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ADAPTIVE UNDER-FREQUENCY LOAD SHEDDING: A CHRONOLOGICAL REVIEW

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Abstract:

With the development of power systems, Adaptive Under-Frequency Load Shedding (AUFLS) has become an important protection method to ensure frequency stability after severe disturbances and generation-load imbalances. Typical Under-Frequency Load Shedding (UFLS) schemes, however, are usually fixed at frequency thresholds and in load shedding, offering little flexibility in the face of varying operating conditions, renewable energy penetration, and lower system inertia. This study is a chronological literature review that explores the development, methodology, and new research trends of AUFLS. Scopus database was systematically searched for the following terms: "Under-Frequency Load Shedding (UFLS)," "Adaptive Under-Frequency Load Shedding (AUFLS)," "Fast Frequency Response (FFR)," "frequency stability," "curtailment," and "Rate of Change of Frequency (RoCoF)." After completing the literature screening process, 51 primary publications were selected for chronological analysis to identify three phases: (1) Foundational and Early Exploration (2007-2013), (2) Research Expansion and Methodological Development (2014-2019), and (3) Research Intensification and Emerging Directions (2020-2027). The results demonstrate a gradual shift towards adaptive protection, which incorporates RoCoF measurements, Phasor Measurement Units

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(PMUs), Wide-Area Measurement Systems (WAMS), Artificial Intelligence (AI), and advanced optimisation methods. While earlier work concentrated on enhancing load shedding decisions and frequency recovery, recent work has begun to address decentralised protection, uncertainty in renewable energy resources, intelligent decision-making, and computational efficiency. New trends further highlight the importance of accurate frequency-nadir estimation, selective load disconnection, and adaptive protection under low-inertia operating conditions. In general, it is concluded that there is substantial improvement in the methodologies used in AUFLS research and there are opportunities to combine FFR resources, energy storage systems, and coordinated adaptive protection to improve power system frequency resilience.
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Keyword:

Adaptive Under-Frequency Load Shedding; Frequency Stability; Rate of Change of Frequency; Fast Frequency Response; Chronological Literature Review; Power System Protection.

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Introduction

Adaptive Under-Frequency Load Shedding (AUFLS) has become an important approach to ensure power system stability during severe disturbances that cause significant generation-load mismatches. A typical Under-Frequency Load Shedding (UFLS) scheme was based on a fixed frequency threshold and predetermined load shed steps. Although simple and easy to implement, this approach could lead to over-shedding or under-shedding (Maresch et al., 2023; Ning et al., 2011). This inflexibility might cause unnecessary power outages or fail to prevent system collapse during significant contingencies (Abdelwahid et al., 2014; Zhang & Zhong, 2006).

As the power system became more complex and interconnected, the conventional UFLS methods were revealed to be increasingly inadequate (Ning et al., 2011). However, with the increasing complexity and volatility of today's power systems, especially as renewable energy sources are added and distributed generation becomes more prevalent, fixed-parameter schemes have proven inadequate. These changes increased variability and uncertainty, making more responsive and intelligent load-shedding methods necessary (Gautam et al., 2020; Pasand & Seyedi, 2007).

To address this, AUFLS schemes have been developed. Unlike traditional methods, adaptive methods dynamically adjust both the frequency thresholds and the amount of load to be shed in real time based on system conditions. Fuzzy logic controllers, synchrophasor measurements, and Empirical Mode Decomposition (EMD) have been applied to improve the adaptability and accuracy of these schemes (Muftić Dedović et al., 2024; Tiguercha et al., 2023). AUFLS can

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adaptively adjust load-shedding actions based on continuous monitoring of system parameters and estimation of disturbance severity. This allows the actions to be tailored to the real needs of the system, reduce the risk of unnecessary load shedding, and improve system resilience (Da Silva & Assis, 2018; Kulkarni et al., 2010; Seyedi et al., 2005).

With the development of AUFLS, advanced measurement and communication technologies have also been introduced. More centralized and coordinated control strategies have been implemented through Wide-Area Measurement Systems (WAMS), Phasor Measurement Units (PMUs), and Supervisory Control and Data Acquisition/Energy Management System (SCADA/EMS) platforms (Boussadia & Belkhiat, 2021; J. D. Wang et al., 2013). These technologies enable rapid identification of system imbalances, finer granularity, and geographically selective load shedding, as well as the use of more advanced algorithms that incorporate frequency and voltage stability concepts (Chandra & Pradhan, 2021; G. Wang et al., 2012).

The evolution from static, experience-based load shedding to dynamic, data-driven load shedding demonstrates a shift from experience-based to data-driven approaches. This development has been fueled by the requirement to improve the security and reliability of power systems as they are confronted with the challenges of their operation (Rudez & Mihalic, 2011b; Shekari et al., 2018). Despite this, the AUFLS remain an active research field, and current projects are aimed at enhancing the responsiveness, accuracy, and integration of AUFLS with other grid protection and control solutions (Alipour & Seyedi, 2017; H. Yang et al., 2013). Figure 1 illustrates the key factors identified from previous studies, highlighting the limitations of conventional UFLS schemes, the development of adaptive load-shedding approaches, and the evolution of enabling technologies that support improvements in power system stability and resilience.

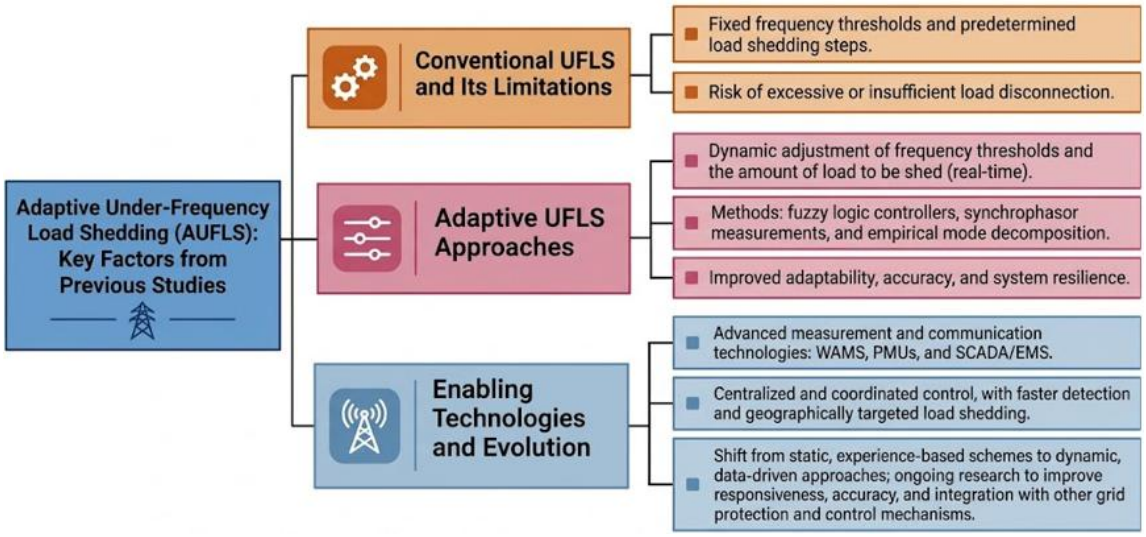


Figure 1: Summary Of Key Factors from Previous Studies.

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Materials and Methods

Data Collection

Data collection is an important part of the chronological review, as it determines the reliability, relevance, and comprehensiveness of the selected literature. This study uses Scopus as the main database, as it covers the widest range of peer-reviewed publications in engineering and related energy fields. Following this, a systematic search procedure was developed and defined using keywords related to UFLS, AUFLS, Fast Frequency Response (FFR), Frequency stability, Curtailment, and Rate of Change of Frequency (RoCoF). This systematic scheme allows the study of the historical development of load-shedding approaches, important technical advances in new technologies and research topics, and gaps in the power system frequency stability field. The data collection process began with formulating a search string based on relevant keywords identified in the Scopus database, which was then used with Boolean operators (AND and OR). Only the titles of the publications were searched, and publications that met the predetermined inclusion and exclusion criteria were selected. Only English-language publications in Engineering (ENGI) and Energy (ENER) were considered. Other subject areas and languages that were not related were excluded. A total of 51 main articles were identified for the chronological review (Table 1). These publications form the foundation for the evolution of conventional UFLS techniques into adaptive load-shedding techniques that include FFR and advanced control and describe important methodological advances and directions for future research.

Table 1: Search Strategy and Eligibility Criteria for AUFLS Literature

Keyword	**Under-Frequency Load Shedding, UFLS, AUFLS, FFR, frequency stability, curtailment, RoCoF**
Inclusion	English, Engineering, Energy
Exclusion	Social Science, Pure science, other languages
Final Search String (Scopus)	TITLE ((("under-frequency load shedding" OR "under-frequency load shedding" OR UFLS OR AUFLS) AND (adaptive OR "fast frequency response" OR FFR OR "frequency stability" OR curtailment OR RoCoF))) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "ENER")) AND (LIMIT-TO (LANGUAGE , "English"))
Number of Primary Articles	51

Data Clustering

Clustering is an indispensable analytical method for conducting a chronological review, as it enables the systematic identification and interpretation of research trends, publishing dynamics, and shifts in scientific interest over time. To ensure the literature retrieved for this study is relevant and reliable, advanced search strategies were employed in Scopus. The publications are clustered into time slices based on the number of publications per year, providing a structured view of changes in research output, periods of growth and fluctuation, and emerging scholarly interest. This classification provides a clearer picture of the

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development of research activity, marking the evolution from early exploration to expanded research and then to increased scientific inquiry. In addition, temporal clustering helps make publication patterns easier to interpret by identifying periods of publication activity that are relatively low and those that are relatively high. This approach provides the basis for contextualizing the chronological evolution of AUFLS research, identifying potential shifts in research priorities, and informing subsequent analyses of methodological developments, new technologies, and future directions.

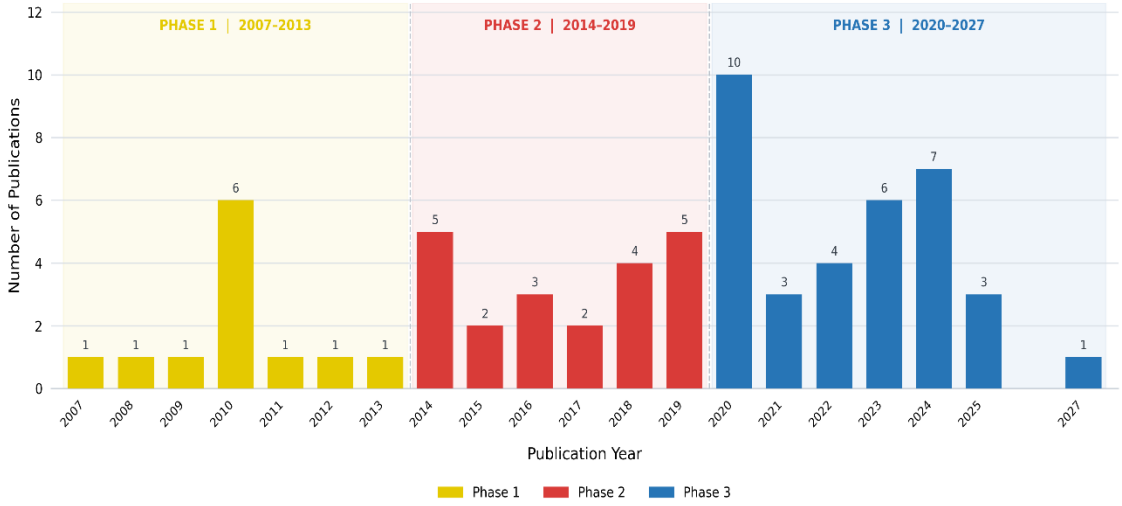


Figure 2: Clustering Documents By Year.

Phase I: Foundational and Early Exploration (2007-2013)

The first phase is the initial research stage of AUFLS, during which relatively few, less frequent publications were published. A total of 12 publications were recorded, comprising approximately 17.9% of the data for the 2007-2013 period. The number of publications has been about one per year, except for an exceptionally high six in 2010. This distribution indicates that research interest is still developing and that annual research productivity reflects little continuity. Thus, this time frame is an ideal opportunity to review and examine what laid the initial groundwork for the research and the challenges that prompted future investigations into adaptive load-shedding strategies.

Phase II: Research Expansion and Methodological Development (2014-2019)

The second phase is a time of growing research activity and greater scholarly focus on AUFLS. A total of 21 publications were identified from 2014 to 2019 (about 31.3%). Publication rates ranged from two to five articles per year, suggesting a more consistent research presence than in earlier stages. Notably, there were five publications over the last two years (2014 and 2019) and four publications in 2018. The annual distribution did not demonstrate continuous growth, but the higher average publication volume suggests greater involvement in research. This phase lays the foundation for an analysis of methodological diversification and the evolution of more advanced load-shedding methods, which are examined in detail through a literature review.

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Phase III: Research Intensification and Emerging Directions (2020-2027)

The third phase is the most productive in terms of published research, with 34 publications, which is about 50.7% of the total. In 2020, the number of publications rose significantly, reaching a high of 10, the highest figure of the year. Subsequently, although the number of publications decreased to three in 2021, research activity gradually recovered, with six publications in 2023 and seven in 2024. These oscillations indicate not uninterrupted growth but rather enhanced (but nonlinear) research activity. This period provides an opportunity to review recent research interests, new techniques and methods, and future avenues for research in adaptive frequency protection and load-shedding strategies.

Results and Discussion

Phase I: Foundational and Early Exploration (2007-2013)

The foundational and early exploration phase (2007-2013) focused on the basic development of AUFLS, with a focus on enhancing frequency stability, avoiding load shedding where it was not needed, and overcoming the drawbacks of existing protection schemes. Similarly, the following two centralised adaptive load-shedding algorithms for both frequency and voltage instability were studied by Pasand and Seyedi (2007). Several potential solutions were considered and assessed using a dynamic model of an actual power system, providing an initial indication of protection strategies that consider various stability situations. The study highlighted the need for integrated frequency and voltage protection during severe disturbances. However, the abstract did not demonstrate quantitative comparative results. The dataset contained no additional analyses for 2008 and 2009, implying no chronological evidence for those years.

During 2010, research reported further methodological advancements through analytical frequency assessment, optimal load selection, RoCoF-based control, and intelligent computational approaches. For example, Amjady and Fallahi (2010) emphasized the validity of an analytical frequency-stability boundary to set appropriate thresholds in UFLS relays for a four-unit test system. Meanwhile, Azab et al. (2010) revealed that adaptive selection of load-shedding locations based on wide-area load-shedding information yields significant benefits in minimizing the number of loads that become disconnected. Arulampalam and Saha (2010) demonstrated fast, smooth load shedding and restoration operations by implementing an RoCoF-based adaptive load shedding method, which was tested on the IEEE 12-bus system. The results support using dynamic frequency information to calculate the amount of load shedding and enhance the protection response. In contrast, another study by Moazzami and Khodabakhshian (2010) identified that an adaptive strategy based on an Artificial Neural Network (ANN) yields faster, more robust performance. It also better determines load-shedding requirements under various loading conditions than conventional methods. Moreover, the results indicated a progressive shift from fixed thresholds for frequency to adaptive strategies that involved disturbance characteristics, innovative algorithms, and better load shedding decisions.

During 2011-2013, further investigations included assessing adaptive protection efficiency, enhancing intelligent decision-making, and introducing synchronised system measurements. Protection efficiency assessments under system conditions have been conducted in Rudez and Mihalic (2011a), in which different AUFLS strategies have been compared against dynamic

power system models. Despite this, the abstract did not report specific numerical comparisons. For the New England power system, Hooshmand and Moazzami (2012) revealed that ANN-based adaptive load shedding performed well in terms of speed and robustness. At the same time, this approach can better determine load-shedding quantities under various operating conditions. The findings validated the effectiveness of adapting protection decisions by incorporating generation capacity, system loading, spinning reserve, and frequency reduction rate. Later, Yang et al. (2013) studied the AUFLS approach from a centralised perspective, using PMU-based information to estimate active power deficits and to calculate updated load-shedding-level requirements. Although the system was investigated under various disturbances on the IEEE 39-bus New England system, no quantitative performance improvements were reported in the abstract. The summary of results from 2007-2013 suggests a gradual evolution toward adaptive (measurement-based, computation-intelligent) frequency protection. The combination of analytical stability assessment, RoCoF measurements, ANN techniques, and PMU information laid the methodological foundations for further AUFLS research. Nevertheless, due to limited quantitative results and differences in the models used, direct performance comparisons across the reviewed studies are not possible.

Phase II: Research Expansion and Methodological Development (2014-2019)

The research and method development period (2014-2019) demonstrated great advancement in AUFLS, including decentralised protection, dynamic frequency assessment, intelligent optimisation, and renewable energy integration. A method for performing multi-agent decentralised load shedding to guarantee frequency stability in islanded distribution networks with limited communication was proposed by Gu et al. (2014). Following this, Shams et al. (2015) presented results from incorporating Dynamic Security Assessment (DSA) to better estimate minimum load-shedding requirements under various inertia and wind generation scenarios, thereby mitigating needless load-shedding. Likewise, Mollah and Nair (2015) studied the application of combined frequency indicators, namely RoCoF together with under-frequency, to the discrimination and flexibility of load blocks when adaptive protection is used. These developments indicated growing research interest in protection accuracy, minimizing unnecessary load shedding, and maintaining system frequency stability under different operating conditions.

The next advancements during 2016-2018 focused on power-deficit estimation, frequency recovery, and protection adaptability. Powell et al. (2016) demonstrated that power imbalance estimation using a modified swing equation-based adaptive scheme achieved within 2% of the true value. Frequency was restored to within 99.5% of normal in less than eight seconds. In the meantime, Shun et al. (2016) reported that dynamic optimisation of the IEEE 39-bus system, using WAMS data, reduced load shedding and enhanced frequency recovery. As renewable energy use increases, S. Li et al. (2017) revealed that equivalent inertia estimation and dynamic power deficit correction can be effective in integrating AUFLS strategies. The results align with the proposed findings: better adaptability to varying wind generation conditions, mitigation of frequency overshoot, and reduced unnecessary load shedding. Together, these studies indicated the growing importance of adaptive frequency protection in assessing load-shedding efficiency, generation uncertainty, and dynamic system characteristics.

More in-depth measurement technologies, smart algorithms, and uncertainty-based optimisation were themes of increasing focus in research during 2018-2019. PMU-based frequency and RoCoF measurements for local load shedding and restoration (Derviskadic et

al., 2018) were evaluated, and the results were used to compare measurement-based protection with conventional frequency-based protection. It was also investigated by Saboune et al. (2018), who proposed a Neuro-Evolution Algorithm to determine the adaptive requirements for load-shedding, and by Amraee et al. (2018), who introduced probabilistic optimisation with uncertainties in system inertia, load damping, and generation deficiency. In line with this, Banijamali and Amraee (2019) suggested a semi-adaptive protection strategy based on RoCoF to set load-shedding levels and apply credible generation-outage scenarios to a mixed-integer linear program. In another study, Elzawawy et al. (2019) reported that a combination of Genetic Algorithm (GA) optimisation and ANN can keep the frequency within acceptable limits under various disturbances. In some cases, it is necessary to disconnect part of the electric load. For instance, Rudez and Mihalic (2019) claimed to achieve better frequency response and fewer load disconnections using local measurement of RoCoF with traditional UFLS relays. Moreover, He et al. (2019) demonstrated the efficacy of decentralised adaptive load shedding using load information and the estimation of equivalent virtual inertia, thereby reducing reliance on centralised communication infrastructure. Overall, the results of the 2014-2019 campaigns suggest a shift towards more flexible, measurement-based, and potentially more computationally efficient classes of AUFLS strategies. The combination of RoCoF, WAMS, PMU, ANN, and optimisation techniques laid the foundations for improved frequency recovery, minimisation of unnecessary load shedding, and solutions to problems in modern power systems due to their increased complexity.

Phase III: Research Intensification and Emerging Directions (2020-2027)

The research intensification and emerging directions phase (2020-2027) demonstrated substantial advances in AUFLS, particularly through continuous load-shedding control, decentralised protection, intelligent optimisation, and improved frequency stability under changing power system conditions. C. Li et al. (2020) demonstrated the adaptability of continuous UFLS control under different operating conditions using the IEEE 39-bus system and Shandong power grid. Fazaeli et al. (2020b) reported improved protection performance through decentralised algorithms incorporating frequency, voltage, and RoCoF. Fazaeli et al. (2020a) investigated voltage-sensitive load-shedding strategies incorporating Static Synchronous Compensator STATCOM-supported operation. Horri and Mahdinia Roudsari (2020) established effective frequency recovery and load-shedding optimisation by considering load dynamics, interruption costs, and voltage corrective actions. Gautam et al. (2020) confirmed that sensitivity-based optimisation could identify suitable load-shedding locations and quantities to restore system stability. Bonetti et al. (2020) highlighted the importance of RoCoF measurement principles and relay standardisation. Zuo et al. (2020) examined how synchrophasor estimation algorithms affect measurement-based frequency protection and evaluated adaptive protection settings under operational uncertainty using a 24-hour scheduling framework. In general, these studies reflected increasing attention towards improving protection adaptability, measurement reliability, and load-shedding efficiency.

Research during 2021-2022 increasingly focused on dynamic frequency estimation, renewable energy integration, and adaptive protection under changing system inertia. Zhu et al. (2021) demonstrated that incorporating load response and primary frequency regulation into frequency-response modelling improved estimation accuracy and maintained frequency stability. Alwaini and Dini (2021) reported that a RoCoF-based AUFLS strategy restored the Lombok Island grid to 49.988 Hz within 33.08 seconds following the disconnection of two 22 MW generators. Subsequently, Wu et al. (2022) revealed that considering the frequency-

regulation contributions of wind turbines and ultra-high-voltage direct current transmission reduced unnecessary load shedding while maintaining the desired frequency recovery. Jinhua and Yanyan (2022) reported faster, more robust adaptive load-shedding decisions using ANN compared with conventional methods. Meanwhile, Baškarad et al. (2022) underscored that dynamically adjusting UFLS frequency thresholds improved protection adaptability in systems with diverse generation technologies. Wu et al. (2022) further confirmed the effectiveness of incorporating wind turbine operating regions into adaptive protection through simulations on the IEEE 39-bus system. Collectively, these findings indicated a growing emphasis on accurately estimating power imbalances and adapting load-shedding decisions to renewable generation variability and changing frequency dynamics.

Additional advancements in 2023 emphasised practical power-system applications, the centre-of-inertia frequency assessment, and selective load-shedding optimisation. Kanjelesa et al. (2023) reported that a 10% UFLS configuration provided the most favourable response among the investigated Zambian power system scenarios, with improved frequency nadir and reduced overshoot under modified interconnected operation. Fazaeli (2023) demonstrated the practical applicability of decentralised protection using locally measured voltage deviation and RoCoF, reducing dependence on communication infrastructure. Dedović Muftić et al. (2023) identified that adaptive load shedding based on centre-of-inertia frequency estimation reduced active power disconnection while achieving a higher frequency nadir than conventional protection. Voloshin et al. (2023) revealed that adaptive load management in an isolated mini-hydropower system preserved up to 15% of consumer load while maintaining frequency stability. Meanwhile, Debbarma et al. (2023) investigated Particle Swarm Optimisation (PSO) based multi-stage UFLS incorporating distributed generation and RoCoF relays. Vadillo et al. (2023) further emphasized that incorporating frequency stability margins improved protection performance by delaying unnecessary load disconnection under moderate RoCoF conditions. These findings reflected increasing research attention to improving the frequency nadir, reducing load interruptions, and enhancing protection reliability in interconnected and isolated networks.

Research published in 2024 presented further methodological diversification through Artificial Intelligence (AI), probabilistic optimisation, advanced signal processing, and coordinated protection. Anderson et al. (2024) introduced a cloud-based data integration framework for adaptive UFLS coordination across transmission and distribution networks with high distributed energy resource penetration. Aghajan et al. (2024) demonstrated that incorporating technical and societal load-priority information improved the equitable distribution of load disconnections without compromising protection effectiveness. Debbarma et al. (2024) investigated a probabilistic multi-stage UFLS that incorporates uncertainties in generation deficiency, system inertia, and load damping, using Monte Carlo simulation and PSO optimisation. Kilembe and Papadopoulos (2024) reported that reinforcement learning-assisted AUFLS reduced load-shedding requirements while maintaining stable system frequency with limited computational overhead. Similarly, Muftić Dedović et al. (2024) revealed improved frequency response and reduced load shedding using synchrophasor measurements, EMD, and centre-of-inertia frequency estimation. Luo et al. (2024) reported that risk-based decentralised optimisation considering wind generation uncertainty improved load-shedding allocation and avoided inflexible disconnection strategies. Tiguercha et al. (2024) further highlighted favourable frequency-protection performance using an Adaptive Neuro-Fuzzy Inference System (ANFIS) involving RoCoF, voltage deviation, and tie-line power information. These

findings highlighted the increasing integration of intelligent decision-making, uncertainty management, and multi-criteria optimisation into AUFLS development.

Recent developments during 2025-2027 further emphasised communication-independent protection, energy-based decision-making, and computationally efficient optimisation. Z. Li and Zhang (2025) demonstrated that decentralised AUFLS using local load measurements and initial RoCoF information improved response speed and frequency nadir preservation compared with conventional methods. J. Yang et al. (2025) investigated an energy-based adaptive protection strategy incorporating rotor kinetic energy deviation and power imbalance to determine appropriate load-shedding requirements. The approach was evaluated using the IEEE 39-bus and CSEE-SSFS 197-bus systems. Subsequently, Hamza Ali and Pandey (2027) introduced the computational scalability of an AC dynamics-aware trajectory optimisation framework incorporating nonlinear network characteristics and binary relay switching decisions. The proposed approach successfully addressed networks exceeding 1,500 nodes, with more than 170,000 continuous and 73,000 binary decision variables and obtained feasible switching solutions that prevented continued frequency decline. Overall, the findings from 2020-2027 indicate a progressive transition towards intelligent, decentralised, and optimisation-driven AUFLS strategies. Integrating RoCoF, PMU measurements, centre-of-inertia frequency, renewable energy response modelling, machine learning, and advanced optimisation techniques improved frequency recovery, reduced unnecessary load shedding, and increased protection adaptability. Nevertheless, differences in simulation conditions, network configurations, and performance indicators limit direct quantitative comparisons. The findings also suggest opportunities for further research into coordinating adaptive load-shedding FFR resources, improving real-time decision-making, and maintaining protection reliability under high renewable energy penetration.

Conclusions

In this study, the history of AUFLS is examined chronologically to obtain an overview of research trends, methodological developments, and new strategies to enhance power system frequency stability. The literature search was conducted in the Scopus database, identifying 51 primary publications for analysis. The chronological analysis was divided into three phases, namely Foundational and Early Exploration (2007-2013), Research Expansion and Methodological Development (2014-2019), and Research Intensification and Emerging Directions (2020-2027). This classification illustrates the evolution of AUFLS research in response to the increasing complexity of power systems, the growing penetration of renewable energy sources, and changing frequency stability requirements.

The results depict a gradual shift from traditional frequency-based load shedding towards more measurement-based and intelligent protection methods. In the early phase, research focused primarily on increasing frequency thresholds, estimating power imbalances, and defining appropriate levels of load shedding. Results of the second phase indicated growing methodological development through the use of RoCoF, PMUs, WAMS, decentralised protection, and optimisation algorithms. In particular, Phase 3 demonstrated continued progress in intelligent control, probabilistic optimisation, uncertainty quantification of renewable energy resources, and dynamic frequency response modelling. In these phases, the reviewed studies mostly reported improved frequency recovery, frequency nadir, protection adaptability, and reduced unnecessary load disconnection compared to traditional UFLS methods.

This study systematically highlights chronological research trends and methodological changes in the development of AUFLS. The analysis systematically presents the evolution from fixed protection settings to adaptive decision-making based on system operating conditions and disturbance characteristics. In practical terms, the results underscore the need for reliable frequency measurement, estimation of the power deficit, allocation of load shedding, and use of low-computation protection algorithms. These factors are especially pertinent for today's power systems, which have lower inertia and increasing penetration of inverter-based renewable energy sources.

However, this review is limited to literature from the Scopus database, using specific keywords, subject categories, and language filters. There is also a lack of quantitative comparisons among the reviewed approaches due to differences in simulation networks, disturbance conditions, and performance indicators. The following are recommended for future research: standardised evaluation criteria, real-time implementation, and validation of the e-learning in a broader operating context. Coordinating AUFLS with FFR, Battery Energy Storage Systems (BESS), and renewable energy resources to provide better frequency support with minimum load shedding is also recommended. Overall, this chronological survey offers a valuable overview of the development of AUFLS research and the potential opportunities for designing more robust, adaptive, and synchronized frequency protection in today's power systems.

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Ethics Statement: This study adhered to established ethical guidelines for research. Informed consent was secured from all voluntary participants prior to data collection. Strict confidentiality and anonymity were maintained throughout the process, with data utilized exclusively for academic purposes. No personally identifiable information is disclosed in this article.

Author Contribution Statement: All authors contributed significantly to this research. Mohd Syukur Azizan and Mohamad Zhafran Zakariya were responsible for preparing the original draft. Mohd Rafi Adzman provided supervision. Muhd Hafizi Idris and Mohd Syamuail bin Mohd Noor contributed to the writing, review, and editing process. All authors have read and agreed to the published version of the manuscript.

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