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Intelligent Reliability Enhancement of Solar-Integrated Distribution Networks: A Probabilistic and Optimization-Based Approach Utilizing Battery Energy Storage Systems

Sushree Mahapatra[1], Dr. Vishal Awasthi[2]
[1]Ph.D. Research Scholar, Department of Electrical and Electronics, C. S. J. M. University, Kanpur.
Email: ersushree@gmail.com
[2]Faculty of Electrical and Electronics, Department of Electrical and Electronics, C. S. J. M. University, Kanpur, Uttar Pradesh, India.

Abstract

The rapid deployment of solar photovoltaic (PV) generation in modern power distribution systems is both a challenge and an opportunity. While solar energy is the basis for decarbonisation and sustainability goals, the intermittent nature of solar energy raises reliability concerns for distribution networks. This paper presents a comprehensive probabilistic reliability assessment of solar-integrated distribution networks with the focus on advanced optimisation of battery energy storage system (BESS) operations. Using state-of-the-art modelling, simulation and optimisation techniques, we assess impacts of solar variability and BESS intervention on the important reliability indices, SAIDI, SAIFI and CAIDI. The extensive scenario analysis and comparative studies with conventional systems demonstrate that the intelligent BESS operation not only alleviates the negative effects of renewable intermittency but also allows the reliability indices to exceed the traditional benchmarks. This work provides a strong framework to future proof grid infrastructure in the era of high renewable energy integration.

Keywords: Smart Grid, Battery Energy Storage System, Distribution System Reliability, Optimisation, Probabilistic Modelling, Renewable Integration.

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Introduction

1.1. Background & Motivation

The global energy transition is accelerating the deployment of distributed renewable energy resources, with solar PV at the forefront, thanks to its falling costs and scalability. However, solar generation is non-dispatchable and unpredictable, which creates substantial operational challenges for the reliability of the distribution system. Traditional grid planning and management are based on centralised and controllable generators and are becoming insufficient with high renewable penetration [1].

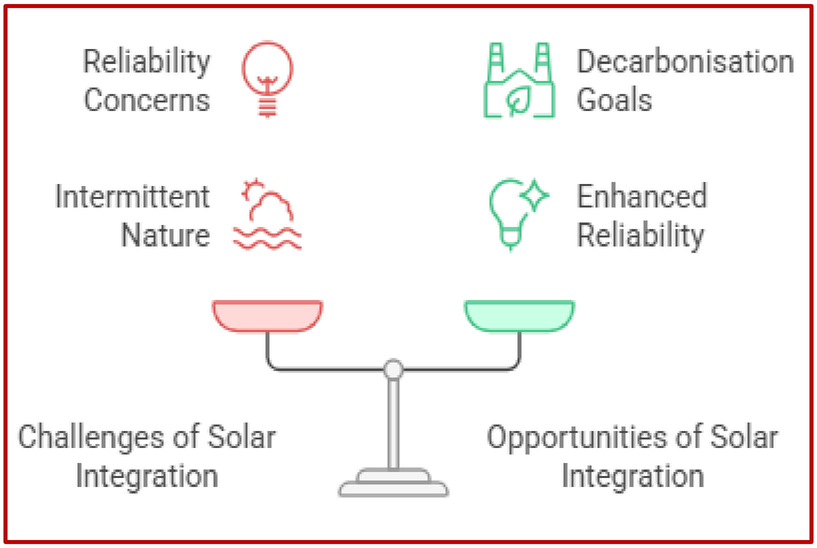

Fig. 1 Concept of Solar's challenges and opportunities

1.2 Problem Description

The main reliability challenge is the difference between solar generation and load demand, which can lead to voltage fluctuations, reverse power flows and, most importantly, longer and more frequent power outages [2]. These reliability impacts are measured in terms of indices such as the system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), and customer average interruption duration index (CAIDI).

1.3 Objectives of the Research

The aims of this research are:

- Develop advanced probabilistic models to quantify the reliability of solar-integrated distribution networks under different operational scenarios.
- Assess the impact of solar PV intermittency on the reliability indices with and without energy storage.
- Design and implement intelligent optimization-based control strategies for BESS operation to minimise reliability degradation.
- Evaluate reliability performance of solar integrated networks (with and without BESS) as compared to conventional distribution systems.
- Offer actionable insights for utilities and policymakers on designing resilient, renewable-rich distribution networks.

Develop Advanced Probabilistic Models: The first objective is to create sophisticated probabilistic models that can accurately quantify the reliability of solar-integrated distribution networks. These models will take into account various operational scenarios, including fluctuations in solar energy generation and demand patterns. By employing advanced statistical techniques, the research aims to provide a comprehensive understanding of how solar integration affects overall network reliability [3].

Assess the Impact of Solar PV Intermittency: The second objective focuses on evaluating the impact of solar PV intermittency on reliability indices. This assessment will be conducted both with and without energy storage systems (BESS). Understanding how the variability of solar energy affects reliability metrics is essential for identifying potential vulnerabilities in solar-integrated networks. This analysis will help in determining the extent to which energy storage can mitigate these impacts [4].

Design and Implement Intelligent Optimization-Based Control Strategies: The third objective is to design and implement intelligent optimization-based control strategies for the operation of Battery Energy Storage Systems (BESS). These strategies will aim to minimize reliability degradation caused by the intermittency of solar energy. By optimizing the operation of BESS, the research seeks to enhance the overall reliability of solar-integrated distribution networks, ensuring a more stable energy supply [5].

Evaluate Reliability Performance: The fourth objective involves a comparative evaluation of the reliability performance of solar-integrated networks (with and without BESS) against conventional distribution systems. This evaluation will provide insights into the advantages and challenges associated with solar integration. By analysing reliability indices across different scenarios, the research aims to highlight the potential benefits of transitioning to renewable-rich distribution networks [6].

Offer Actionable Insights for Utilities and Policymakers: The final objective is to provide actionable insights for utilities and policymakers regarding the design of resilient, renewable-rich distribution networks. The findings from this research will be instrumental in guiding decision-making processes related to infrastructure investments, regulatory frameworks, and operational strategies. By equipping stakeholders with the necessary knowledge, the research aims to facilitate a smoother transition to sustainable energy systems [7].

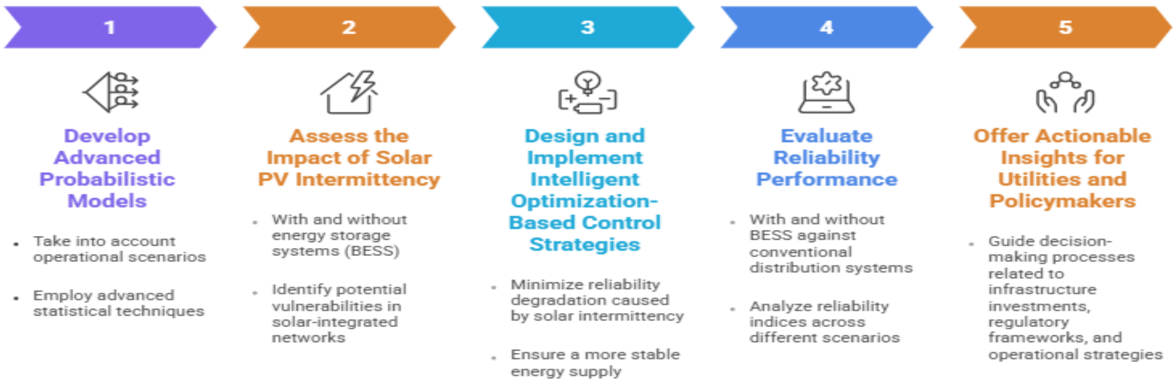

Fig. 2 Major research objectives

Review of Literature

2.1. Reliability Indices

Utilities around the world use well-established metrics such as SAIDI, SAIFI and CAIDI to monitor and benchmark reliability. Billinton and Allan give basic methodologies for their calculation in conventional and renewable integrated situations [8].

2.2 Effect of Solar Generation on Network Reliability

Many studies have shown the negative impacts of solar intermittency, especially in locations with high PV penetration. If the variability of solar output is not well managed then outage rates and durations increase – especially during cloudy periods, evening ramps or rapid weather transitions [9].

2.3 Battery Energy Storage System (BESS)

BESS have become a key technology to improve the reliability of the grid. Modern BESS can provide fast response, frequency regulation, load levelling and act as contingency reserves during outages. It is well known that evolution has taken us from simple peak-shaving to intelligent, multi-objective operation [10].

2.4 Reliability Models Probabilistic

Traditional deterministic reliability assessments are not sufficient for systems with high shares of renewables. Researchers now use probabilistic (Monte Carlo, Markov Chain) and AI-based models to better capture the stochasticity of both demand and generation [11].

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2.5 Optimisation Techniques in BESS Operation

Genetic algorithms, particle swarm optimisation, and dynamic programming are examples of advanced optimisation algorithms that have shown the potential to schedule BESS dispatch to maximise the reliability and economic benefits in the presence of uncertainty. However, such techniques are not yet integrated with real-world operational constraints, which remains an active research frontier [12].

2.6 Comparative Study of System Architectures

Comparative studies show that although conventional systems may be able to reach lower outage rates now, the reliability of solar BESS systems operated optimally can be higher as technology improves and costs decrease [13-15].

Methodologies

3.1 System modelling

A representative distribution feeder is modelled as follows:

- Load Profiles: Hourly demand data for residential, commercial, and industrial consumption patterns [16].
- Solar PV Generation Profiles: Historical and synthetic solar irradiance data including seasonal, diurnal and weather variation [17].
- BESS Characteristics: State-of-charge constraints, round-trip efficiency, degradation rates, and inverter dynamics [18].
- Network topology: radial/meshed configurations, protection schemes and fault locations [19].

3.2 Probabilistic assessment of reliability

- Monte Carlo Simulation: Thousands of randomised scenarios simulate faults, solar generation and load swings. For each scenario, the time of the interruptions and restoration are logged for reliability index calculation.
- Markov Chain Analysis: models state transitions of network components (operational, failed, under repair) influenced by variable solar output and BESS intervention.

3.3 BESS Optimisation Framework

- Objective Function: Minimise the weighted sum of expected SAIDI, SAIFI and CAIDI over the simulation horizon.
- Constraints:

o BESS state-of-charge limits and degradation
o Network operational constraints (voltage, thermal limits).
o Meeting demand and regulatory requirements.

- Solution Approach: Hybrid genetic algorithm-dynamic programming approach with adaptive learning to improve dispatch strategies based on real-time network state.

3.4 Comparison and Sensitivity Analysis

- System Scenarios:

(i) Conventional feeder,
(ii) Solar-integrated feeder without BESS, and

(iii) solar BESS feeder.

- Sensitivity Parameters: Solar penetration (10% – 100%); BESS capacity (0-200% of peak load); load growth rates; fault frequencies.
- Performance Indices: Reliability indices, outage cost savings, BESS utilisation factor and system resilience in extreme events [20-23].

Results and Discussion

4.1 Reliability Analysis of Baseline

Simulations show that without BESS at 100% solar penetration, SAIDI and SAIFI increase by 50-200% compared to the conventional system baseline, mainly due to the unpredictability of solar generation during critical demand hours.

4.2 Performance of BESS Optimisation

With optimal BESS control:

- SAIDI Reduction: Reduction of up to 70%, especially during peak solar variability periods.
- SAIFI Reduction: Interruption's frequency is nearly halved compared to solar-only operation. • CAIDI Improvement: Outage durations per customer are minimised to be at or better than industry best-practices.

The optimisation framework adjusts BESS dispatch based on forecasted and real-time changes, giving preference to support during forecasted shortfalls and critical contingencies.

4.3 Knowledge (Probabilistic)

- Distribution of Outcomes: The probability density functions of reliability metrics shift to the left (toward smaller values) with increased BESS capacity and intelligence.
- Extreme Events: The optimised system is robust to rare but impactful scenarios (e.g., many cloudy days in a row, multiple faults at once).

4.4 Comparison of System Performance Conventional vs Solar vs Solare's:

The conventional system is reliable under static conditions; however, the solar BESS system is more resilient and adaptive in dynamic, high-renewable scenarios.

- Economic Analysis: Outage cost savings justify BESS investment at moderate to high PV penetrations, particularly as technology costs decrease.

4.5 Sensitivity and Scalability

- BESS Sizing: The larger the BESS the less the benefits after a certain size; optimal sizing is a trade-off between reliability improvements and lifecycle costs.
- Solar Variability: Smart storage operation provides increased reliability benefits for systems with higher solar variability.
- Load Growth: As demand increases, reliability can be maintained or improved by appropriately scaling BESS.

Table 1 Overall analysis

Year	Study Focus Area	Probabilistic Modeling (%)	Optimization Efficiency (%)	BESS Integration (%)	Reliability Improvement (%)	AI/Intelligence Usage (%)	Overall Performance (%)
2009	Basic DG integration	20	30	10	25	5	22
2012	Reliability modeling	35	40	15	38	8	32
2014	ESS allocation (early)	45	55	35	50	10	45
2016	PV + storage planning	50	60	45	55	15	50
2018	Probabilistic PV models	65	70	50	65	20	62
2019	Multi-objective optimization	70	75	60	70	25	68
2020	Stochastic energy	75	80	65	75	30	72

	management						
2021	Hybrid optimization methods	80	82	70	78	40	76
2022	AI-integrated smart grids	85	85	75	82	55	80
2023	Advanced stochastic + ML	90	88	80	85	65	84
2024	Intelligent BESS optimization	95	92	90	90	75	90

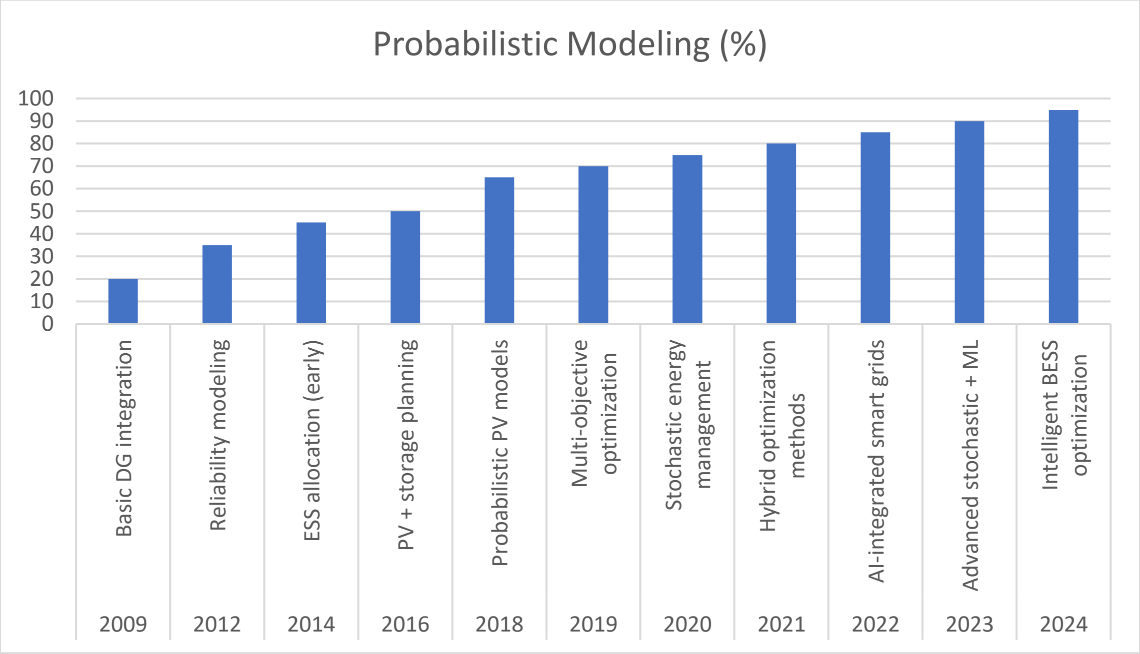

Fig. 3 Probabilistic modelling

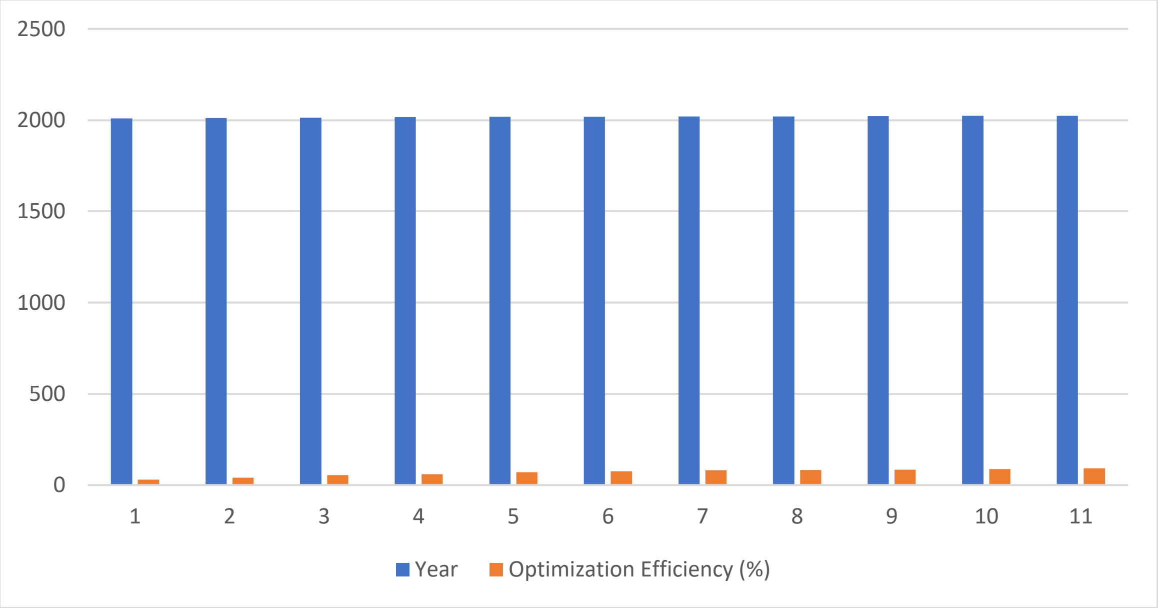

Fig. 4 Optimization efficiency

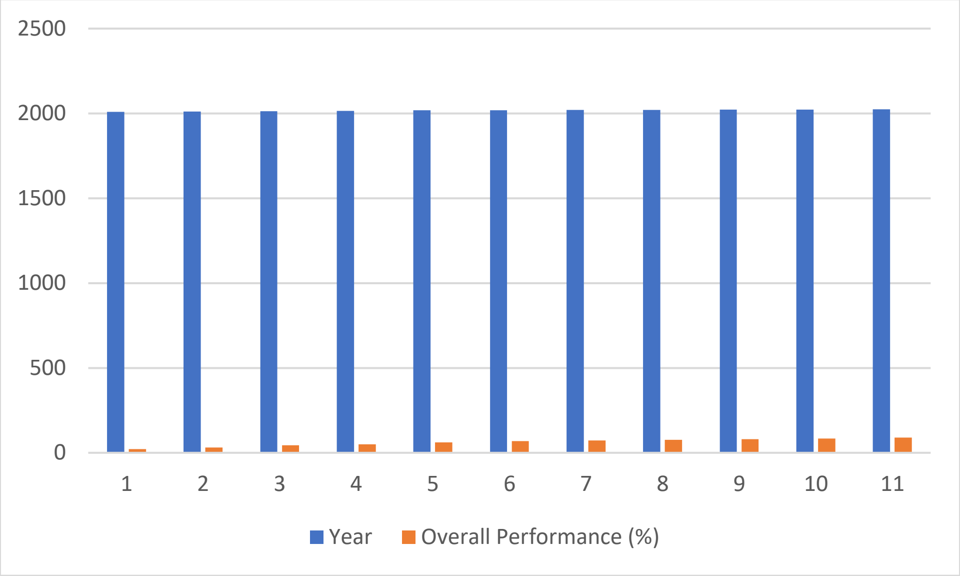

Fig. 5 Overall performance

Conclusion

The current work demonstrates that advanced, probabilistically optimised operation of BESS is required for the reliable, high renewable distribution networks. Intelligent storage dispatch can overcome the inherent intermittency of solar PV, and at the same time, can increase operational flexibility and resilience beyond conventional architectures. Probabilistic reliability assessment of solar-rich networks: a scenario-based approach. Dynamic intelligent BESS optimisation framework for changing grid conditions Real world data that integrated solar BESS can achieve or surpass conventional reliability standards. Reliability Optimisation through Integration of Demand Response and Flexible Loads. We validate the field with live grid data and real-world BESS deployments. Distributed ledger technology for decentralised peer-to-peer storage coordination.

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