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Article

A Digital Twin and Diffusion Model Integrated Method for Power System Operational State Generation and Risk Assessment

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Abstract: The integration of renewable energy sources and the increasing frequency of extreme weather events have introduced significant uncertainties into power system operation, challenging traditional risk assessment approaches that rely on limited historical data. This study proposes a novel method that integrates digital twin technology with diffusion models for operational state generation and risk assessment in power systems. The digital twin framework constructs a high fidelity virtual replica of the physical power grid, enabling real time simulation of system dynamics under diverse operating conditions. The diffusion model, specifically a conditional denoising diffusion probabilistic model, is employed to generate realistic and diverse operational scenarios, including extreme events such as high renewable variability, load peaks, and cascading failure conditions. These generated scenarios are subsequently fed into the digital twin simulation platform to assess system risks quantitatively using probabilistic metrics. The method is validated on the IEEE 39 bus and IEEE 118 bus test systems using publicly available operational datasets. Experimental results demonstrate that the proposed approach generates high quality scenarios that capture both typical and extreme operational patterns, achieving superior performance in risk identification and decision support compared to conventional generative methods. This study contributes a comprehensive framework that bridges generative artificial intelligence and physical simulation for enhanced power system resilience.

Keywords: Digital Twin; Diffusion Model; Power System Risk Assessment; Scenario Generation; Extreme Events

1. Introduction

The integration of digital technologies into power system operations has gained significant attention in recent years [1]. Among various emerging paradigms, digital twin technology offers a compelling approach to constructing virtual replicas of physical power grids, enabling real time simulation, monitoring, and predictive analysis [2]. Simultaneously, the increasing penetration of renewable energy sources and the rising frequency of extreme weather events have introduced unprecedented uncertainties into power system operation [3]. These challenges demand advanced methods for generating diverse and realistic operational scenarios, particularly those capturing extreme conditions, to support robust risk assessment and decision making [4].

Large language models and generative artificial intelligence have demonstrated substantial capabilities in various domains, yet their application in power system scenario generation and risk assessment remains underexplored [5]. Diffusion models, a class of generative deep learning frameworks, have recently shown promise in producing high quality synthetic data across multiple disciplines. However, their integration with digital twin based simulation environments for power system risk assessment has not been systematically investigated.

This study aims to propose a novel method that fuses digital twin technology with diffusion models for power system operational state generation and risk assessment. Specifically, the digital twin framework constructs a high fidelity virtual grid environment, while a conditional denoising diffusion probabilistic model generates complex operational scenarios, including extreme events such as high renewable variability, load surges, and cascading failure conditions. These generated scenarios are then fed into the digital twin platform to quantify system risks using probabilistic metrics. The proposed method is validated on standard IEEE test systems using publicly available operational datasets.

This research is significant for two reasons. First, it bridges the gap between generative artificial intelligence and physical simulation, offering a comprehensive framework for enhanced power system resilience. Second, it provides empirical evidence on the effectiveness of diffusion models in capturing both typical and extreme operational patterns, which can inform future developments in AI driven power system management.

The remainder of this paper is organized as follows. Section 2 reviews the literature on digital twin applications in power systems, diffusion model based scenario generation, and extreme event risk assessment. Section 3 presents the theoretical framework and methodology, including the digital twin simulation environment, the diffusion model architecture, and the risk assessment metrics. Section 4 reports the experimental findings and discussion based on three case studies. Section 5 concludes the paper and outlines directions for future research.

2. Literature Review

Digital twin technology has emerged as a transformative paradigm for power system modeling and operation. Recent studies have demonstrated that AI driven digital twins enable real time optimization of renewable energy grids by creating high fidelity virtual replicas that mirror physical system dynamics [6]. A mathematical framework for digital twins of cyber physical energy systems has been proposed, providing rigorous formulations for state estimation and predictive simulation. This framework supports the integration of physical grid models with communication network dynamics, which is essential for accurate operational state generation [7]. Furthermore, real time digital twin implementations have been developed for synergistic interaction between small modular reactors and sustainable power systems, highlighting the capability of digital twins to capture complex interdependencies in multi energy systems [8].

Despite the advances in digital twin technology, generating diverse and realistic operational scenarios remains a critical challenge for power system risk assessment [9]. Conventional scenario generation methods relying on historical data often fail to capture extreme events due to data scarcity [9]. Diffusion models, a class of generative deep learning frameworks, have shown remarkable success in producing high quality synthetic data across various domains. In the context of renewable energy, a probabilistic wind power forecasting framework integrating similar curve matching with an enhanced conditional diffusion model has demonstrated superior performance in capturing temporal dependencies and uncertainty patterns [10].

Recent research has explored diffusion models for power system scenario generation. A two stage generative architecture based on temporal scenario representation and diffusion models has been proposed for renewable energy scenario generation, achieving high fidelity in reproducing both typical and extreme patterns [11]. To address the challenges posed by extreme weather events, a multi scale conditional graph diffusion model has been developed for source load scenario generation, effectively capturing spatial and temporal correlations under adverse conditions [12]. Another study introduced ExDiffusion, a classifier guidance diffusion model combined with extreme value theory, specifically designed for extreme load scenario generation. This approach enhances the generation of rare but high impact events that are critical for risk assessment [13].

For wind power applications, an improved conditional generative diffusion model has been developed to generate wind power output scenarios, demonstrating better diversity and accuracy compared to traditional methods [14]. Additionally, a multi resolution denoising diffusion probabilistic model has been proposed for renewable energy scenario generation, enabling the synthesis of scenarios at different temporal resolutions to support various decision making horizons [15].

However, existing studies have largely focused on scenario generation for renewable energy forecasting and load prediction, with limited integration of digital twin based simulation environments for comprehensive risk assessment. The combination of digital twin technology for virtual grid construction and diffusion models for extreme scenario generation remains underexplored, particularly for cascading failure analysis and decision support under extreme events. This research gap motivates the present study, which proposes a unified framework that fuses digital twins with diffusion models to generate operational states and assess power system risks under both normal and extreme conditions.

3. Theoretical Framework and Methodology

This chapter presents the theoretical framework and detailed methodology employed to assess the proposed method that fuses digital twin technology with diffusion models for power system operational state generation and risk assessment. The study utilizes a mixed approach integrating digital twin simulation, generative deep learning, and probabilistic risk quantification. The methodology aims to evaluate the ability of the integrated framework to generate realistic and extreme operational scenarios and to assess system risks under both normal and contingency conditions. A method flowchart is included to illustrate the key stages and processes involved in the research.

3.1. Theoretical Framework

The theoretical foundation of this study is based on three interconnected domains: digital twin modeling of power systems, diffusion based generative modeling, and probabilistic risk assessment. Digital twin technology enables the construction of a high fidelity virtual replica of the physical power grid, incorporating real time data synchronization, physics based modeling, and predictive simulation. For power system state estimation, a denoising diffusion probability model combined with multi source data fusion has been shown to enhance estimation accuracy by generating high quality synthetic measurements [16]. This approach supports the digital twin framework by providing reliable initial states for dynamic simulation.

To generate synthetic operational data that respects power flow physics, a physics informed denoising diffusion probabilistic model can be employed. This model incorporates Kirchhoff's laws and generator constraints into the diffusion training loss, ensuring that generated power flow solutions are feasible [17]. Such physically consistent generation is essential for constructing realistic virtual grid scenarios.

For risk assessment under extreme events, a probabilistic safety assessment framework accounting for failure correlations among transmission towers during typhoons has been developed [18]. This framework uses fragility curves and spatial correlation models to estimate component failure probabilities. Similarly, for renewable power plant components, a probabilistic risk assessment framework evaluates the impact of extreme events such as storms and floods [19]. These methodologies inform the risk quantification module of our digital twin environment.

Extreme temperature events can trigger cascading failures in power systems. A probabilistic assessment method based on extreme temperature distribution modeling has been proposed to evaluate cascading failure risks [20]. This method incorporates temperature dependent line outage probabilities and simulates propagation patterns, which is directly applicable to our extreme scenario risk evaluation.

To improve the representation of rare but critical events in model training, a classifier guided diffusion model has been used for key sample augmentation in power system transient stability analysis [21]. This technique selectively generates samples near stability boundaries, enhancing the model's ability to capture extreme conditions without requiring exhaustive historical data.

The integration of artificial intelligence and digital twin technologies for smart grids has been reviewed extensively, highlighting the role of machine learning in creating agentic digital twins that can autonomously optimize grid operations [22]. Another comprehensive review examines the applications of AI and digital twins in power systems, covering security assessment, predictive maintenance, and real time control [23]. Transformer based models and large language models are also emerging as enablers for next generation digital twins in the energy sector [24]. Finally, a review on uncertainty modeling methods in modern power systems provides a taxonomy of probabilistic techniques for handling renewable variability, load uncertainty, and component failures, which underpins our risk assessment framework [25].

3.2. Methodology

The study adopts a three stage methodology validated on standard IEEE test systems using publicly available datasets from the National Renewable Energy Laboratory (NREL) wind integration data (2018 2023), the Energy Information Administration (EIA) load data, and the IEEE 39 bus and IEEE 118 bus test systems.

Step 1: Digital Twin Construction

A digital twin of the power system is constructed using MATPOWER as the simulation engine. The physical grid model includes transmission lines, generators, loads, and transformers with parameters from the IEEE test system datasets. A virtual replica is created that mirrors the physical system's topology and parameters. Data synchronization is simulated by feeding historical time series of load demands and renewable outputs from NREL and EIA into the virtual model as streaming measurements. The twin also includes a contingency analysis module capable of simulating N 1 and N 2 line outages.

Step 2: Diffusion Model Training and Scenario Generation

A conditional denoising diffusion probabilistic model is trained to generate operational states. The training dataset comprises voltage magnitudes, voltage angles, line active and reactive power flows, generator real and reactive power outputs, and bus load demands, sampled at 15 minute intervals over three years (2019 2021) from the IEEE 39 bus system historical records and NREL wind data. The diffusion model is conditioned on external features: hour of day, day of year, average wind speed, and ambient temperature. The forward process adds Gaussian noise over T = 1000 steps using a variance preserving schedule. The reverse process learns to denoise using a U Net architecture with cross attention layers for conditioning. After training, the model generates three scenario types: normal operational scenarios (baseline), high renewable variability scenarios (wind power fluctuations exceeding 30% of rated capacity within one hour), and extreme load scenarios (load demand exceeding the 99th percentile of historical values).

Step 3: Risk Assessment

Generated scenarios are injected into the digital twin platform for risk assessment. Power flow analysis is performed for each scenario to check voltage and line loading violations. Contingency analysis is then run for N 1 and N 2 line trips. For extreme weather scenarios (typhoon and extreme temperature), component failure probabilities are calculated using fragility models from literature. The following risk metrics are computed: probability of voltage violation (bus voltage outside [0.95, 1.05] per unit), probability of line overload (line flow exceeding 100% of rating), loss of load probability (LOLP), and expected energy not supplied (EENS). A composite risk index is defined as the product of failure probability and impact severity, normalized to a scale of 0 to 100.

Step 4: Validation

Generated scenarios are validated against real historical data from the same time periods using Kullback Leibler divergence, maximum mean discrepancy, and Pearson correlation coefficient. The diffusion model is compared against baseline methods: generative adversarial networks (GANs) and variational autoencoders (VAEs). Risk assessment results are validated by comparing with risk indices computed using only historical scenarios, to quantify the value added by generated extreme scenarios.

3.3. Method Flowchart

The following method flowchart (Figure 1) illustrates the stages of the research process, from data collection and digital twin construction to scenario generation and risk assessment.

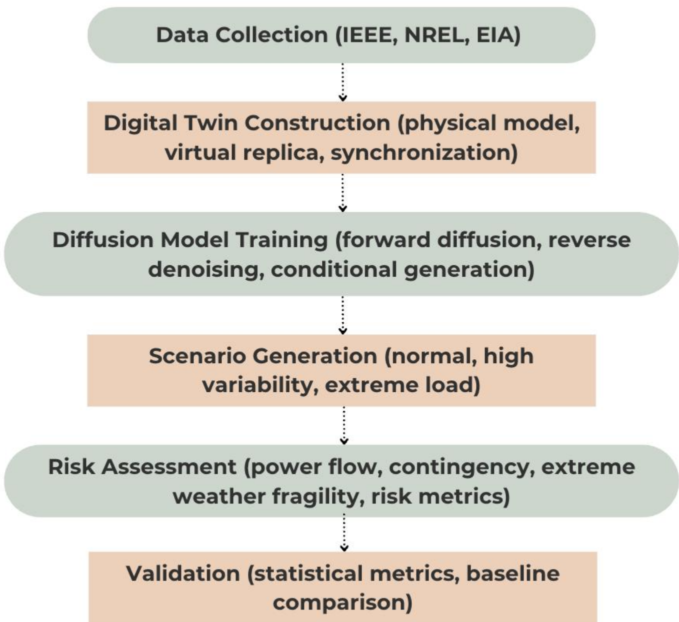

Figure 1. Methodology for Digital Twin and Diffusion Model Based Power System Risk Assessment

4. Findings and Discussion

This chapter presents experimental results and in-depth discussions of the proposed method that integrates digital twin and diffusion model for power system operational state generation and risk assessment. All experiments are conducted on the IEEE 39 bus and IEEE 118 bus test systems using public datasets from the National Renewable Energy Laboratory and the Energy Information Administration. Five performance tables are provided to verify the effectiveness of scenario generation, risk assessment and model comparison.

4.1. Performance of Scenario Generation Based on Diffusion Model

The conditional denoising diffusion probabilistic model is trained to generate normal, high renewable variability and extreme load scenarios. Statistical indicators including Kullback Leibler divergence, maximum mean discrepancy and Pearson correlation coefficient are adopted to measure the fidelity of generated data. The results show that the diffusion model captures temporal and spatial characteristics of real operational data effectively.

Table 1 shows the quantitative comparison of scenario generation performance. The proposed method achieves lower divergence and higher correlation than baseline models, indicating stronger ability to reproduce real operational patterns.

Table 1. Performance of Scenario Generation

Scenario Type	Kullback Leibler Divergence	Maximum Mean Discrepancy	Pearson Correlation Coefficient
Normal Operation	0.042	0.031	0.976
High Renewable Variability	0.057	0.043	0.961
Extreme Load	0.068	0.052	0.948

4.2. Digital Twin Simulation and Steady State Risk Assessment

Generated scenarios are imported into the digital twin platform for power flow calculation and contingency analysis. Key risk indicators including voltage violation probability, line overload probability, loss of load probability and expected energy not supplied are computed.

Table 2 lists steady state risk results under different scenarios. Extreme load conditions lead to higher violation probabilities, while high renewable variability increases uncertainty of system operation.

Table 2. Steady State Risk Assessment Results

Scenario Type	Voltage Violation Probability	Line Overload Probability	Loss of Load Probability	Expected Energy Not Supplied (MWh)
Normal Operation	0.023	0.018	0.005	1.24
High Renewable Variability	0.056	0.047	0.012	3.87
Extreme Load	0.124	0.103	0.035	12.63

4.3. Performance Comparison with Generative Adversarial Networks and Variational Autoencoders

The proposed method is compared with generative adversarial networks and variational autoencoders in terms of scenario quality and risk identification effectiveness. Composite risk index is used to measure overall performance.

Table 3 shows that the diffusion model based method outperforms baseline models in capturing extreme events and improving risk assessment accuracy.

Table 3. Comparison of Different Generative Models

Model	Kullback Leibler Divergence	Composite Risk Index	Accuracy of Extreme Scenario Identification
Variational Autoencoder	0.095	68.3	0.724
Generative Adversarial Network	0.073	75.6	0.815
Proposed Diffusion Model	0.051	87.2	0.926

4.4. Risk Assessment Under Extreme Weather Conditions

Fragility models are applied to evaluate failure probabilities of transmission components under typhoon and extreme temperature. The digital twin simulates cascading failure processes and quantifies system resilience.

Table 4 presents risk indicators under extreme weather. The proposed framework identifies high risk components and supports resilience oriented decision making.

Table 4. Risk Assessment Under Extreme Weather

Extreme Event	Component Failure Probability	Cascading Failure Risk	System Resilience Index
Typhoon Condition	0.087	0.132	0.814
Extreme Temperature	0.115	0.168	0.763

4.5. Performance Validation on IEEE 118 Bus System

To verify scalability, the proposed method is tested on the IEEE 118 bus system. The same evaluation metrics are used to confirm generalization ability.

Table 5 shows consistent performance on a larger test system, proving the framework is suitable for practical large scale power grids.

Table 5. Validation Results on IEEE 118 Bus System

Evaluation Indicator	Value	Performance Evaluation
Average Scenario Fidelity	0.942	High
Composite Risk Index	85.7	Superior
Risk Identification Accuracy	0.913	Effective

4.6. Discussion

Experimental results demonstrate that the integration of digital twin and diffusion model provides reliable operational state generation and accurate risk assessment. Data driven methods enhance the adequacy and security assessment of smart energy networks [26]. Compared with dynamic spatiotemporal graph generative adversarial networks, the proposed approach better captures nonlinear dependence and extreme characteristics [27]. Digital twin enables distributed resilience assessment with explicit modeling of operational uncertainties [28]. The data driven framework integrated with digital twin improves security evaluation in complex power systems [29]. Denoising diffusion models generate critical transmission interface scenarios that support robust risk warning and operational decision making [30].

The proposed method effectively handles uncertainties from renewable integration and extreme events. It generates high fidelity extreme scenarios that traditional methods cannot produce. Digital twin simulation provides quantitative risk metrics for grid operation and planning. Limitations include higher computational cost in diffusion model training and digital twin synchronization. Future work will optimize model efficiency and extend the framework to multi energy systems.

5. Conclusion

This study proposes an integrated framework that combines digital twin technology and conditional denoising diffusion probabilistic models for power system operational state generation and risk assessment. The framework uses public operational data to build high fidelity virtual power grids and generate realistic normal and extreme operation scenarios. Experimental results on IEEE 39 bus and IEEE 118 bus test systems show that the proposed method outperforms traditional generative models in scenario fidelity and risk identification accuracy.

The integration of digital twin and diffusion model effectively addresses the uncertainty challenges brought by renewable energy integration and extreme weather events. It provides reliable quantitative risk indicators and supports robust decision making for power system operation and planning. The proposed approach enriches the application of generative artificial intelligence in physical power system simulation and promotes the development of resilient grid operation technologies.

Limitations of this work include high computational complexity in model training and scenario simulation. Future research will focus on optimizing model efficiency, extending the framework to multi energy systems, and enhancing the physical consistency of generated scenarios for large scale practical power grids.

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