational cost (USD)
Centralized	0.00	11.58	723.48
Phase 7 – Renewables	10.02	15.78	1531.86
Phase 8 – Sustainability	10.02	15.78	1531.86
Phase 9 – Optimized	10.02	15.79	1531.72

The results in Table 2 demonstrate that integrating renewables and sustainability-aware control substantially improves environmental performance while maintaining acceptable economic cost levels.

3.8. Frequency Quality and Power Balance Assessment

Beyond the peak frequency deviation and settling time, some more frequency quality indicators are assessed to estimate the overall effectiveness of the proposed ALFC framework. These metrics are an important insight into long-term frequency behaviour and provide supply - demand coordination in sustainable operation. For the configuration of sustainability-oriented configuration, the mean system frequency stays close to the nominal value, which indicates stable long-term operation. The lower and higher observed frequencies are within acceptable limits showing effective dampening of negative and positive deviations. In addition, the root mean square (RMS) frequency deviation is also low, indicating that the oscillatory energy is less and the frequency is smoother under the coordination of CPF and renewable energy. The quality of power balance is further assessed with the help of the indicators of mean and maximum imbalance generation-load. This small value of mean imbalance takes off the successful distribution of the responsibility of generation among GENCOs and limited maximum imbalance indicates the capability of the control system to manage momentary disturbances without too much mismatch. The findings define the importance of CPF-based coordination and the rate constraint of generators in the tight power balance maintenance under realistic operating conditions.

4. DISCUSSION

The results reported in this work show that a concerted approach to load frequency control including contractual allocation, physical constraints and renewable participation can have a great impact on both operational performance and sustainability outcomes in regional energy systems. The comparative analysis in the centralised, deregulated, and sustainable configurations underscores the effect of a progressive increase in combining market coordination and physical realism on the dynamics of the frequency and behaviour of the system.

The centralised ALFC results confirm limitations widely presented in the literature for traditional frequency control schemes operating under modern conditions. Large frequency deviations and lengthy recovery time in the baseline case are a manifestation of the ineffectiveness of aggregated control structures in effectively coping with demand variability in systems with distributed generation and lower inertia (Liu et al., 2023; Kumari and Pathak, 2024). These findings add to the case for greater inappropriateness of centralized approaches to regional power systems in the process of energy transition.

Introducing Contract Participation Factors in the deregulated configuration makes a significant contribution to better frequency regulation performance by spreading generation responsibility across several GENCOs. This synchronized reply decreases the frequency variations of the peaks and transient behavior; it supports earlier studies that CPF-based frameworks increase the fairness and stability in the deregulated environment (Arora et al., 2022; Kumar and Prasad, 2024; Lalngaihawma et al., 2024). Unlike the centralized control, CPF-based allocation allows a decentralized participation while ensuring the balance at the system level which is crucial for the regional grids with diverse stakeholders.

The connection of wind and solar generation is another example to show the flexibility of the proposed framework. Although the intermittency of the renewable sources causes variability in the power balance, the results indicate that the frequency stability is maintained if CPF-based coordination is maintained. This verifies that the concept of renewable integration does not necessarily undermine the frequency regulation in case it is backed up by the corresponding control structures, which is also in line with the results about the wind- and hybrid-integrated systems (Asghar et al., 2023; Rouhanian et al., 2023). Importantly, the results show that thermal generation adjusts smoothly in order to compensate renewable fluctuations and display their effective interaction between dispatchable and non-dispatchable resources.

One of the main contributions of the current work is the fact that the Generator Rate Constraints are explicitly integrated. Enforcing GRCs makes the generator responses physically feasible so that unrealistic ramping is avoided and is often overlooked in theoretical studies of LFC. The smoother generator trajectories found in the case of GRC enforcement are in line with the recent findings that highlighted the importance of constraint-aware control in systems with renewable abundance with lower inertia (Jiang et al., 2025; Wang et al., 2023; Zeng et al., 2025). Although GRC enforcement may cause a slight increase in settling time, this tradeoff is warranted by the resulting improved operational realism and implementability.

From a sustainability point of view the findings highlight the benefits of integrating renewable energy sources into a coordinated frequency control framework in terms of providing real benefits on environment. The renewable penetration and associated variation in CO 2 emissions and operating cost, thus the focus on considering the LFC strategies outside the classical frequency indicators. This is in line with a new body of research that is calling for consideration of environmental and economic indicators when assessing control performance (Ma et al., 2023; Ramesh et al., 2026). Although the operational expenses will rise when there is a renewable involvement in the configuration under study, the consistency of costs during sustainability-oriented stages implies that the benefits of the environment will be attained without unreasonable economic punishment.

The reason for a PID-based controller, even as there are advanced techniques of artificial intelligence and data-driven methods, is the fact that this was a conscious choice in the design focused on transparency, robustness, and practical applicability. Although promising outcomes have been recently achieved with reinforcement learning and adaptive control approaches (El-Hameed et al., 2025; Zheng et al., 2023), they are complicated and demand a lot of data to be implemented in regional grids. The present results show that the use of suitably tuned classical controllers in conjunction with combined allocation and constraint enforcement of resources remains a viable solution for sustainable frequency regulation.

Overall, the results prove that the operation of the sustainable regional energy systems requires an integrated control viewpoint that balances dynamic performance, contractual coordination, physical limitations and environmental goals. The proposed ALFC framework using CPF under GRC gives the suggested integration and gives a viable way of having a reliable and sustainable frequency regulation in the shift to power systems.

5. CONCLUSION

This study investigated a Contract Participation Factor based Automatic Load Frequency Control framework under Generator Rate Constraints for sustainable energy systems of the region. By gradually analyzing the centralized, deregulated and sustainability-oriented operating modes, the work showed that coordinated control, physical realism and integration of renewables together have a major impact on frequency regulation performance and sustainability results. The results validate the fact that the traditional centralized ALFC schemes have poor dynamic performance under actual load disturbance conditions, and the schemes are not suitable for modern regional power systems. Introducing CPF based coordination is important to achieve much better frequency stability by allowing the proportional load sharing between multiple GENCOs. CPF framework is effective at lowering peak frequency deviations and control effort at tolerable transient performance. The integration of wind and solar generation is another important example that the accommodation of renewable resources within deregulated frequency control does not affect the system stability. Although the renewable intermittency causes variability the coordinated CPF-based control makes sure that the frequency deviation is kept within acceptable limits. Clear implementation of Generator Rate Constraints are essential towards physically realistic generator response where unrealistic ramping behaviour is avoided and realism in the operation is improved. From the sustainable point of view, the proposed framework is achieved in terms of increased renewable penetration and enhanced environmental performance with stable operational cost in sustainability-oriented configurations. These findings highlight the need for assessing the frequency control strategies not only with dynamic, but also with sustainability metrics. In general, CPF-based ALFC framework under GRC is a realistic and clear way of ensuring that the frequency regulation in the local energy systems is attained in a stable and sustainable way. Future directions include an expansion of this methodology to multi-area systems, the addition of energy storage and electric vehicles, the expression of more resilient adaptive or data-driven control approaches to the problem and future investigations.

REFERENCES

1. Amir, M. and Singh, K., 2024. Frequency regulation strategies in renewable energy-dominated power systems: Issues, challenges, innovations, and future trends. In Advanced Frequency Regulation Strategies in Renewable-Dominated Power Systems (pp. 367–381). Academic Press. doi: 10.1016/B978-0-323-95054-1.00001-9
2. Arora, K., Joshi, G.P., Ragab, M., Rawa, M., Milyani, A.H., Mansour, R.F. and Yang, E., 2022. Bilateral Contract for Load Frequency and Renewable Energy Sources Using Advanced Controller. Computers, Materials & Continua, 73(2). doi: 10.32604/cmc.2022.026966
3. Asad, M., Faizan, M., Zanchetta, P. and Sánchez-Fernández, J.Á., 2025. FACTS controllers' contribution for load frequency control, voltage stability and congestion management in deregulated power systems

over time: A comprehensive review. Applied Sciences, 15(14), p.8039. doi: 10.3390/app15148039

4. Asghar, R., Riganti Fulginei, F., Wadood, H. and Saeed, S., 2023. A review of load frequency control schemes deployed for wind-integrated power systems. Sustainability, 15(10), p.8380. doi: 10.3390/su15108380
5. Bu, X., Zeng, Y., Yin, Y. and Liang, J., 2024. Event-triggered data-driven load frequency control for multi-area power system with wind penetration under deregulation environment. Journal of Renewable and Sustainable Energy, 16(1). doi: 10.1063/5.0168895
6. El-Hameed, M.A., Saeed, M., Kabbani, A. and Abd El-Hay, E., 2025. Efficient load frequency controller for a power system comprising renewable resources based on deep reinforcement learning. Scientific Reports, 15(1), p.18379. doi: 10.1038/s41598-025-03310-2
7. Fan, W., Hu, Z. and Veerasamy, V., 2022. PSO-based model predictive control for load frequency regulation with wind turbines. Energies, 15(21), p.8219. doi: 10.3390/en15218219
8. Gbadega, P.A. and Sun, Y., 2023. Multi-area load frequency regulation of a stochastic renewable energy-based power system with SMES using enhanced-WOA-tuned PID controller. Heliyon, 9(9). doi: 10.1016/j.heliyon.2023.e19199
9. Jiang, B., Guo, C. and Chen, Z., 2025. Frequency constrained dispatch with energy reserve and virtual inertia from wind turbines. IEEE Transactions on Sustainable Energy. doi: 10.1109/TSTE.2025.3528948
10. Jiang, Y. and Zhao, S., 2025. Voltage and Frequency Stability Constrained Unit Commitment for Power Systems with Heterogeneous Regulation Resources. IEEE Transactions on Sustainable Energy. doi: 10.1109/TSTE.2025.3570507
11. Kumar, A., Gupta, D.K., Ghatak, S.R., Appasani, B., Bizon, N. and Thounthong, P., 2022. A novel improved GSA-BPSO driven PID controller for load frequency control of multi-source deregulated power system. Mathematics, 10(18), p.3255. doi: 10.3390/math10183255
12. Kumar, N.M. and Chopra, S.S., 2023. Blockchain-assisted spent electric vehicle battery participation for load frequency control problems in interconnected power systems is resilient, low-carbon, and offers revenues to the operators. Sustainable Energy Technologies and Assessments, 57, p.103209. doi: 10.1016/j.seta.2023.103209
13. Kumar, R. and Prasad, L.B., 2024. Optimal load frequency control of multi-area multi-source deregulated power system with electric vehicles using teaching learning-based optimization: a comparative efficacy analysis. Electrical Engineering, 106(2), pp.1865–1893. doi: 10.1007/s00202-023-02027-7
14. Kumari, S. and Pathak, P.K., 2024. A state-of-the-art review on recent load frequency control architectures of various power system configurations. Electric Power Components and Systems, 52(5), pp.722–765. doi: 10.1080/15325008.2023.2234373
15. Lalngaihawma, S., Datta, S., Das, S., Alsaif, F. and Ustun, T.S., 2024. Automatic generation control of hybrid sources incorporating renewable energy sources and electric vehicles in an interconnected power system considering a deregulated environment. IEEE Access. doi: 10.1109/ACCESS.2024.3454229
16. Liu, X., Qiao, S. and Liu, Z., 2023. A survey on load frequency control of multi-area power systems: Recent challenges and strategies. Energies, 16(5), p.2323. doi: 10.3390/en16052323
17. Ma, S., 2024. Optimal scheduling of electric vehicle aggregators for frequency regulation and cost efficiency in renewable-powered grids. Computers and Electrical Engineering, 118, p.109317. doi: 10.1016/j.compeleceng.2024.109317
18. Ma, Y., Hu, Z. and Song, Y., 2023. A reinforcement learning based coordinated but differentiated load frequency control method with heterogeneous frequency regulation resources. IEEE Transactions on Power Systems, 39(1), pp.2239–2250. doi: 10.1109/TPWRS.2023.3262543
19. Nayak, P.C., Mishra, S., Prusty, R.C. and Panda, S., 2023. Hybrid whale optimization algorithm with simulated annealing for load frequency controller design of hybrid power system. Soft Computing, pp.1–24. doi: 10.1007/s00500-023-09072-1
20. Ramesh, M., Yadav, A.K. and Pathak, P.K., 2026. Optimal robust PI-type load frequency control of renewable penetrated power system with delayed electric vehicles aggregators. International Journal of Information Technology, 18(1), pp.645–654. doi: 10.1007/s41870-025-02798-1
21. Rasolomampionona, D.D., Połecki, M., Zagrajek, K., Wróblewski, W. and Januszewski, M., 2024. A comprehensive review of load frequency control technologies. Energies, 17(12), p.2915. doi:

10.3390/en17122915

22. Rouhanian, A., Aliamooei-Lakeh, H., Aliamooei-Lakeh, S. and Toulabi, M., 2023. Improved load frequency control in power systems with high penetration of wind farms using robust fuzzy controller. Electric Power Systems Research, 224, p.109511. doi: 10.1016/j.epsr.2023.109511
23. Ruan, S., 2023. Robust fractional-order proportional-integral controller tuning for load frequency control of a microgrid system with communication delay. Energies, 16(14), p.5418. doi: 10.3390/en16145418
24. Saxena, A., Shankar, R., Al Zaabi, O., Al Hosani, K. and Muduli, U.R., 2023. Rule-based adaptive frequency regulation with real stochastic model intermittency in a restructured power system. IEEE Transactions on Industrial Informatics, 20(2), pp.2907–2919. doi: 10.1109/TII.2023.3299422
25. Shangguan, X.C., Yang, Y.H., He, Y., Wei, C.G., Zhang, C.K. and Jiang, L., 2025. Dissipativity-based integral-sliding-mode load frequency control considering disturbances and denial-of-service attacks. IEEE Transactions on Power Systems. doi: 10.1109/TPWRS.2025.3593776
26. Sharma, M., Dhundhara, S. and Sran, R.S., 2023. Impact of hybrid electrical energy storage system on realistic deregulated power system having large-scale renewable generation. Sustainable Energy Technologies and Assessments, 56, p.103025. doi: 10.1016/j.seta.2023.103025
27. Wang, G., Wang, C., Hao, Q. and Shahidehpour, M., 2023. Load frequency control method for cyber-physical power systems with 100% renewable energy. IEEE Transactions on Power Systems, 39(2), pp.4684–4698. doi: 10.1109/TPWRS.2023.3301303
28. Wang, L., Fan, H., Liang, J., Xu, L., Li, T., Luo, P., Hu, B. and Xie, K., 2023. Multi-area frequency-constrained unit commitment for power systems with high penetration of renewable energy sources and induction machine load. Journal of Modern Power Systems and Clean Energy, 12(3), pp.754–766. doi: 10.35833/MPCE.2023.000002
29. Zeng, Y., Li, J., Luo, Y., Yu, Y., Zhang, C. and Zhu, L., 2025. Frequency Dynamics-Constrained Renewable Energy Hosting Capacity Evaluation With Synthetic Inertia and Multi-Resource Frequency Support. IEEE Transactions on Industry Applications. doi: 10.1109/TIA.2025.3559029
30. Zheng, Y., Tao, J., Sun, Q., Sun, H., Chen, Z. and Sun, M., 2023. Adaptive active disturbance rejection load frequency control for power system with renewable energies using the Lyapunov reward-based twin delayed deep deterministic policy gradient algorithm. Sustainability, 15(19), p.14452. doi: 10.3390/su151914452