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A review on innovative strategies for stability, planning, and dispatch in modern electricity systems

Abstract

The evolving landscape of electrical power systems demands robust methodologies for ensuring stability, resilience, and efficiency. This review synthesizes recent research developments in grid-connected inverter stability criteria, energy system planning under extreme price scenarios, risk assessment in integrated energy infrastructures, and optimal dispatch strategies for industrial applications. Emphasizing novel mathematical models, risk management techniques, and multi-level optimization methods, these approaches provide critical insights into enhancing the robustness and sustainability of future power systems. The integration of these strategies supports resilient operations in the face of operational uncertainties and extreme conditions, contributing toward sustainable and stable electricity delivery.

Keywords: Inverter stability, energy system planning, scenario analysis, risk assessment, dispatch optimization, industrial energy management

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Introduction

The modern power grid faces numerous challenges stemming from the increasing penetration of renewable energy sources, deregulation, and operational uncertainties. Achieving stable, reliable, and cost-effective power supply necessitates the development of innovative analytical and control strategies.[1-3] Researchers are exploring diverse areas, including inverter stability under grid disturbances, planning for volatile energy markets, assessing systemic risks, and deploying effective dispatch mechanisms in energy-intensive settings.[4,5] This review synthesizes existing literature to explore four distinct topics in power system planning and operation. The scope encompasses research published from 2019-2024, identified through searches in IEEE Xplore, ScienceDirect, and Google Scholar using keywords related to each sub-area. Sources included theoretical analyses, empirical studies, and simulation-based research, selected to ensure representative coverage of advancements in each domain. This review highlights current advances in four critical areas: stability assessment of grid-connected inverter systems, planning for energy systems considering extreme energy price fluctuations, quantitative evaluation of supply risks considering pipeline failure modes, and optimal dispatch models for ancillary services in industrial parks.[6-8] These topics are interconnected within a logical flow: inverter stability ensures reliable integration of renewables, extreme scenario planning prepares for market volatility, risk assessment mitigates infrastructure failures, and bi-level optimization enhances real-time operational efficiency. An integrated visual framework of these interdependencies is illustrated in Figure 1. By integrating insights across these domains, the goal is to provide a comprehensive understanding of how mathematical and computational tools can improve the resilience, security, and economic performance of future electric power systems.[9,10]

Stability of grid-connected inverters: a novel coordinate transformation criterion

Inverter-based resources are vital for integrating renewable energies into the grid; however, their stability during grid disturbances remains a key concern.[11,12] Traditional stability criteria often involve complex parameter tuning and may lack adaptability to different system conditions. Recent research introduces a pioneering stability assessment approach grounded in coordinate transformations, which simplifies the stability analysis by converting complex system dynamics into more manageable forms.[13-15] This method relies on transforming the system's state-space representation to a new coordinate system where stability can be assessed more readily. Assumptions include the linearity of the transformed system and the existence of a suitable transformation. Limitations arise from the difficulty in finding optimal transformations for highly non-linear systems. This method involves selecting appropriate transformation parameters to ensure the system's eigenvalues remain within stability bounds, effectively guaranteeing stability under a variety of operating conditions.[16,17] Optimal parameters are selected by minimizing a cost function that penalizes eigenvalue migration outside the stable region. A reproducible numerical example can be found in Appendix A. The proposed criterion improves upon existing methods by providing clearer guidelines for parameter selection, enhancing robustness, and simplifying the stability verification process.[18] Compared to classical approaches like Lyapunov stability, this method offers improved computational efficiency but may require more sophisticated parameter tuning. By adopting this approach, system operators can better ensure inverter stability during transient events, thereby supporting reliable integration of inverter-based sources.[19,20]

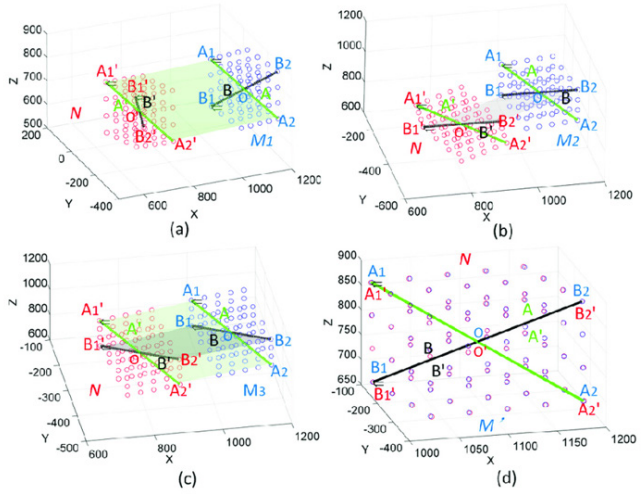

Figure 1 Illustration of coordinate transformation process in stability analysis.

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Scenario-based planning of energy systems under extreme price fluctuations

Energy markets are characterized by significant price volatility, especially during periods of geopolitical crises, supply disruptions, or market shocks. Traditional planning methods often overlook the potential for extreme price scenarios, leading to impractical or fragile investment strategies.[21,22] Emerging approaches employ risk-based planning frameworks using Conditional Value at Risk (CVaR) metrics, which quantify the expected losses beyond a specified confidence level. Extreme price scenarios are often generated through Monte Carlo simulations or historical data analysis, calibrated to reflect specific market conditions and future uncertainties. The confidence parameter of the CVaR metric is defined based on stakeholder risk preferences and regulatory requirements. Strategic decisions vary significantly with this threshold; higher confidence levels result in more conservative investments. This enables planners to prepare for the worst-case scenarios, ensuring system resilience amidst market upheavals.[23,24] The recent work models various extreme energy price scenarios and integrates them into the planning process, balancing operational costs with risk mitigation.[25] This method facilitates the development of energy infrastructure that remains flexible and adaptable during market shocks, thus safeguarding investments and ensuring ongoing service stability. Figure 2 presents a comparison of energy planning with and without CVaR analysis. Flexible assets, such as energy storage and dispatchable demand response programs, are incorporated to mitigate price risk by providing alternative sources of supply or reducing demand during peak price periods (Table 1).

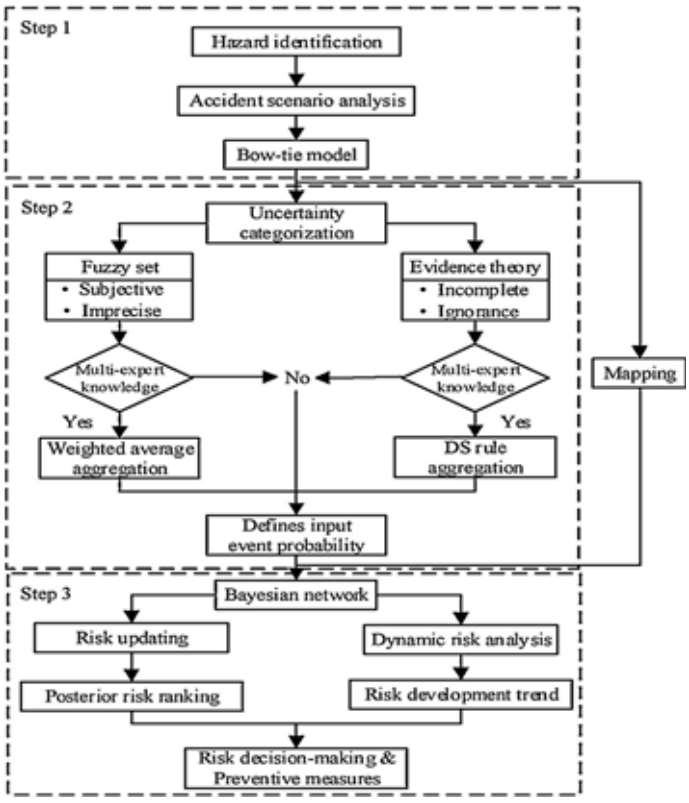

Figure 2 Flowchart depicting process of pipeline failure risk modeling.

Table 1 Comparative analysis of traditional vs. CVaR-based planning approaches in energy systems

Traditional Transport Planning	Sustainable Urban Mobility Planning
Focus on traffic	Focus on people
Primary objectives: Traffic flow capacity and speed	Primary objectives: Accessibility and quality of life, as well as sustainability, economic viability, social equity, health and environmental quality
Modal-focused	Balanced development of all relevant transport modes and shift towards cleaner and more sustainable transport modes
Infrastructure focus	Integrated set of actions to achieve cost-effective solutions
Sectorial planning document	Sectorial planning document that is consistent and complementary to related policy areas (such as land use and spatial planning; social services; health; enforcement and policing; etc.)
Short- and medium-term delivery plan	Short- and medium-term delivery plan embedded in a long-term vision and strategy
Related to an administrative area	Related to a functioning area based on travel to work patterns
Domain of traffic engineers	Interdisciplinary planning teams
Planning by experts	Planning with the involvement of stakeholders using a transparent and participatory approach
Limited impact assessment	Regular monitoring and evaluation of impacts to inform a structured learning and improvement process

Risk assessment for integrated energy systems considering pipeline failures

Beyond operational uncertainties, physical infrastructure failures pose significant threats to energy supply continuity. Pipelines, which carry fuel, water, or other critical resources, can suffer from multiple failure modes, including leaks, blockages, or ruptures, with cascading effects on the entire system. Failure modes are formally represented using fault tree analysis and Bayesian networks, enabling the probabilistic modeling of failure events. The probabilities of these failures are estimated from historical data, expert opinions, and inspection records. Recent risk assessment methodologies incorporate multiple failure states within pipeline networks into a comprehensive framework. These models simulate various failure scenarios, assess their probabilities, and evaluate the resulting system impacts. The approach provides a quantitative measure of system risk, supporting decision-makers to prioritize maintenance, diversify resource dependencies, and design contingency plans. This holistic risk assessment enhances the resilience of integrated energy systems, especially critical in climates prone to natural disasters or in aging infrastructure.

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Bilevel optimization for peak regulation in industrial parks

Industrial parks with high energy consumption require sophisticated dispatch models to provide ancillary services such as peak regulation, ensuring grid stability during demand surges. These systems operate on multiple levels: the upper level formulates strategic plans, while the lower level executes operational decisions. The recent bilevel optimization models integrate these levels to jointly optimize production schedules, energy storage utilization, and demand responses. The upper level aims to minimize costs while satisfying constraints related to peak regulation requirements, whereas the lower level optimizes the real-time dispatch of generation units and storage devices. The uncertainty arising from renewable generation and demand variability is addressed through stochastic programming and robust optimization techniques. The upper avatar level aims to minimize costs while satisfying constraints related to peak regulation requirements, whereas the lower level optimizes the real-time dispatch of generation units and storage devices. Mathematically, the upper level solves a mixed-integer linear program (MILP), while the lower level solves a series of linear programs (LPs). Approximate problem sizes and calculation times depend on the number of generators, loads, and storage units. Decomposition techniques, such as Benders decomposition, can accelerate computation. This hierarchical approach allows for more effective coordination between strategic planning and operational execution, particularly in scenarios with high variability in energy loads. Including performance metrics tailored to this service and sensitivity tests for different price signals would strengthen the practical usefulness of the model. It accounts for uncertainties in renewable generation, market prices, and demand patterns, leading to more resilient and cost-efficient demand management (Figure 3).

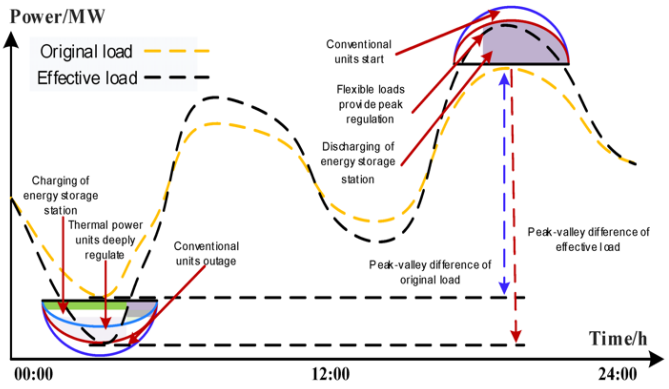

Figure 3 Structure of bilevel optimal dispatch model for peak regulation service.

Practical implications and future perspectives

The integration of advanced stability criteria, risk-informed planning, and hierarchical dispatch models significantly enhances the robustness and efficiency of contemporary power systems. The novel stability analysis offers a practical tool for inverter integration, critical for renewable-rich grids. Scenario-based planning approaches provide resilience against volatile markets, while comprehensive risk assessments strengthen infrastructure reliability. Furthermore, hierarchical dispatch models enable sophisticated demand response and resource coordination, vital for managing the complexities of modern industrial and utility systems. Looking ahead, future research should focus on combining these methodologies within integrated decision-making frameworks, leveraging artificial intelligence, big data, and real-time monitoring. The development of adaptive models that can dynamically respond to evolving conditions will be key to realizing truly resilient, sustainable, and flexible power systems.

Conclusion

Recent advancements in stability analysis, scenario-based planning, risk management, and hierarchical dispatching are transforming how modern power systems are designed and operated. These innovative methodologies address critical challenges such as inverter stability, market fluctuations, infrastructure failures, and demand surge management. By adopting these strategies, stakeholders can significantly improve operational resilience, reduce costs, and accelerate the transition toward sustainable energy futures.

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