Journal of **N**ovel **R**esearches on **S**mart **P**ower **S**ystems - Vol. 14 - No. 2 – Summer 2025
P-ISSN: 2322-2468, E-ISSN: 2981-0272, https://jeps.dezful.iau.ir/

Review Article

A Brief Overview of Reliability Approaches in the Restructured Power System

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Extended Abstract:

The reliability of electric power systems—defined as the ability to deliver electricity continuously to meet consumer demand without interruption—is a foundational pillar of modern societal function, economic productivity, and national security. Historically, this reliability was ensured within vertically integrated utility models, where a single entity controlled generation, transmission, and distribution, enabling centralized planning and operational coordination. However, the global trend toward power system restructuring—driven by goals of market liberalization, cost reduction, enhanced efficiency, and consumer choice—has fundamentally transformed the institutional and operational landscape of the electricity sector. While restructuring introduces potential economic benefits through competition and innovation, it simultaneously fragments responsibility for system reliability across multiple independent actors, thereby introducing new complexities and vulnerabilities that demand novel analytical and operational approaches.

This review article provides a comprehensive and structured overview of reliability assessment methodologies, challenges, and frameworks within restructured power systems. It begins by delineating the dual dimensions of power system reliability: adequacy—the long-term ability of the system to supply the aggregate electrical demand and energy requirements, accounting for scheduled and unscheduled outages of system components—and security—the short-term ability of the system to withstand sudden disturbances (e.g., generator trips, line faults) without cascading failures. In a restructured environment, these dimensions can no longer be managed by a single, monolithic entity. Instead, they become the shared, yet often misaligned, responsibility of Generation Companies (GENCOs), Transmission Companies (TRANSCOs), and Distribution Companies (DISCOs), an Independent System Operator (ISO), and Market Operators or Traders (MOTS).

A core contribution of this review is its systematic classification of the analytical techniques employed to evaluate reliability in this complex new paradigm. The article distinguishes between analytical methods and simulation-based methods. Analytical approaches, such as state enumeration and recursive techniques, offer closed-form solutions but are computationally intractable for large-scale, modern systems. In contrast, simulation-based methods, particularly Monte Carlo simulation (both sequential and non-sequential), have become the de facto standard for reliability assessment in restructured systems. These methods excel at modeling the stochastic nature of component failures, the time-dependent behavior of system states, and the intricate market-driven dispatch logic that characterizes restructured operations. The review details how these simulations are enhanced with Reliability Network Equivalent (RNE) techniques to manage computational complexity by aggregating subsystems, and how they are integrated with market-clearing algorithms to reflect the true operational decisions that impact system security.

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[DOI: 1082362/jeps.2025.2.1.540.fa]

Furthermore, the paper provides a granular analysis of reliability evaluation across the three primary subsystems—generation, transmission, and distribution—highlighting the unique challenges and metrics for each. In generation, reliability is often assessed using indices like the Loss of Load Expectation (LOLE) and Expected Demand Not Served (EDNS), which quantify the risk of insufficient capacity. The integration of variable renewable energy sources (VREs) like wind and solar has rendered these assessments significantly more complex, as they must now account for the joint probability distributions of weather-driven generation and load. In transmission, reliability is evaluated through criteria such as the N-1 security standard, transient and dynamic stability margins, and the ability to manage congestion without resorting to costly and disruptive load shedding. The review notes that restructuring can lead to underinvestment in transmission infrastructure, as the investment incentives for private entities may not align with the system-wide reliability benefits. At the distribution level, end-user experience is quantified using standardized indices: the System Average Interruption Frequency Index (SAIFI), which measures the average number of outages per customer; the System Average Interruption Duration Index (SAIDI), which measures the average outage duration; and the Customer Average Interruption Duration Index (CAIDI), which reflects the average restoration time. The article underscores that distribution reliability is increasingly impacted by the upstream uncertainties introduced by the restructured wholesale market and VRE integration.

The review also synthesizes key findings from recent research on managing reliability in this new context. It discusses strategies such as coordinated maintenance scheduling between GENCOs and TRANSCOs under an ISO's oversight to minimize the simultaneous unavailability of critical assets. It explores the use of demand response and distributed energy resources (DERs), including electric vehicles, as flexible tools that can be dispatched by the ISO to provide ancillary services and enhance local reliability. The paper further examines advanced frameworks like fuzzy-logic-based fault tree analysis for handling the epistemic uncertainties inherent in VRE forecasting and market participant behavior. A critical theme that emerges is the necessity of a holistic, system-wide perspective that transcends the boundaries of individual market participants, as the reliability of the whole is often compromised by the siloed optimization of its parts.

In conclusion, this article establishes that while the goals of power system restructuring are economically compelling, they necessitate a paradigm shift in how reliability is conceived, measured, and managed. The transition from a single, hierarchical reliability manager to a multi-agent, market-coordinated system requires robust, computationally efficient, and forward-looking assessment tools that can handle high-dimensional uncertainty and complex interdependencies. The review identifies several critical research gaps for future work: (1) the development of dynamic, real-time reliability indices that can inform operational decisions in control rooms; (2) the creation of market mechanisms and regulatory frameworks that properly price and incentivize reliability contributions from all participants, including consumers and DERs; (3) the integration of resilience and robustness concepts alongside traditional reliability to address high-impact, low-probability (HILP) events like extreme weather or cyber-physical attacks; and (4) the advancement of data-driven and AI-based methods to leverage the vast data streams from smart meters and phasor measurement units (PMUs) for predictive reliability analytics. Addressing these challenges is essential to ensure that the pursuit of a more efficient and competitive electricity market does not come at the cost of a less secure and dependable power system.

Keywords: distribution system, market operation, reliability, restructured system, transmission system.

Received: 15 May 2025
Revised: 17 July 2025
Accepted: 23 July 2025

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Citation: M. Shahgholian, M.R. Vasili, G. Shahgholian, "A Brief Overview of Reliability Approaches in the Restructured Power System", Journal of Novel Researches on Smart Power Systems, vol. 14, no. 2, pp. 1-18, September 2025 (in Persian).

[DOI: 1082362/jeps.2025.2.1.540.fa] [Downloaded from jeps.dezful.iau.ir on 2026-11-13]
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