



# A Comprehensive Review on Load Frequency Control in Renewable-Integrated and HVDC-Connected Power Systems

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**ABSTRACT:** The rapid integration of renewable energy sources and the widespread adoption of high voltage direct current (HVDC) transmission links have significantly altered the operational dynamics of modern interconnected power systems, leading to reduced system inertia, increased uncertainty, and greater frequency instability. Under such conditions, Load Frequency Control (LFC) plays a vital role in maintaining system reliability by regulating frequency deviations and tie-line power exchanges in multi-area networks. This review provides a comprehensive overview of LFC strategies in renewable-integrated and HVDC-connected power systems, covering the impact of wind, solar, energy storage systems, and electric vehicles on frequency dynamics and system stability. It critically examines conventional and advanced control approaches, including PI/PID, fractional-order, model predictive, adaptive, and intelligent optimization-based controllers such as fuzzy logic, machine learning, and nature-inspired algorithms, in the context of hybrid AC/DC grids. The role of HVDC technologies, including LCC and VSC systems, in providing virtual inertia, fast frequency support, and enhanced power sharing is also discussed. In addition, emerging challenges such as cyber-attacks, low-inertia operation, communication delays, and coordinated control with energy storage devices are analysed to highlight their influence on LFC performance. A comparative synthesis of recent studies is presented based on key performance indicators such as settling time, overshoot, robustness, and disturbance rejection, followed by the identification of research gaps and future directions toward developing resilient, AI-driven, and cyber-secure frequency control frameworks for next-generation renewable-dominated power systems.

**KEYWORDS:** Load Frequency Control, Renewable Energy Integration, HVDC-Connected Power Systems, Frequency Stability, Intelligent Control Techniques, Low-Inertia Power Systems

## I. INTRODUCTION

The modern power system is undergoing a significant transformation due to the rapid penetration of renewable energy sources, such as wind and solar, and the increasing deployment of high voltage direct current (HVDC) transmission technologies for long-distance and interregional power transfer. While these advancements enhance system flexibility, efficiency, and sustainability, they also introduce new operational challenges, particularly in maintaining frequency stability. The intermittent and stochastic nature of renewable generation, coupled with the reduction in system inertia caused by the replacement of conventional synchronous generators with inverter-based resources, has made frequency regulation more complex in interconnected multi-area power systems. As a result, LFC has emerged as a crucial mechanism to ensure the balance between generation and load, minimize frequency deviations, and maintain reliable power system operation under dynamic disturbances.

In renewable-integrated and HVDC-connected power systems, the frequency dynamics are influenced by hybrid AC/DC interactions, communication delays, and fast power electronic interfaces. HVDC links, including line-commutated converter (LCC) and voltage source converter (VSC) based systems, provide enhanced controllability, fast power modulation, and the capability to support frequency regulation through virtual inertia emulation and coordinated tie-line control. However, the integration of such technologies introduces additional control complexity, requiring advanced and adaptive LFC strategies that can effectively handle nonlinearities, uncertainties, and varying operating



conditions. Moreover, the increasing participation of energy storage systems, electric vehicles, and distributed energy resources further alters the system response, necessitating robust and intelligent control frameworks.

Over the years, various LFC methodologies have been developed, ranging from conventional proportional–integral (PI) and proportional–integral–derivative (PID) controllers to more advanced approaches such as fractional-order control, model predictive control, adaptive control, and robust control techniques. Recently, intelligent and optimization-based controllers, including fuzzy logic, neural networks, machine learning, and nature-inspired algorithms, have gained significant attention due to their superior dynamic performance and adaptability in complex power system environments. These methods have been widely applied in multi-area systems with renewable penetration, HVDC tie-lines, and hybrid energy storage support to improve frequency regulation and disturbance rejection capabilities.

The emerging concerns such as cyber-security threats, false data injection attacks, communication constraints, and low-inertia grid operation have created new research directions in LFC design for modern smart grids. The coordinated control of HVDC links, energy storage devices, and inverter-based renewable units is increasingly being explored to enhance system resilience and operational reliability. In this context, a comprehensive review of existing LFC strategies for renewable-integrated and HVDC-connected power systems is essential to understand the current research trends, technological advancements, and existing limitations.

Therefore, this review aims to present a systematic and comprehensive analysis of LFC techniques applicable to renewable-integrated and HVDC-interconnected power systems. The study examines the impact of renewable penetration and HVDC technologies on frequency dynamics, reviews conventional and advanced control approaches, and highlights recent developments in intelligent and cyber-resilient frequency control strategies. In addition, the review identifies key research gaps and outlines future directions for developing efficient, robust, and adaptive LFC frameworks suitable for next-generation low-inertia and renewable-dominated power systems.

## II. LITERATURE REVIEW

The literature on LFC has expanded considerably with the growing integration of renewable energy sources and HVDC transmission in modern power systems. Researchers have proposed various conventional, advanced, and intelligent control strategies to enhance frequency stability in multi-area interconnected grids under low-inertia and uncertain operating conditions shown in table 1. Pham et al. (2015) presented an improved stability criterion for time-delay power systems incorporating electric vehicles and HVDC power links, emphasizing enhanced robustness in frequency regulation under delayed communication environments. Zuo et al. (2015) analyzed frequency stability in thermal–wind generation systems with HVDC islanded sending, showing that coordinated HVDC control can effectively mitigate frequency oscillations caused by renewable intermittency. Pham and Trinh (2015) proposed distributed functional observer-based LFC for power systems with diverse transmission links and electric vehicles, demonstrating improved decentralized frequency control performance. Ersdal et al. (2015) introduced model predictive LFC, highlighting its capability to handle multivariable constraints and system uncertainties more effectively than classical controllers. Gonzalez-Longatt et al. (2015) developed a flexible automatic generation control framework incorporating embedded HVDC links, which enhanced dynamic frequency support in interconnected grids.

Kouba et al. (2016) proposed an optimized fuzzy-PID controller for two-area power systems connected through HVDC links, achieving better damping and reduced settling time compared to conventional PID control. Kanimozhi et al. (2013) investigated DFIG-based wind farm integration using matrix converters, establishing the importance of renewable interfacing technologies in maintaining system stability. Debbarma and Dutta (2016) explored fractional-order controllers utilizing electric vehicles for LFC in restructured power systems, revealing improved robustness under load disturbances. Rakhshani et al. (2016) analyzed virtual inertia controllers based on VSP in HVDC links, demonstrating their effectiveness in enhancing inertia support in low-inertia systems. Shayeghi et al. (2016) studied FOPID-based LFC in multi-source power systems with high distributed generation penetration, indicating superior dynamic response under renewable variability.

Tada et al. (2017) investigated frequency control of power systems with solar and wind plants using HVDC interconnection flow control, confirming that HVDC tie-line modulation significantly improves frequency stability. Shankar et al. (2017) provided a comprehensive survey on LFC mechanisms, outlining the transition from classical control to intelligent and adaptive strategies in modern power systems. Kolluri et al. (2017) proposed improved dynamic control for MMC-based HVDC transmission, enhancing stability in long-distance power transfer systems. Jahan et al. (2017) developed simplified modeling approaches for HVDC systems connecting offshore wind farms,



facilitating accurate LFC studies in renewable-integrated grids. Pathak et al. (2018) modeled HVDC tie links for AGC/LFC in multi-area systems and demonstrated improved frequency regulation through coordinated AC/DC control.

Tavakoli et al. (2018) examined LFC in multi-source power systems connected to wind farms through multi-terminal HVDC systems, highlighting the benefits of coordinated renewable and HVDC control. Pham et al. (2018) proposed distributed HVDC link control for primary frequency regulation in time-delay systems, improving system resilience against communication delays. Debbarma and Shrivastwa (2018) utilized V2G aggregators and HVDC links for grid frequency support in systems with nonsynchronous units, showing enhanced frequency stabilization. Shrivastwa et al. (2018) developed coordinated control strategies using V2G and synchronous power controller-based HVDC links under wind and PV penetration, achieving better disturbance rejection. Murali and Shankar (2019) introduced inertia emulation-controlled HVDC tie-lines, which significantly reduced frequency deviations in interconnected systems.

Niino et al. (2019) implemented virtual synchronous generator control using HVDC interconnection lines for systems with large wind farms, demonstrating improved dynamic stability. Rakhshani et al. (2019) designed optimal LQR controllers for interconnected systems with HVDC links to emulate inertia and enhance frequency response. Prakash et al. (2019) proposed an I-PDF controller for LFC with AC/DC tie-lines, achieving faster settling and reduced overshoot. Onuka et al. (2019) presented coordinated control of HVDC lines and batteries for renewable-integrated systems, improving transient frequency performance. Xiao et al. (2020) focused on advanced control strategies in multi-infeed LCC-HVDC systems considering harmonics, contributing to stable system operation under complex conditions.

Pan et al. (2020) investigated false data injection attacks on hybrid AC/HVDC systems with virtual inertia, highlighting cybersecurity vulnerabilities in modern LFC frameworks. Ali et al. (2020) applied multi-verse optimizer-based model predictive LFC for hybrid renewable plants, demonstrating improved optimization and control accuracy. Lin and Wu (2021) provided an overview of frequency-control technologies for VSC-HVDC-integrated wind farms, emphasizing fast controllability and virtual inertia support. Babu et al. (2021) analyzed the impact of wind systems and redox flow batteries on LFC, confirming the role of energy storage in enhancing frequency regulation. Shouran et al. (2021) reviewed LFC strategies in conventional and modern power systems, identifying the growing importance of intelligent and adaptive control approaches.

Elmelegi et al. (2021) proposed optimized tilt fractional-order cooperative controllers for renewable-based power systems, achieving robust frequency stabilization under uncertainties. Lee et al. (2022) introduced communication-free grid frequency and voltage control for hybrid LCC-VSC HVDC systems, improving reliability in offshore wind integration. Meseret et al. (2022) developed intelligent optimized controllers for multi-area hydrothermal systems with wind and HVDC links, demonstrating enhanced dynamic performance. Roy et al. (2022) applied machine learning-based multi-agent systems for detecting cyber-attacks in AGC and HVDC systems, improving system resilience. Kamarposhti et al. (2022) optimized fuzzy-PID controllers for LFC in hydro-thermal systems connected to wind farms through HVDC lines, achieving superior damping characteristics.

Khan et al. (2023) utilized golden eagle optimization for LFC in AC/HVDC interconnected multi-area systems with hybrid energy storage, reporting improved stability and robustness. Yan et al. (2023) reviewed frequency control and optimal operation of low-inertia systems with HVDC and renewable energy, emphasizing the need for advanced coordinated control strategies. Boopathi et al. (2023) investigated microgrid frequency regulation using ant colony optimization-based controllers, demonstrating effective secondary frequency management. Kalyan et al. (2023) studied combined LFC and AVR systems with HVDC integration, highlighting enhanced overall system stability. Ramadhan and Yoon (2023) proposed plant-level control of inverter-based resources in embedded HVDC links to improve grid stability.

Presekal et al. (2024) reviewed cybersecurity threats and defense mechanisms in HVDC systems, underlining the importance of secure LFC frameworks in smart grids. Zhang et al. (2024) proposed adaptive event-triggered frequency regulation for dual-link LFC systems under cyber-attacks, improving robustness and resilience. Trinh et al. (2024) developed state-space based modern LFC strategies considering stability analysis for interconnected power systems. Kalyan et al. (2024) introduced algorithm-tuned IDDF controllers for multi-area systems with HVDC lines, enhancing stability under disturbances. Omar et al. (2026) proposed hybrid fuzzy-PIDD<sup>2</sup> control for coordinated LFC and AVR in renewable-integrated multi-area systems, achieving superior dynamic performance.

Satheeshkumar et al. (2023, 2024, 2026) and related works emphasized optimization algorithms, AI techniques, and energy storage integration for effective frequency management in standalone and interconnected power systems,



demonstrating improved control accuracy and robustness. Nguyen et al. (2026) and Thanh et al. (2026) further advanced improved LFC design methodologies for interconnected renewable systems, while Ramesh et al. (2026) and Thorat and Bhatt (2026) highlighted the growing role of electric vehicle aggregators in optimized LFC of restructured multi-area systems. Overall, the reviewed literature indicates a clear progression from classical LFC approaches to intelligent, optimization-based, cyber-secure, and HVDC-coordinated control strategies tailored for low-inertia, renewable-dominated modern power systems.

**Table 1. Summary of literature on LFC strategies in renewable-integrated and HVDC-connected multi-area power systems**

Ref.	Author(s) & Year	System/Focus Area	Method/Controller Used	Key Contribution/Findings
[1]	Pham et al., 2015	Time-delay power system with EV & HVDC	Stability approach criterion	Improved stability analysis for delayed LFC systems with HVDC links and EV integration
[2]	Zuo et al., 2015	Thermal-wind system with HVDC	Frequency control stability	Enhanced frequency regulation in wind-integrated HVDC sending systems
[3]	Pham & Trinh, 2015	Power systems with diverse links & EV	Distributed functional observers	Improved decentralized LFC performance and robustness
[4]	Ersdal et al., 2015	Multi-area power systems	Model Predictive Control (MPC)	Effective handling of constraints and uncertainties in LFC
[5]	Gonzalez-Longatt et al., 2015	Embedded HVDC-AGC systems	Flexible AGC framework	Improved dynamic frequency support using HVDC links
[6]	Kouba et al., 2016	Two-area HVDC-connected system	Optimized Fuzzy-PID	Reduced settling time and better damping characteristics
[8]	Debbarma & Dutta, 2016	Restructured power system with EV	Fractional Order Controller	Enhanced robustness in frequency control using EV participation
[9]	Rakhshani et al., 2016	HVDC interconnected systems	Virtual inertia controller (VSP)	Improved inertia emulation and frequency stability
[11]	Shayeghi et al., 2016	Multi-source system with DG	FOPID Controller	Superior dynamic response under high renewable penetration



[12]	Tada et al., 2017	Solar-wind integrated system with HVDC	HVDC flow control	Significant improvement in frequency stability
[13]	Shankar et al., 2017	Conventional & modern power systems	Review of LFC mechanisms	Identified transition to intelligent and adaptive LFC strategies
[16]	Pathak et al., 2018	Multi-area system with HVDC tie-links	HVDC-AGC modeling	Enhanced frequency regulation via coordinated AC/DC control
[17]	Tavakoli et al., 2018	Wind-integrated multi-terminal HVDC	Coordinated LFC strategy	Improved dynamic performance and renewable integration
[19]	Debbarma & Shrivastwa, 2018	Nonsynchronous units with V2G & HVDC	V2G-based frequency support	Enhanced grid frequency support in hybrid systems
[21]	Murali & Shankar, 2019	Interconnected system with HVDC	Inertia emulation control	Reduced frequency deviations and improved stability
[22]	Niino et al., 2019	Wind farm with HVDC interconnection	Virtual Synchronous Generator (VSG)	Improved dynamic stability and inertia support
[24]	Prakash et al., 2019	AC/DC tie-line LFC system	I-PDF Controller	Faster settling and reduced overshoot
[25]	Onuka et al., 2019	Renewable system with HVDC & battery	Coordinated control	Enhanced transient frequency performance
[27]	Pan et al., 2020	Hybrid AC/HVDC systems	Cyber-attack detection analysis	Highlighted vulnerability of LFC under false data injection
[29]	Ali et al., 2020	Hybrid renewable plants	Optimized MPC (MVO)	Improved optimization and frequency regulation accuracy
[30]	Lin & Wu, 2021	VSC-HVDC wind farm	Frequency control technologies	Fast controllability and virtual inertia support



[31]	Babu et al., 2021	Wind & battery integrated systems	LFC with energy storage	Improved frequency response with storage support
[32]	Shouran et al., 2021	Modern power systems	State-of-the-art review	Identified need for adaptive and intelligent LFC
[33]	Elmelegi et al., 2021	Renewable-based systems	Tilt Fractional Order Controller	Robust frequency stabilization under uncertainties
[35]	Lee et al., 2022	Hybrid LCC-VSC HVDC systems	Communication-free control	Reliable frequency and voltage regulation
[36]	Meseret et al., 2022	Hydrothermal-wind system with HVDC	Intelligent optimized controller	Enhanced dynamic and steady-state performance
[37]	Roy et al., 2022	AGC & HVDC systems	ML-based multi-agent system	Cyber-attack detection and resilient control
[38]	Kamarposhti et al., 2022	Hydro-thermal with wind & HVDC	Optimized Fuzzy-PID	Improved damping and frequency stability
[40]	Khan et al., 2023	AC/HVDC multi-area with storage	Golden Eagle Optimization	Improved robustness and frequency stability
[41]	Yan et al., 2023	Low-inertia renewable systems with HVDC	Review of frequency control	Emphasized coordinated and advanced LFC frameworks
[43]	Kalyan et al., 2023	Combined LFC-AVR with HVDC	Integrated control strategy	Enhanced overall grid stability
[45]	Kouba & Sadoudi, 2023	Islanded microgrid with HVDC	Optimal Fuzzy-PID + HESS	Effective frequency control in microgrids
[49]	Presekal et al., 2024	HVDC systems cybersecurity	Cybersecurity review	Identified threats and defense strategies in HVDC-LFC



[52]	Zhang et al., 2024	Dual-link LFC under cyber-attacks	Adaptive event-triggered control	Improved resilience against mixed attacks
[53]	Trinh et al., 2024	Modern interconnected systems	State-space LFC strategy	Enhanced stability and robustness
[60]	Omar et al., 2026	Renewable multi-area systems	Hybrid Fuzzy-PIDD <sup>2</sup> Controller	Superior coordinated LFC and AVR performance
[62]	Nguyen et al., 2026	Interconnected power systems	Improved LFC design	Enhanced frequency regulation and stability
[63]	Ramesh et al., 2026	Renewable system with EV aggregators	Robust PI-type LFC	Improved performance under delays and EV participation
[64]	Thorat & Bhatt, 2026	Multi-area restructured system	EV-based optimized LFC	Effective frequency control using EV support

**Summary of Literature:**

The surveyed literature reveals that LFC in modern power systems has evolved significantly due to the increasing penetration of renewable energy sources, HVDC interconnections, energy storage units, and electric vehicles as portrayed in Fig 1. Early studies (2013–2016) primarily focused on conventional LFC models, stability criteria, and classical controllers such as PID and model predictive control for multi-area systems with time delays and HVDC links. Researchers also investigated distributed functional observers, fuzzy-PID, and fractional-order controllers to enhance dynamic performance and robustness in interconnected power systems with diverse transmission links and distributed generation.

Between 2017 and 2019, the research direction shifted toward renewable-integrated and multi-source power systems, where HVDC tie-lines, virtual synchronous generators, and inertia emulation techniques were introduced to address low-inertia challenges. Several works emphasized coordinated control of HVDC links, batteries, and wind farms to improve frequency stability. Additionally, advanced control approaches such as LQR, I-PDF controllers, and coordinated AC/DC tie-line control were proposed to achieve faster settling time and reduced frequency deviation under fluctuating renewable power inputs.

From 2020 onwards, the literature increasingly explored intelligent and optimization-based LFC strategies, including multi-verse optimizer, golden eagle optimization, and hybrid energy storage-supported controllers. Researchers also examined cyber-physical aspects such as false data injection attacks and cybersecurity of HVDC and AGC systems, highlighting the vulnerability of modern interconnected grids. Reviews during this period emphasized the importance of frequency regulation in low-inertia systems dominated by inverter-based renewable resources and VSC-HVDC transmission.

Recent studies (2022–2026) demonstrate a strong trend toward hybrid intelligent controllers, machine learning-based multi-agent systems, adaptive event-triggered control, and AI-assisted optimization techniques for LFC in renewable-integrated multi-area power systems. The integration of energy storage systems, electric vehicle aggregators, and hybrid AC/HVDC transmission has been shown to significantly enhance frequency regulation and resilience. Moreover, emerging research focuses on coordinated LFC-AVR control, robust PI-type controllers, and nature-inspired optimization algorithms to handle uncertainties, communication delays, and cyber-attacks. Overall, the literature

indicates a transition from conventional centralized control to intelligent, distributed, and cyber-secure LFC frameworks capable of maintaining frequency stability in complex, renewable-rich, and HVDC-connected modern power grids.

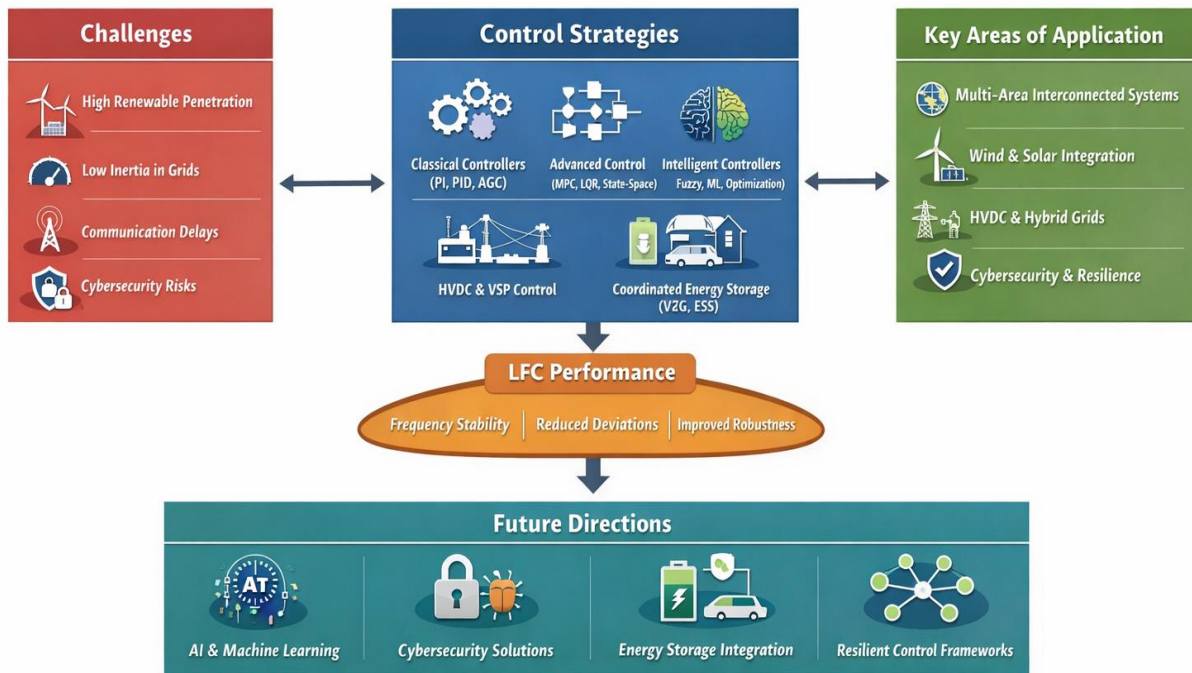


Fig 1: Conceptual framework of LFC in renewable-integrated and HVDC-connected power systems.

### III. CONCLUSION

This review has comprehensively examined the developments in LFC for renewable-integrated and HVDC-connected power systems, highlighting the transition from conventional control strategies to advanced, intelligent, and coordinated control frameworks. The increasing penetration of renewable energy sources, inverter-based resources, electric vehicles, and hybrid AC/DC transmission networks has introduced significant challenges such as reduced system inertia, intermittency, communication delays, and cyber vulnerabilities, which directly affect frequency stability and dynamic performance. The surveyed studies demonstrate that HVDC links, virtual inertia control, energy storage systems, and coordinated secondary control schemes play a crucial role in enhancing frequency regulation in multi-area power systems.

Furthermore, the literature indicates that traditional PI/PID controllers are gradually being replaced or augmented by fractional-order, adaptive, model predictive, and optimization-based controllers to achieve improved robustness, faster settling time, and better disturbance rejection under variable operating conditions. The integration of artificial intelligence, machine learning, and nature-inspired optimization algorithms has shown promising results in handling nonlinearities, uncertainties, and complex interactions in modern power grids. In addition, recent research emphasizes the importance of cyber-secure and distributed control architectures to mitigate false data injection attacks and ensure reliable operation of AGC and HVDC systems in smart grids.

Despite significant progress, several research gaps remain, including the need for unified control frameworks for hybrid AC/DC grids, real-time implementation of AI-driven LFC schemes, and coordinated control of multiple energy storage and renewable units under high penetration scenarios. Future research should focus on developing resilient, adaptive, and cyber-secure LFC strategies incorporating digital twins, multi-agent systems, and advanced forecasting techniques to address low-inertia and high-uncertainty environments. Overall, an intelligent, coordinated, and secure LFC framework supported by HVDC technology and renewable integration is essential for maintaining frequency stability and ensuring reliable operation of next-generation sustainable power systems.



## Nomenclature:

LFC	Load Frequency Control
HVDC	High Voltage Direct Current
LCC	Line Commutated Converter
VSC	Voltage Source Converter
RES	Renewable Energy Sources
ESS	Energy Storage System
EV	Electric Vehicle
V2G	Vehicle-to-Grid
SMES	Superconducting Magnetic Energy Storage
AVR	Automatic Voltage Regulator
MPC	Model Predictive Control
FOPID	Fractional Order Proportional–Integral–Derivative Controller
VSG	Virtual Synchronous Generator
VSP	Virtual Synchronous Power
HESS	Hybrid Energy Storage System
DG	Distributed Generation
IBR	Inverter-Based Resources

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