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MATHEMATICAL MODELS FOR CONTROLLING ACTIVE EMERGENCY FREQUENCY AND POWER REGULATORS IN POWER SYSTEMS WITH POTENTIAL INTEGRATION OF WIND AND SOLAR POWER PLANTS. PRIORITY DIRECTIONS

Abstract. *The rapid integration of renewable energy sources (RES), such as wind power plants (WPPs) and solar power plants (SPPs), into modern Integrated Power Systems (IPS) has introduced new challenges and opportunities for grid stability and control. One critical aspect of power system operation is the regulation of controlling active emergency frequency and power regulators (EFPR). EFPR plays a pivotal role in this process, and its effective operation is increasingly dependent on advanced mathematical models that account for the dynamic and intermittent nature of RES. The article emphasizes the importance of interdisciplinary research, combining power system engineering, applied mathematics, and data science, to develop innovative solutions for the challenges of modern power systems. The development of advanced mathematical models for EFPRs is essential for ensuring the stability and reliability of power systems in the era of renewable energy. An overview of mathematical models and approaches used to control active emergency frequency and power regulators in power systems with potential participation of wind and solar power plants is presented. Priority areas for possible research and development are highlighted.*
Keywords: renewable energy sources, Integrated Power Systems, grid stability and control, active emergency frequency and power regulators, mathematical models.

1. Introduction

The integration of renewable energy sources (RES), such as wind power plants (WPPs) and solar power plants (SPPs), into power systems has introduced new complexities in maintaining grid stability, particularly during emergency conditions. Frequency and power regulation are critical aspects of power system operation, ensuring that supply and demand remain balanced even during disturbances. Emergency frequency and power regulators (EFPRs) are essential for mitigating the effects of sudden imbalances, which can be exacerbated by the intermittent and variable nature of RES (Fig. 1) [1−3].

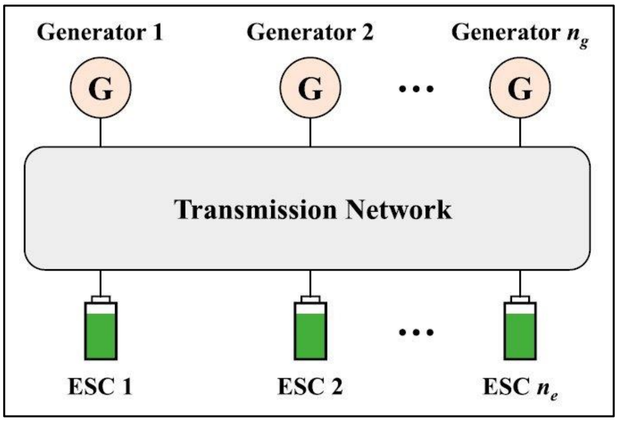

Fig. 1. Topology of the power system with energy storage clusters (ESC) [1]

This article explores the mathematical models used for controlling active EFPRs in power systems with the potential integration of WPPs and SPPs, highlighting priority directions for research and development.

EFPRs are designed to respond rapidly to frequency deviations and power imbalances caused by sudden changes in generation or load (Fig. 2).

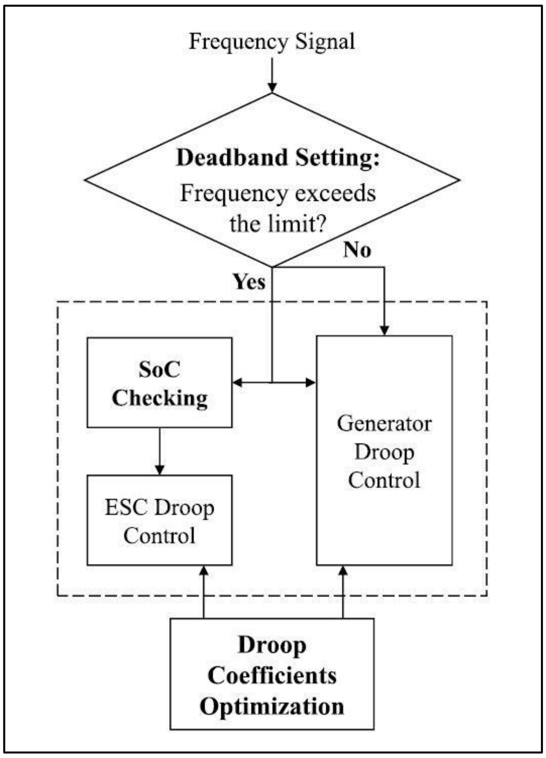

Fig. 2. Framework of the optimal-droop-based frequency emergency control (FEC) [1]

These systems typically involve:

- Primary Control: Immediate response from governors and inertial responses to stabilize frequency.
- Secondary Control: Automatic Generation Control (AGC) to restore frequency to its nominal value.
- Tertiary Control: Economic dispatch and long-term adjustments to optimize system operation.

The aim of the research is a review of the mathematical models used for controlling active emergency frequency and power regulators in power systems, with the potential involvement of WPPs and SPPs. Highlighting priority directions for research and development.

With the increasing penetration of WPPs and SPPs, which lack inherent inertia and are subject to rapid fluctuations, the role of EFPRs has become more challenging. Advanced mathematical models are required to ensure effective control under these conditions.

Mathematical Models for EFPRs in RES-Integrated Power Systems

The integration of RES necessitates the development of sophisticated mathematical models [4−10], that account for their unique characteristics, such as variability, uncertainty, and lack of inertia. Below are key modeling approaches for EFPRs:

Dynamic Frequency Response Models

Dynamic frequency response models are critical for understanding how EFPRs can mitigate frequency deviations caused by RES variability. These models typically include:

- Differential equations representing the dynamics of synchronous generators, loads, and RES [2].
- Inertia emulation models for WPPs and SPPs to simulate synthetic inertia (Fig. 6,7) [11].
- Stochastic models to account for the uncertainty in wind speed and solar irradiance (Fig. 3) [12].

Model Predictive Control (MPC)

MPC is a powerful tool for optimizing EFPR operation over a finite time horizon [13]. Key features include:

- Prediction of RES generation and load demand using time-series data [14].
- Incorporation of system constraints and operational limits.
- Real-time adjustment of control actions to minimize frequency deviations and power imbalances (Fig. 4) [15].

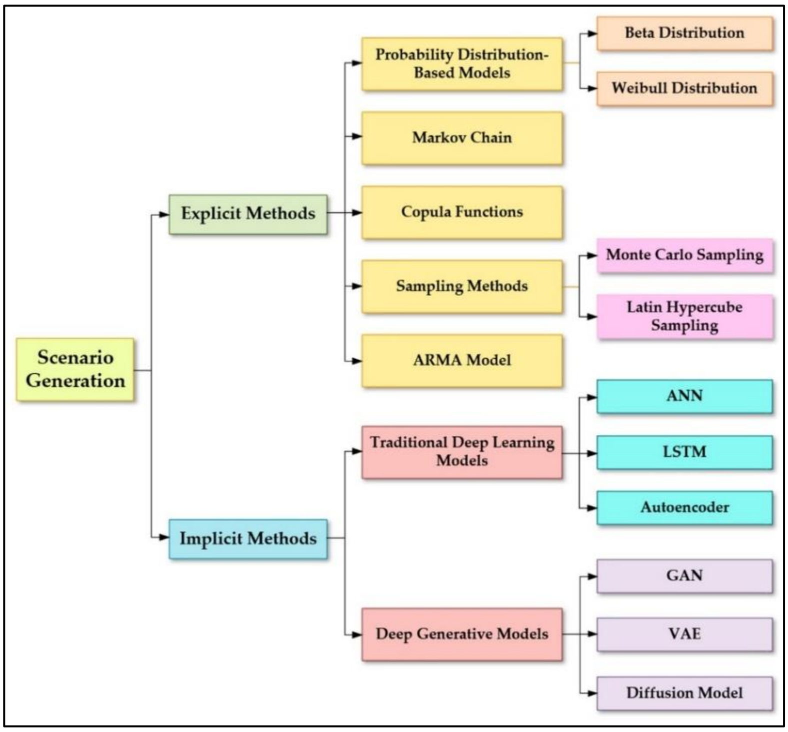

Fig. 3. Classification of scenario generation methods [12]

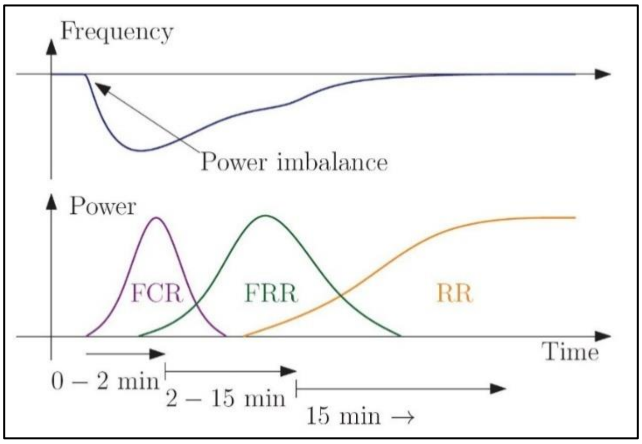

Fig. 4. Activation of frequency containment reserve (FCR), frequency restoration reserve (FRR) and replacement reserve (RR) after power imbalance [15]

Optimal Power Flow (OPF) with Emergency Constraints

OPF models [16] are extended to include emergency constraints for EFPRs. These models involve:

– Nonlinear constraints representing power flow equations during disturbances.
– Objective functions that minimize frequency deviations, load shedding, or operational costs.
– Integration of RES forecasts to improve the accuracy of emergency control actions.

Data-Driven and Machine Learning Models

Data-driven approaches leverage historical and real-time data to enhance EFPR performance. These models include:

– Prediction of frequency deviations and power imbalances using machine learning algorithms (Fig. 5) [17].
– Identification of optimal control strategies using reinforcement learning [18].
– Enhanced fault detection and diagnosis in EFPR systems.

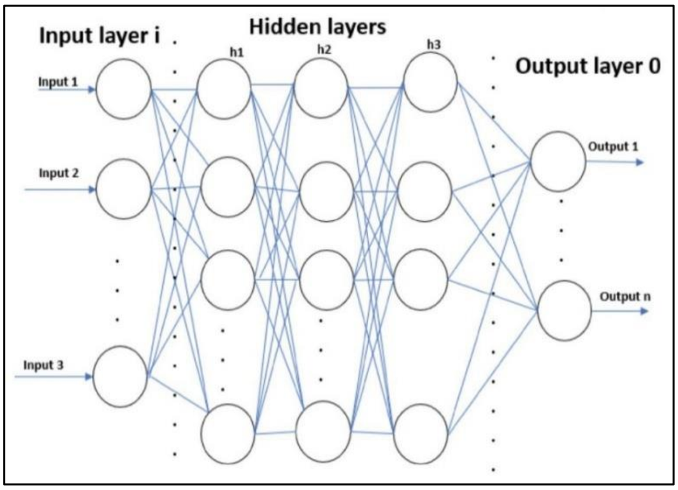

Fig. 5. Neural network architecture [17]

Priority Directions for Research and Development

To address the challenges posed by RES integration, several priority directions have emerged in the development of mathematical models for EFPRs:

Synthetic Inertia and Fast Frequency Response

WPPs and SPPs lack the inherent inertia of conventional generators, making frequency regulation more challenging. Research should focus on:

– Developing models for synthetic inertia and fast frequency response from RES [11].
– Integrating these models into EFPR control strategies.

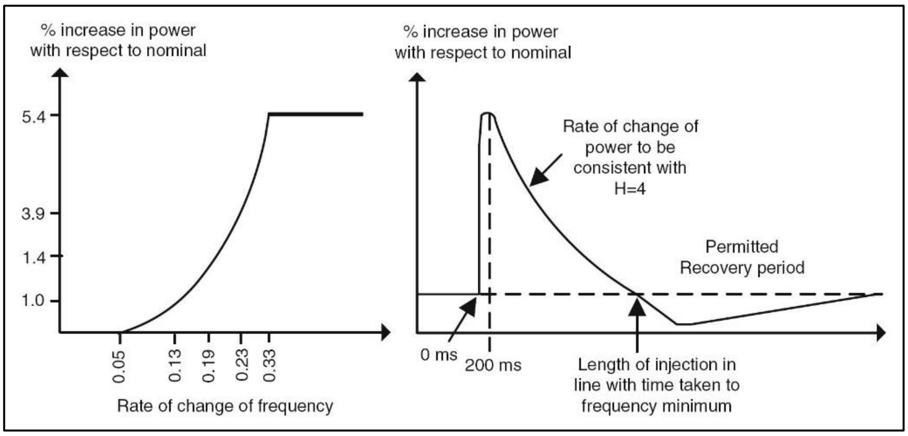

Fig. 6. Proposed synthetic inertia from wind turbines [11]

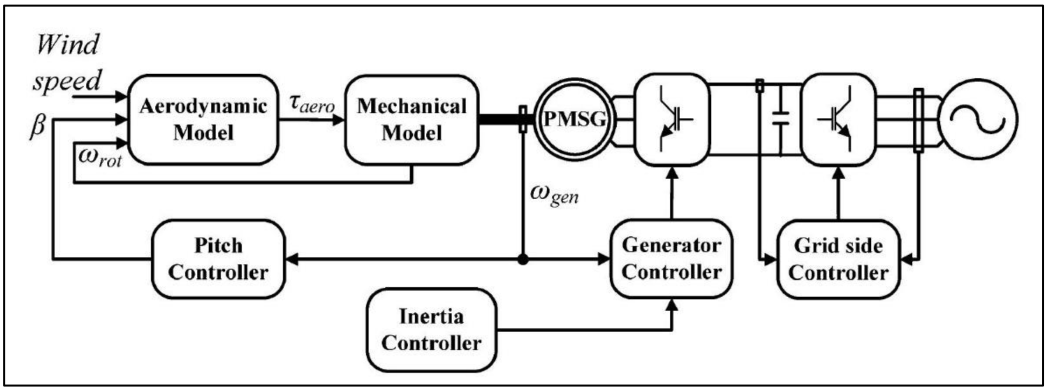

Fig. 7. Schematic diagram of full-rated power converter (FRPC) – permanent magnet synchronous generator (PMSG) wind turbine implemented in Simulink [11]

Enhanced Uncertainty Modeling

The variability of WPPs and SPPs introduces significant uncertainty into power system operation. Advanced probabilistic and robust optimization techniques are needed to account for this uncertainty in EFPR models.

Coordination Between EFPRs and RES Inverters

Modern WPPs and SPPs are equipped with power electronic inverters that can provide fast frequency response. Developing models that enable seamless coordination between EFPRs and RES inverters is crucial for maximizing grid stability.

Paper [19] presents an innovative approach for real-time emergency voltage control strategies for transient stability enhancement through the integration of edge-graph convolutional networks with reinforcement learning. Thus, a method is proposed that allows you to transform the traditional problem of optimizing emergency management, replacing it with a sequential decision-making process.

Real-Time Implementation

The transition from offline models to real-time control systems is a key challenge. Research efforts should focus on developing computationally efficient algorithms that can be implemented in real-time EFPR systems. The study [20] first analyzes the optimal solution for a single-zone system and then extends it to a two-zone interconnected system. In many cases, traditional control methods are applied without considering the potential advantages of using Genetic Algorithm (GA) for various Load Frequency Control (LFC) in interconnected networks. By examining the effectiveness of these intelligent optimization methods in both single and interconnected power systems, this study aims to enhance the understanding of their applicability and performance in real-world scenarios. The research methodology includes a comprehensive analysis of various LFC strategies, including traditional methods and those optimized using GA and Particle Swarm Optimization (PSO).

Resilience to Cyber Threats

As EFPRs become more reliant on digital communication and control systems, ensuring their resilience to cyber threats is critical. Mathematical models should incorporate cybersecurity considerations to protect against potential attacks. Intrusion Detection and Prevention (IDP) systems are very important for Cyber-Physical System (CPS) security because they watch for and respond to cyber dangers in real time (Fig. 8) [21].

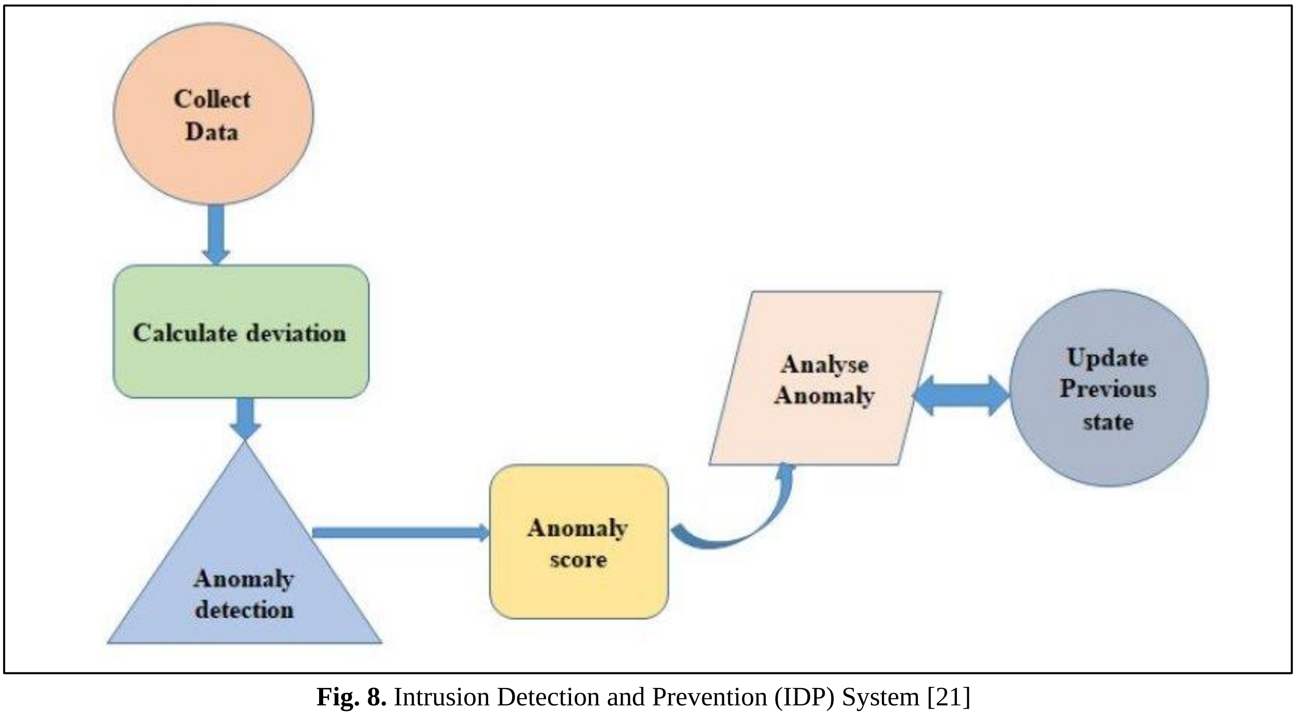

Fig. 8. Intrusion Detection and Prevention (IDP) System [21]

Integration with Energy Storage Systems

Energy storage systems (ESS) can provide additional flexibility for frequency and power regulation. Developing models that integrate EFPRs with ESS is a promising area of research (Fig. 9) [22, 23].

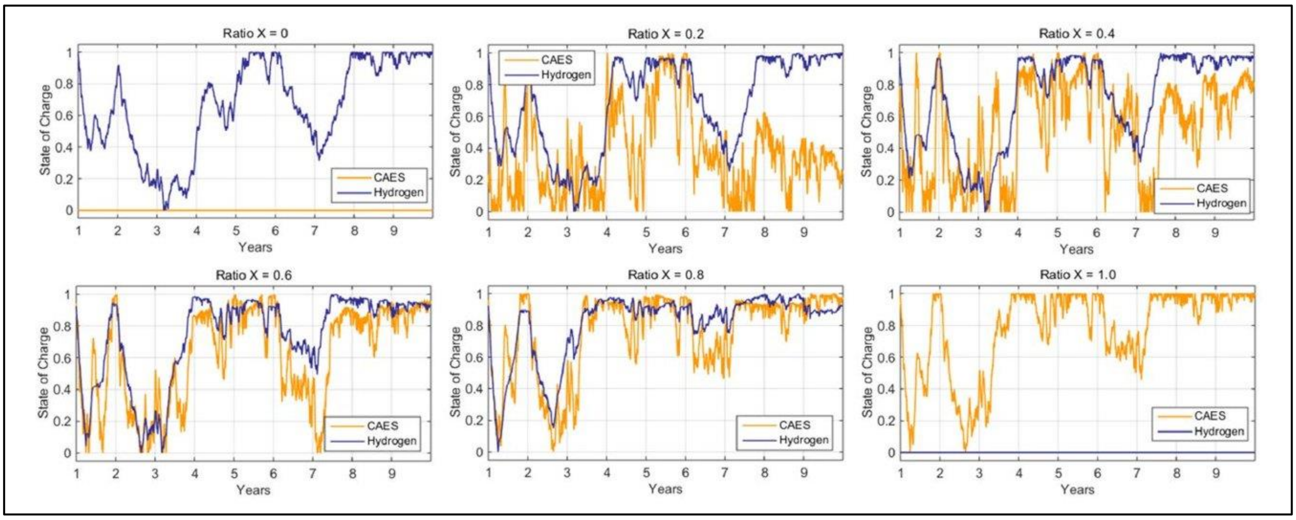

Fig. 9. Comparison of the state of charge for some energy storage devices for different ratios of their capacity [22]

4. Discussion

The increasing penetration of renewable energy sources (RES), particularly wind power plants (WPPs) and solar power plants (SPPs), has significantly transformed power system dynamics. This transition has necessitated the development of advanced mathematical models for controlling active emergency frequency and power regulators (EFPRs) to maintain grid stability. This discussion highlights key findings, implications, and future research directions based on the review of mathematical models for EFPRs.

One of the most critical challenges in EFPR control is the variability and intermittency of RES. Unlike conventional generators, WPPs and SPPs lack inherent inertia, making power systems more susceptible to frequency deviations and sudden imbalances. The development of synthetic inertia and fast frequency response mechanisms has emerged as a promising solution. However, these solutions require further refinement to enhance their accuracy and effectiveness in real-time applications.

The inclusion of Model Predictive Control (MPC) and Optimal Power Flow (OPF) techniques has demonstrated significant potential in improving EFPR response under emergency conditions. However, these methods require high computational capabilities and real-time data integration. Future research should focus on developing more efficient algorithms that reduce computational complexity while maintaining high accuracy in predicting system responses.

The increasing reliance on data-driven approaches, including machine learning and artificial intelligence, presents both opportunities and challenges. Machine learning models, such as neural networks and reinforcement learning, can enhance EFPR decision-making by predicting frequency deviations and optimizing control strategies. However, the reliability of these models depends on the quality and availability of real-time data. To improve robustness, hybrid approaches that integrate traditional control methods with machine learning should be explored.

Additionally, the cybersecurity vulnerabilities associated with data-driven EFPR systems require further investigation. As EFPRs become more reliant on digital communication and automated control, they are increasingly susceptible to cyber threats. Future research should prioritize the development of intrusion detection and prevention (IDP) systems that can safeguard EFPR operations from potential cyberattacks.

Energy storage systems (ESS) have been identified as a crucial component in enhancing EFPR performance. By providing additional flexibility, ESS can help mitigate the impact of RES variability and improve the reliability of emergency frequency response mechanisms. However, optimizing the coordination between EFPRs and ESS remains a challenge. Advanced mathematical models should incorporate ESS characteristics, such as state of charge, response time, and degradation factors, to maximize their effectiveness in real-time frequency control.

Based on the reviewed mathematical models, the following priority research directions have been identified:

1. Development of Hybrid Control Strategies: Combining traditional EFPR methods with machine learning and optimization algorithms can enhance response accuracy and adaptability under dynamic grid conditions.

2. Enhanced Probabilistic and Stochastic Modeling: Addressing the uncertainty in RES generation through advanced probabilistic models can improve the robustness of EFPR strategies.

3. Cybersecurity-Integrated Control Mechanisms: Strengthening cybersecurity measures within EFPR systems to protect against cyber threats and ensure secure grid operation.

4. Real-Time Implementation and Computational Efficiency: Reducing computational burdens while maintaining the accuracy of EFPR models for real-time applications.

5. Seamless Coordination Between EFPRs, RES Inverters, and ESS: Developing integrated models that enable efficient interaction between EFPRs, RES inverters, and energy storage solutions to optimize power system stability.

The successful implementation of these research directions will significantly contribute to the development of resilient and adaptive EFPR systems, ensuring the stability and reliability of modern power grids in the era of renewable energy.

5. Conclusion

The integration of renewable energy sources, particularly WPPs and SPPs, has introduced new challenges for maintaining power system stability. The role of EFPRs in mitigating frequency deviations and power imbalances has become increasingly critical in modern power systems. This article reviewed various mathematical models that enhance the effectiveness of EFPRs, including dynamic frequency response models, Model Predictive Control, Optimal Power Flow approaches, and data-driven techniques.

Advanced mathematical modeling is essential to address the variability and uncertainty of RES. The inclusion of synthetic inertia, enhanced probabilistic modeling, and machine learning-based control strategies can significantly improve EFPR performance. Additionally, the integration of ESS and cybersecurity measures will further enhance system resilience.

Future research should focus on real-time implementation, computational efficiency, and seamless coordination between EFPRs, RES inverters, and energy storage systems. By advancing these areas, power system operators can ensure reliable and stable grid operation in the face of increasing renewable energy penetration. The continued development of sophisticated mathematical models will be instrumental in achieving a sustainable and secure energy future.

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МАТЕМАТИЧНІ МОДЕЛІ КЕРУВАННЯ АКТИВНИМИ АВАРІЙНИМИ РЕГУЛЯТОРАМИ ЧАСТОТИ ТА ПОТУЖНОСТІ В ЕНЕРГОСИСТЕМАХ З ПОТЕНЦІЙНОЮ ІНТЕГРАЦІЄЮ ВІТРОВИХ ТА СОНЯЧНИХ ЕЛЕКТРОСТАНЦІЙ. ПРІОРИТЕТНІ НАПРЯМКИ

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Анотація. *Швидка інтеграція відновлюваних джерел енергії (ВДЕ), таких як вітрові електростанції (ВЕС) та сонячні електростанції (СЕС), у сучасні об'єднані енергетичні системи (ОЕС) створила нові виклики та можливості для стабільності та контролю мережі. Одним з найважливіших аспектів роботи енергосистеми є управління активними аварійними регуляторами частоти і потужності (АРЧП). АРЧП відіграють ключову роль у цьому процесі, і їх ефективна робота все більше залежить від передових математичних моделей, які враховують динамічний та переривчастий характер ВДЕ. У статті наголошується на важливості міждисциплінарних досліджень, що поєднують інженерію енергетичних систем, прикладну математику та науку про дані, для розробки інноваційних рішень для подолання викликів сучасних енергосистем. Розробка передових математичних моделей для АРПЧ має важливе значення для забезпечення стабільності та надійності енергосистем в епоху відновлюваної енергетики. Представлено огляд математичних моделей та підходів, що використовуються для керування активними аварійними регуляторами частоти та потужності в енергосистемах за потенційної участі вітрових та сонячних електростанцій. Виділено пріоритетні напрями можливих досліджень і розробок.*

Ключові слова: відновлювані джерела енергії, інтегровані енергосистеми, стабільність та управління мережею, активні аварійні регулятори частоти та потужності, математичні моделі.

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