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Load Distribution Control in Power Systems: A Survey

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***Abstract* - Load distribution control in power system means the proper and coordinated allocation of power generation to meet the load demands and maintaining the system stability. There are various methods for load distribution which includes classical load–frequency control (LFC) or automatic generation control (AGC), economic dispatch, and distributed control methods in smart grids. In the present times, the traditional power sources are being made shift towards renewable energy sources (like solar or wind energy) and distributed energy resources. This has increased the need for advanced load distribution mechanisms that can easily handle the voltage changes and the direction of power flow. This survey provides information about the various systems that are already in use over the past decade. The various systems used are broadly classified into the sections like (i) Classical AGC/Economic Dispatch system which is used for frequency regulation and cost reduction, (ii) Decentralized/Distributed Control system which is used in microgrids, (iii) Model Predictive and Optimization-Based Control which generally include methods such as MPC and metaheuristic tuning of controllers, (iv) Multi-Agent and Consensus-Based Control, system which generally use local communication, (v) Renewable Integrated and Demand Response Strategies which integrate storage and flexible loads, and (vi) Communications and Cybersecurity Aware Methods which address network delays and cyber-attacks. This paper also the main advantages of the test systems (e.g., IEEE bus cases, microgrid models) and performance metrics (frequency deviation and economic efficiency). This paper shows comparison tables of various load distribution systems and provides complete information about their strengths and limitations[1][2]. The challenges discussed include renewable intermittency, communication delays, cybersecurity vulnerabilities and lack of standard benchmarks. The paper also discusses the future techniques for designing intelligent and resilient load distribution systems.**

Keywords - Load Distribution Systems, Automatic Load Generation Control (AGC), Economic Load Dispatch, Droop Control System, Consensus based Control, Demand Response Control.

I. INTRODUCTION

Electrical power systems must continuously balance generation with load demands to maintain nominal frequency. Load distribution control refers to the techniques that allocate the load among generation units and adjust loads to achieve this balance. There are various techniques for Load distribution Control Systems. In the past, this was done via Load Frequency Control (LFC), the hierarchical schemes where the primary droop control is followed by the secondary AGC actions to restore frequency and control tie-line power [1]. The Other technique used for load distribution is known as Economic Dispatch (ED) System. This system gives the information about the load generation schedule for cost optimization to meet the demands of power systems [3]. These traditional power systems were designed for grids with a few power plants and stable demands whereas modern grids are more decentralized and uncertain in terms of power demands because of the different energy sources such as renewable energy, Distributed energy resources (DERs) and electrification of transport system.
For Example, renewable sources have variable and uncertain outputs and generally leads to faster and larger load changes [4].

In the distributed power generation systems and microgrids, there are multiple controls pertaining to the different areas must coordinate with each other, even without a single central control system. The smart grid communications and data allow new control paradigms (e.g., multi-agent consensus). These are some of the changes that provides a reason for collecting the survey of modern load distribution techniques.

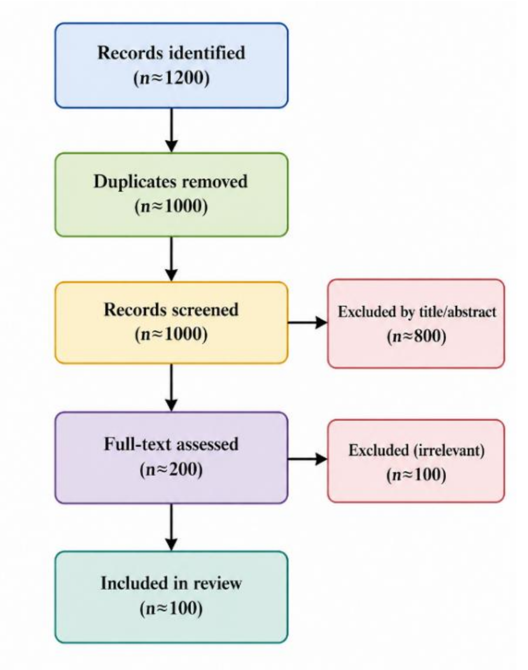
II. METHODOLOGY

The survey paper is designed from the research of some of the popular databases such as IEEE Xplore, Scopus, Web of Science, and Google Scholar etc. The papers published between 2016-2025 were thoroughly researched for the Load Distribution Control systems.

We identified roughly 1000 records in initial searches. After removing the duplicates and screening titles/abstracts for relevance, about 150 full text articles were assessed for load distribution system of these, approximately 100 were deemed directly relevant (addressing generation load balancing, frequency control, dispatch, or load sharing). The

Figure 1 also known as PRISMA flow diagram summarizes our overall selection and processing of the information extracted from the already published papers. The Data extracted from each paper includes various sections such as which model is used (e.g., single area, two area, microgrid), control method used (e.g., PID, MPC, consensus, etc.), the datasets or test cases, performance metrics based on frequency deviation, cost, convergence time, and identified advantages limitations of the systems.

Assumptions: In the absence of explicit time range instruction, we assumed 10 years (2016–2025) and explicitly noted this assumption. Search also covered 2026 publications up to early May 2026 when available. While conference papers and theses were considered (e.g., IEEE CDC/ACC), priority was given to archival journal articles (IEEE TSG, EPSR, RSE, etc.) and top conferences (IFAC, PES GM, etc.).



III. BACKGROUND AND FUNDAMENTALS

This section reviews fundamental concepts underlying load distribution control.

Load Frequency Control (LFC) or Automatic Generation Control (AGC). In the interconnected power system, each area must balance generation and load to keep frequency stable around its nominal (e.g. 50/60 Hz)[1]. Primary control (governor droop) responds immediately to frequency changes, but typically yields a steady state error (frequency offset) under load change. LFC (secondary control) uses integral controllers (AGC) to drive the area control error (ACE) to zero, restoring frequency and scheduled tie line flows[1]. Standard multi area models use linearized transfer functions for turbines, governors, and tie lines (e.g, IEEE two area system). The Key variables include speed regulation, governor dead band, governor response time, etc. Performance metrics are frequency deviation (Hz), tie line power error, settling time, and overshoot. Classical AGC typically uses decentralized PI or PID loops[12], tuned per area.

Economic Dispatch (ED). The ED problem allocates generation among units to minimize total fuel cost subject to demand and generator limits[3]. In the simple form, cost is a quadratic function of power, and solutions satisfy equal incremental cost across units (Lagrange multipliers). In the multi area or deregulated systems (MAED), areas exchange power optimally[13]. ED must satisfy transmission constraints in the complex networks, leading to AC optimal power flow or approximations. The Cost functions may include emissions or ramping. Modern ED often uses optimization techniques (linear/quadratic programming, etc.) and can be run in dispatch centers on an hourly or real time basis in the system . Key challenges include handling non convex costs, multiple objectives (emission, losses), and uncertainties in the load forecast system.

Droop Control and Decentralized Sharing. In the parallel operation of inverters and generators in an islanded microgrid, droop control is widely used[10]. The frequency power droop law ($\Delta f = -kp\ \Delta P$) in the ensures proportional load sharing without communication. Similarly, voltage–reactive power droop shares V/Q. This method relies on passive network impedances; it incurs a steady-state frequency/voltage deviation and requires a high aggregate droop to share high loads (trade off vs. accuracy)[10]. Issues include line impedance mismatch (leading to unequal Q sharing) and slow transient response. Variants include virtual impedance loops, adaptive droop, or master slave schemes where one unit holds frequency/voltage setpoint[10][11].

Model Predictive Control (MPC). MPC predicts future system behavior using a dynamic model and optimizes control over a horizon subject to constraints (e.g., generator limits, tie-line flow constraints). For LFC/ED, MPC can coordinate multi-area generation by solving an optimization at each step, inherently handling delays and limits. (Example: Xu et al. 2019 [44] used finite-time MPC for microgrid frequency control).

Multi-Agent or Consensus Methods. Multi-agent control is a technique in which each generator or area is treated as an agent that exchanges limited information (e.g., neighbour’s power or state) and updates its control to reach a consensus on a global objective[2]. For example, consensus-based load method allows each agent to adjust its control by itself which is generally based on the weighted averages of local frequency errors and the neighbouring states. This enables the distribution of LFC without a central generation control. The advantage of this method is scalability and privacy but it requires communication networks with reliability.

Demand Response and Load-Side Control. The modern grids use demand response (DR) for load distribution. The demand response provides controllable loads which can be adjust consumption in the real time to assist in balancing. DR can be treated as a negative generation in LFC formulations[7]. For example, an FR (frequency responsive) load reduces the voltage when frequency falls. When the DR is added with a power storage like batteries or flywheels, it stabilises the power fluctuations.

Communication and Cybersecurity. The modern load distribution control systems depend on measurement of loads and communication between grids such as SCADA and PMUs. This makes power distribution systems vulnerable to various attacks such as DoS or false data injection which can disrupt LFC[8]. This leads to delays or packet loss and overall degrades the performance. Therefore modern control are designed taking these things in mind such as cyber-physical security, detection mechanisms, resilient control laws, and secure power distribution architectures.

IV. TAXONOMY OF LOAD DISTRIBUTION CONTROL

A clear taxonomy helps to understand the diverse literature of any topic. Therefore, we have classified the load distribution in various categories. The Figure 1 illustrates our classification of load distribution control. Categories include classical AGC/ED techniques, decentralized droop/master slave strategies for microgrids, predictive and optimization-based controls, multi agent consensus approaches, renewable integration with demand response, and methods addressing communication and cybersecurity. Each node can further branch (e.g., AGC controllers may be PI, robust, fuzzy, etc.; metaheuristics include GA, PSO). This taxonomy will structure the detailed literature review in Section 6. It highlights how each category addresses aspects of the load distribution problem, and facilitates identifying overlaps (e.g., MPC might be used in both centralized and multi agent settings) and gaps (e.g., fewer works on cyber-physical security of ED).

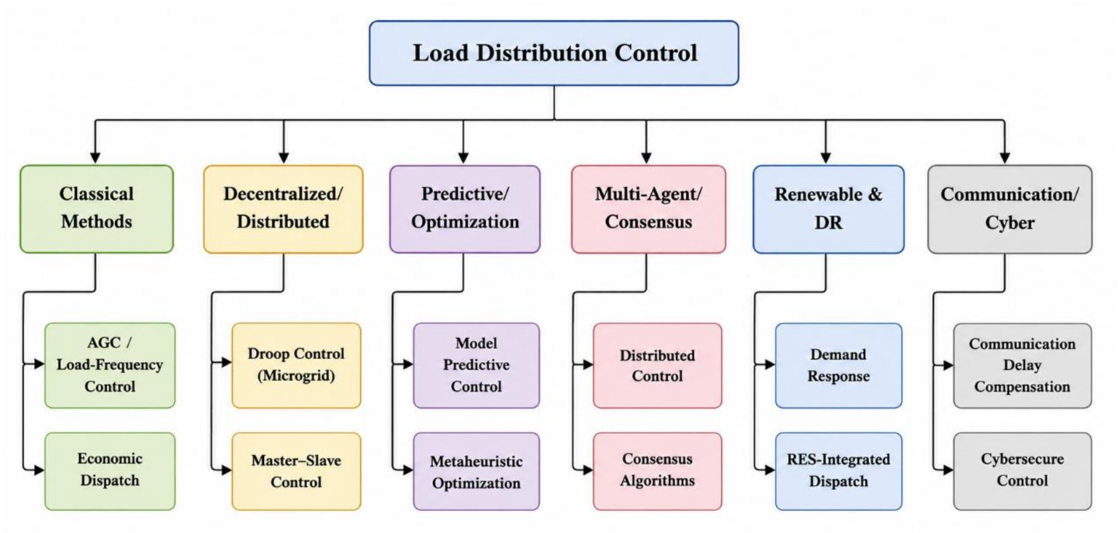


FIGURE 1: Taxonomy of load distribution control methods in power systems.

V. LITERATURE REVIEW BY CATEGORY

A. Classical AGC and Economic Dispatch

Load Frequency Control (AGC): in the Traditional AGC regulates system frequency by adjusting generator outputs. Many studies focus on the improving PID based in AGC. provide a broad review of AGC controllers (integer/fractional order, intelligent, cascade) and note that heuristic tuning (GA, PSO) it has become common in recent years[14]. In the summary, classical LFC works rely on linear models of generator and governor dynamics[1] and typically assume fixed exchange schedules. The Performance is often evaluated on standard benchmarks (e.g., two area thermal systems), the measuring metrics like frequency deviation and tie line error system

Economic Dispatch (ED): ED allocates the generation cost effectively. Kunya et al. in year (2023) survey multi area ED (MAED) techniques, the covering of centralized and decentralized approaches [13]. In the Centralized ED solves a global optimization (requiring full data), whereas the decentralized ED splits the grid into areas, optimizing locally with the limited information exchange. They found that the decentralised ED load distribution preserves privacy and reduces the overall communication overhead [13].

The common methods used in the Economic Dispatch include Lagrangian relaxation and augmented Lagrangian algorithms. ED formulations handle constraints like transmission limits and ramp rates; stochastic or dynamic ED accounts for changing load and unit availability. In the Performance is measured in terms of cost savings and convergence speed. Still, classical ED often neglects grid security constraints and fast dynamics, leaving room for more integrated dispatch control schemes.

B. Decentralized/Distributed Control (Droop, Master–Slave)

In the microgrids and parallel generator systems, decentralized control the schemes are prevalent. The droop control method are (frequency power droop for active power, voltage Q droop for reactive) is widely used because it requires no communications[10]. Tayab et al. (2017) the review droop techniques are widely used in the system , noting that higher droop slopes improve load sharing but worsen voltage regulation[10]. Several variants exist:

- The Conventional droop assumes inductive lines and yields good active power sharing but poor reactive sharing under line mismatches in the system [10].
- The Virtual impedance loops mimic impedance to improvement reactive sharing [15].
- Adaptive/robust droop modifies the droop coefficients or adds control loops to enhance transient response [15].

The Master slave control assigns one source as a voltage/frequency reference (master) while others (slaves) share the remaining load. For example, Caldognetto et al. (2014) describe a microgrid where the utility interface (UI) acts as a master dispatching power setpoints to DER inverters[11]. the Master slave ensures fast load sharing but is less scalable (single point of failure).in the Hybrid methods combine droop and master slave (e.g., Kalke et al. 2019 modify droop gains adaptively with a leader follower scheme in AC microgrids, improving sharing performance in the power system [11]).

The Parallel DC/DC converters (power electronic interfaces) also require load sharing. Jiang et al. (2019) propose an adaptive virtual resistance droop for the DC microgrids with batteries[11], showing that virtual resistances can improve stability. Chen et al. (2019) used bat algorithm to tune a two DOF PID for the DC converter the current sharing, achieving equal power distribution network under time varying loads[11].

In summary, decentralized schemes trade communication complexity for reliance on local measurements. They are robust and simple, but often cannot guarantee optimality or compensate as well for grid impedance variations[10]. Hybrid and improved droop methods attempt to overcome these limits at the cost of more complex control.

C. Model Predictive and Optimization-Based Control

Model Predictive Control (MPC): MPC has been applied to load distribution to handle multi period dispatch and constraints. Although comprehensive surveys are a rare, recent works demonstrate MPC’s utility. For example, the adaptive MPC for robust LFC was proposed by Liu et al. (2020) [47†L1-L4], it is showing improved performance under disturbances. Another study integrated distributed MPC for Realtime ED, balancing economic and frequency objectives. The benefit of MPC is handling of multi objective optimization (cost vs. stability) within the constraints, but challenges include model accuracy and computational load for real time implementation.

Metaheuristic Optimization: Evolutionary and swarm algorithms (GA, PSO, Grey Wolf, Bat, etc.) are widely used to tune Load frequency control or solve non convex dispatch problems. Singh et al. (2025) note that such algorithms have become “widely adopted” for finding optimal control parameters [14]. For instance, Genetic Algorithms are used to tune PI gains in AGC (as in [4]), and Particle Swarm is used for multi objective dispatch. Heuristics excel in handling nonlinearity and multiple constraints (e.g., valve-point effects in cost curves) but may require many iterations and lack formal stability guarantees. In the surveyed literature frequently reports metaheuristic based controller designs achieving better objective values (lower area control error or cost) compared to the traditional tuning methods. However, the authors often note the trade off of higher computational effort and the need for offline tuning.

D. Multi-Agent and Consensus-Based Control

The recent researches are emphasizing over the distributed or consensus control, where the agents use local information and less communication to handle the load distribution’s objectives. Gamage et al. (2024) proposed a model in which a multi-level consensus LFC with is equipped with distributed batteries[2], each node shares information like SoC, power etc with the neighbours to reach a common consensus on LFC. This paper shows that when multi-agent strategy is used it stabilizes frequency and voltage compared to centralized LFC[2][16]. Each agent can act as a generator or load to balance any fluctuations or losses.

Similarly, Alghamdi et al. (2025) developed a model in which distributed consensus voltage and frequency is combined for an microgrid [18]. The controller utilizes local frequency and voltage changes and communicates with the other neighbouring agents. This approach combines reactive (voltage) and active (frequency) controls via consensus loops[18].

In general, consensus controllers are used to maintain the robustness and flexibility of load distribution. They do not rely on a central coordinator. However, they require reliable peer-to-peer communications and may converge more slowly[2].

E. Renewable-Integrated Control and Demand Response

Renewable integration: The High penetration of stochastic RES complicates load distribution network. LFC must now compensate for the rapid power swings from solar and wind. The Recent reviews (e.g., Singh et al. 2025[4], Ranjan & Shankar 2022 [12]) highlight that existing LFC strategies need augmentation in the system . the Solutions include coordinating energy storage and flexible resources with LFC. Liu et al. (2018) propose an LFC scheme combining Realtime pricing demand energy response and battery storage in a small grid[7]. They consider four scenarios (DR only, RES output control only, both, neither) on a 10-bus island system. Simulation results show that enabling both DR and RES control yields in the best frequency regulation (smaller deviation and faster recovery) compared to the base case[7]. This demonstrates that the demand side flexibility can act as virtual generator to stabilize frequency control.

Other works incorporate electric vehicles (V2G) and thermal loads into dispatch models. Zhou et al. (2023) the EVs and demand response can interact with LFC via auxiliary control signals [13]. In the summary, integrating renewables demands multi faceted load control (e.g., the dynamic dispatch updates, adaptive droop gains). Trends include using forecasting (solar and wind) within MPC or stochastic optimization frameworks to anticipate variability.

Demand Response (DR): DR is treated in control algorithms by including the load elasticity. For example, an LFC controller might incorporate a feedback loop that modulates controllable loads (water heaters, air conditioners) in the proportion to frequency error. This effectively increases system inertia and damping. While the fewer papers target DR explicitly in the surveys, it is a key component in microgrid energy management. In Future work needs standard models for aggregated DR and coordination with the wholesale markets.

F. Communication-Aware and Cybersecurity

In the Modern load distribution control relies on communication networks (SCADA, PMUs, IoT). This section reviews works that consider communication issues and cyber threats.

Communication Delays and Packet Loss: Time delays in measurement and actuation can degrade LFC performance. Some studies design controllers robust to constant or stochastic delays. For instance, a robust adaptive control may include delay compensation or event-triggered updates to reduce communication load. The review by Babu et al. (2022) mentions event triggered control schemes for Load frequency control under delays[17], which reduce bandwidth while ensuring stability. Distributed LFC schemes also often analyze the stability under graph to connectivity changes (loss of links).

Cyber-Attacks: Power grids are cyber physical systems vulnerable to digital attacks. The paper given by the Saxena et al. (2021) present a survey of Load frequency control specific cyber security [8]. They have categorized various attacks such as jamming, DoS, false and data injection and have discussed their impact on AGC loops. For example, FDI attacks on frequency measurements can cause incorrect AGC responses. The mitigation strategies include anomaly detection filters and resilient control laws that ignore suspicious data.

The recent works have exclusively designed the models to control the cyber-attacks. The paper by Mei et al. (2025) have also discussed such attacks which include DoS and FDI attacks on LFC[9]. They have introduced a probability model for Markovian DoS which reduces the need for exact transition probabilities.
They have formulated the control as a switch which is normally stochastics system. This system derives Lyapunov conditions for stability under uncertain attack modes[9].

VI. COMPARATIVE ANALYSIS

In this section, we have generated the overall insights from the available systems, we compare all these studies in tabular form. Table I contrasts some of the notable works in LFC/Economic Dispatch and secure control. The Table II focuses mainly on microgrid load-sharing methods.

Paper	**Approach**	**System/Test Case**	**Performance Metrics**	**Pros / Results**	**Cons / Limitations**
Gamage et al., 2024[2]	Multi-level consensus LFC with distributed multi-battery storage	IEEE 14-bus islanded grid	Frequency deviation, voltage deviation, and convergence	Achieves stable frequency with consensus; outperforms traditional LFC with MBESS	Requires a communication graph; assumes perfect neighbor connectivity; implementation complexity
Kalke et al **Liu et al., 2018[7]**	LFC with real-time pricing, demand response, and battery storage	Real 10-bus Okinawa island model	Frequency deviation under scenarios: pole-zero stability	Combining DR and battery yields the smallest frequency deviation and the smoothest response	Case-specific study; requires DR infrastructure and pricing signals
Saxena et al., 2021[8]	Survey of cybersecurity in LFC	Two-area power system model (case)	N/A (survey)	Classifies attack types; reviews detection/mitigation methods	No new control design; mostly a conceptual framework
Mei et al., 2025[9]	Sojourn-probability + NN-based LFC control under hybrid attacks	Two-area power system (simulated)	Frequency error, stability under DoS+FDI	Robust to DoS and FDI; Lyapunov analysis guarantees stability under attacks.	High theoretical complexity; needs accurate attack statistics; only simulated example
Kunya et al., 2023[13]	Review of economic dispatch (MAED)	Multi-area power grid (model)	N/A (survey)	Covers centralized/decentralized ED; links to ancillary services	Broad review; lacks performance data
Zhou et al., 2023	Robust AGC (H-infinity) controllers	Three-area power system model	Overshoot, settling time, and inertia robustness	Improved stability under parameter variations, delays	Implementation details limited; specific to LFC

TABLE I: Comparison of load frequency and dispatch control methods

Features major works and surveys in centralized/distributed AGC and security-aware LFC. Metrics include frequency deviation, stability margins, and computational requirements.

Paper	**Method**	**Microgrid Type / Test Case**	**Key Results**	**Pros / Results**	**Cons / Limitations**
Tayab et al., 2017[10]	Survey of droop control techniques	Generic AC microgrid model	NA (review)	Summarizes conventional vs. advanced droop; highlights reactive	No new data; identifies key challenges (impedance mismatch, slow

				sharing issues[10]	response)
Guerrero et al., 2011[11]	Hierarchical control (droop + secondary)	AC/DC hybrid micrgrids (theoretical)	NA (proposal + experiments)	Proposes 3-layer control (droop, secondary restore, tertiary grid exchange)	Early work; experimental validation limited; no renewable dynamics
Kalke et al., 2019[11]	Modified droop + master–slave	Islanded AC microgrids	Improved power sharing accuracy	Reduces circulating currents; maintains stability under load changes	Added comparator blocks; mainly simulation
Alghamdi et al., 2025[18]	Distributed consensus VFC	Islanded inverter-based microgrid (CIGRE)	Fast recovery from faults (FIDVR scenarios)	Coordinates voltage and frequency control; robust to communication delays	Complex coordination, specific to fault mitigation, requires event detection logic
Gamage et al., 2024[2]	See Table 1	IEEE 14-bus islanded grid	As above (frequency regulation)	As above (improved performance with consensus and storage)	As above (requires communication)
Liu et al., 2019 (example)	Adaptive droop for DC MG	Two parallel inverters (lab-scale)	Equal current sharing under a mismatch	Uses virtual resistance adaptation; tested on hardware	Limited to DC system; not peer-reviewed (conference paper)

TABLE II: Comparison of decentralized and microgrid load-sharing methods.

Entries include survey and original research on droop/control strategies. Focus is on how these methods achieve load sharing and voltage/frequency regulation. Note that Guerrero (2011) is foundational for hierarchical MG control (cited via[11]).

These tables illustrate the tradeoffs: for example, adding energy storage and consensus communication (Gamage) generally improves regulation at the cost of complexity, whereas pure droop (Tayab) is a simple but less precise. The cyber aware methods (Mei, Saxena) highlight vulnerabilities unique to modern grids very important.

Table 1 shows the progression in classical AGC to secure a AI based control, while Table 2 contrasts passive (droop) vs. active (consensus) approaches. Their metrics guide design choices: an approach that fully eliminates frequency error (e.g., GA optimized AGC[6]) may introduce implementation complexity, whereas faster response might be achieved via high droop inverters but with voltage deviation.

VII. DATASETS AND TEST SYSTEMS

This section covers the test systems and datasets used to validate the load control strategies:

- **IEEE Standard Test Systems**: The test systems of IEEE include 14 bus and 39 bus systems. These are frequently used for to study the LFC or ED methods. For instance, Gamage et al. (2024) test their consensus LFC on the IEEE-14 bus system is a island mode[2]. Similarly, two area (four generator) thermal systems from IEEE are a standard LFC benchmark[6][1].

- **Microgrid Benchmarks:** Isolated microgrid models (e.g., CIGRE benchmark microgrid, IEEE 33 bus AC MG) are used for decentralized control testing. Alghamdi et al. (2025) use a modified CIGRE distribution microgrid to evaluate distributed VFC[18]. Realistic rooftop solar battery testbeds (hardware in the loop) are also reported, but less commonly.

- **Specialized Cases**: Real-world inspired models appear, such as a 10-bus Okinawa island system for LFC under renewables[7], and an EV charging station network (Jiuqing et al., 2015) for PCS control.

- **Datasets**: Most papers use simulated data, not publicly shared. A few use real load or generation traces (e.g., wind/PV profiles) in scenarios, but benchmark datasets specific to LFC or dispatch (like grid event records) are lacking.

- **Hardware/Simulators**: Some studies use real-time digital simulators (e.g., OPAL-RT) for proof-of-concept (Gamage et al., 2024 on OP5700[16]), or lab-scale microgrid controllers for droop tests.

In summary, while IEEE cases dominate, there is a need for standardized, open test cases that include high renewables or cyber-attack scenarios.

VIII. CHALLENGES AND RESEARCH GAPS

Despite advances to several challenges which persist in a load distribution control:

- Renewable Variability: High-RES penetration causes rapid and unpredictable power fluctuations. Traditional AGC and dispatch are not designed for minute by minute solar and wind changes[4][5]. There is a gap in controllers that can handle extreme variability without sacrificing stability (e.g., fractional or robust controls).

- Communication Constraints: The distributed methods are based on the communication networks. This leads to the delays, jitter or sometimes the data loss. Some of the problems were addressed under robust control systems. The paper of Zhang et al. has noted that Markovian or Bernoulli models for network failures are ideal for this purpose[17].

- Cybersecurity: According to the surveys [33], LFC is quite vulnerable to various cyber-attacks.

- Integration of Demand Side and Storage: In this regard some of the works have shown that Demand Response and batteries (refer Table 1) collectively optimize the dispatch and demand. However, these are still under development.

- Scalability and Coordination: For this issue, multi-agent works pretty well for scaling but often assume small networks. Therefor the question still remains that how to extend consensus control to very large hierarchical grids along with guaranteeing convergence speed remains unresolved.

- Standardization of Test Cases: As noted, there is no standard dataset for “load distribution” problems with renewables or cyber scenarios. This hinders benchmarking. e.g., cyber-attack resilience.

- Model Uncertainties: Many controllers assume accurate system parameters such as inertia, damping etc but in practice, inertia and load sensitivities can vary from system to system and this affects performance. Adaptive or learning controllers are needed to cope with parameter of uncertainties and the problem of nonlinearity of systems.

- Regulatory and Market Factors: Most of load control strategies assume a technical framework which integrates it with electricity market operations, reserve requirements, and cross-border trades is a challenge.

The summary of this section is that it provides the challenges of existing works which often address one aspect but may ignore practical issues like communications, uncertainty, or economics. Future research will bridge these gaps to deploy load distribution control in real grids.

IX. FUTURE DIRECTIONS

We outline concrete research problems suggested by the gaps:

1. Cyber-Resilient Control Algorithms: in the Building on [33] and [34], develop LFC and dispatch algorithms that can detect and isolate cyber attacks in real time. For example, designing a distributed in the estimators to identify false data inputs and reconfigure AGC if needed.

2. The Data Driven and AI Methods: we use machine learning to compliment MPC, especially for unpredictable renewables energies. Leverage to large historical datasets to train controllers

3. In the Integration of Demand Flexibility: Formulate co-optimization problems that jointly dispatch generation and schedule flexible loads/EVs. Investigate pricing mechanisms within control the loops that guide DR participation without an undermining market fairness.

4. Multi timescale Coordination: Research hierarchical control that connects fast LFC (seconds) with slower economic dispatch (minutes/hours) and even slower planning a (day-ahead scheduling), possibly via multi-rate MPC or multi-agent hierarchies.

5. Inertia Emulation and Virtual Inertia: With low inertia grids, explore advanced load control (e.g., fast load shedding or synthetic inertia

from inverters) to stabilize frequency. How can loads provide "virtual inertia" as part of droop or consensus schemes?

6. Standardized Testbeds: in the Develop open-source test systems that include detailed models of renewables, storage, loads, and communication links (similar to the IEEE Reliability Test System but extended). Create benchmarks for various control tasks (e.g., LFC under high PV penetration).

7. Resilience to Natural Disturbances: The Expand load distribution control to account for resilience after extreme events (storms, faults). This includes self-healing microgrids.

8. Blockchain and Decentralized Transactions: in the Investigate whether blockchain or peer to peer energy trading can be integrated with distributed control, enabling secure direct DR activation and generator dispatch at local levels.

The directions given require the full expertise in the field of control systems theory, power system, communications and economics.

X. CONCLUSION

This survey is collected on the base topic "load distribution control systems", which ranges from the classic AGC and Economic Dispatch to the modern distributed networks which are based on predictive and cyber aware methods. The traditional control schemes have setup the base for optimisation, intelligence and coordination of technologies. The key findings of this survey paper are consensus based multi agent controls can match centralized performance with improved flexibility[2], adding demand response and storage significantly enhances frequency regulation under renewables[7], and accounting for cyber risks is now indispensable[8][9]. However, the challenges are still existed there in the integration of these findings into large scale operations.

In the conclusion, advancement of load distribution control demands is a quite holistic approach and requires development of robust controllers that can have better capabilities. These should provide better control over demands, handle a variable demand along with the attacks, providing better communication infrastructures for distributed agents, and creating all the standards for evaluation. The taxonomy of survey, comparison tables, and all the identified gaps is to give the base for researchers in this field. By addressing the discussed challenges and future work will enable power in systems to meet a load reliably and economically in an increasingly complex and renewable driven era.

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