International Journal for Housing Science and Its Applications
Publish September 8, 2025. Volume 47, Issue 1 Pages 138-145

https://doi.org/10.70517/ijhsa47111

Lifecycle management and disaster simulation of power systems based on digital twin and multi-objective optimization

Guiqin Hao[1,*] and Jun Wang[2]
[1]Guang Zhou Electric Power Construction Co., Ltd
[2]Huiyuantong Group Co., Ltd
Corresponding authors: (e-mail: 75467053@qq.com).

Abstract Given the increasing complexity and vulnerability of modern power systems, traditional electric power network (EPN) design and management methods have proven insufficient in the face of extreme weather events such as hurricanes. This paper explores the potential of digital twin (DT) technology as a dynamic tool for real-time monitoring, predictive analysis, and system optimization. By constructing a three-dimensional digital replica of the entire substation infrastructure, the study demonstrates how DT integration can significantly enhance the resilience of power grids and improve the efficiency and accuracy of engineering design processes. A thorough digital twin model of the electric power network is created in this study, which includes important system components such power plants, substations, transmission and distribution lines, and end-user connections. According to simulation results derived from this modeling technique, Hurricane Ike is predicted to result in major power disruptions that will impact the majority of users. In particular, it is estimated that 96.4% of residential structures, 96.0% of commercial buildings, and 94.2% of industrial buildings will experience power outages, illustrating the serious effects of such natural disasters on the supply of electricity in many industries.

Index Terms digital twin, electric power network, power system resilience, hurricane impact, vulnerability analysis

I. Introduction

In the increasingly intricate modern power system, substations are essential hubs for the transmission and distribution of electrical power. The quality of these substations' design and construction has a significant impact on the overall grid's stability and dependability [1]. Nowadays, a lot of detailed drawings, extensive equipment integration, complicated wiring configurations, a lot of virtual circuits, and significant data handling requirements characterize the design process for substation construction drawings, particularly the logical wiring diagrams. Conventional methods that use paper-based or simple electronic drawings have several drawbacks, including hard accessibility, loss risk, and difficulties verifying data. The expectations of modern digital substation operation and maintenance management are not met by these elements, which also make it difficult for construction teams to operate efficiently [2].

Substation design workflows have been increasingly streamlined through the use of digital design tools and three-dimensional modeling software in response to these issues. As a crucial interface that makes it easier to integrate digital technologies into the construction and operational lifecycle, the idea of digital handover is crucial [3].

By creating virtual copies of tangible assets, digital twin technology offers a single platform that unifies the logical and physical components of substations. In addition to improving productivity throughout the design and construction stages, this capacity enables complete lifecycle management and provides precise decision-making support during operation and maintenance [4], [5]. Therefore, there is great practical value and exciting application prospects in furthering research on full-process 3D design of substation infrastructure based on digital twin frameworks as well as investigating cutting-edge digital handover and management systems.

Since digital twin technology allows for real-time monitoring and virtual modeling of actual equipment to improve efficiency and reliability, it is becoming more widely acknowledged as an essential tool for substation operation and management. Despite its potential, there are a number of obstacles to overcome in real-world use.

Building precise and current digital twin models is challenging since substations may contain a variety of intricate equipment. Furthermore, environmental limitations frequently restrict data collecting, and the computational requirements and intricacy of data processing of digital twin systems further impede their broad use.

Numerous ideas have been put up, including integrating machine learning algorithms to increase predictive capabilities and improving sensor networks to improve data quality. These methods, however, are highly dependent on data integrity and frequently call for major changes to current systems, which increases expenses and creates implementation challenges. Furthermore, there are still difficulties in guaranteeing prompt action and accurate decision-making in emergency situations [6], [7].

The majority of digital twin applications in substations today concentrate on the logical and physical modeling phases, while digital handover procedures are still in their infancy. The true potential of digital design is largely restricted to simple layout and cable routing activities due to the fragmentation of design software and the absence of integration between two-dimensional and three-dimensional design data.

Conventional construction drawing transfer techniques are inefficient, have accessibility problems, and lose data, which makes operations more difficult and doesn't meet the demands of digital management. One crucial yet unsolved issue is achieving unified management platforms and a smooth digital handover [8].

Through 3D design and visualization, digital twin technology can increase design and construction accuracy, streamline cooperation, and combine multidisciplinary data on a single platform. Additionally, it makes it possible to track construction and operational status in real time, which improves safety and maintenance efficiency and offers precise decision support [9], [10].

However, its broad application is still limited by expensive implementation costs, demanding data quality requirements, and insufficient standards for logical model creation. Current software frequently only covers a portion of design functions and lacks tools for efficient data exchange. Comprehensive digital design application is further limited by the poor connection between 2D and 3D design data [11], [12].

Based on digital twin technology, this article promotes the creation of integrated digital platforms for substation modeling, handover, and visualization. By digitally managing the full lifecycle—from design and construction to operation and maintenance—these platforms can increase overall project results, improve collaboration, improve construction quality, and lower errors.

II. Research framework

II. A. Data collection and processing for power infrastructure

An electric power network (EPN) typically consists of power plants, substations, transmission lines, distribution networks, and end users [13]. Since power plants are frequently less impacted by hurricanes, they are not included in the suggested digital twin (DT) model. Instead, this DT model focuses on integrating detailed information on the location, properties, and connections of key components to produce a high-fidelity representation of the EPN. Since utility corporations typically own these assets, access to such data is frequently restricted due to privacy concerns. A specific testbed environment is offered where researchers can access pertinent data to hone and validate analytical techniques in order to get over these limitations and promote resilience research [14].

The information is fed into Bayesian Network (BN) models following data preparation and cleaning, creating a directed graph that depicts the network flow from substations to end users. Multinomial trees, which are networks designed so that any two nodes are connected by a single path, are also used in the model [15]. Efficient BN inference algorithms, whose computational cost increases linearly with input size, are made possible by this structure [16]. The majority of power grids in the United States function radially or imitate radial designs [17], making it easy to create a directed network that is free of loops. The shortest path between the start and finish nodes is chosen to break cycles in situations when loops are present [18]. As a result, the EPN model that is produced is a directed network that is connected and clear of loops, making it appropriate for sophisticated vulnerability and reliability research.

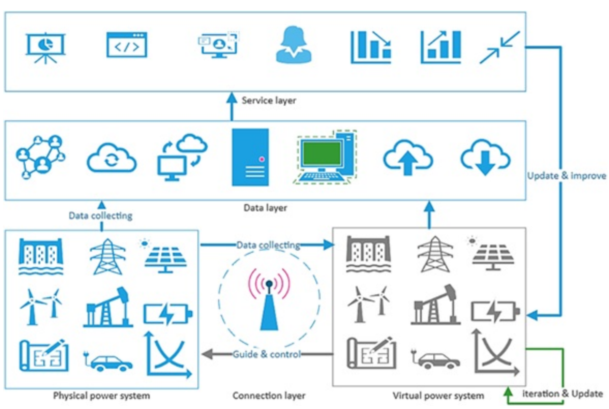

Figure 1: Overview of the digital power network framework

A method of centralizing and combining components into aggregated "super nodes" is used to preserve the network's connectivity and relationships while decreasing its total size. This method lowers computing complexity and improves scalability, and it is backed by current research [19]. Transmission and distribution line depictions usually incorporate distribution poles and towers. Buildings are also categorized into clusters according to their nature and proximity to one another.

DBSCAN (Density-Based Spatial Clustering of Applications with Noise) is a popular spatial clustering technique for this purpose that groups data points based on calculating their maximum distance from one another [20]. Clusters that match terminal nodes in the distribution network can be produced by applying DBSCAN on building data. Without sacrificing the accuracy of the underlying mathematical model, this clustering successfully lowers the number of network nodes. In conclusion, substation, transmission, and distribution nodes will all be included in the suggested Bayesian network (BN) model; more information about their setup and handling will be provided in the sections that follow.

II. B. Modeling digital twins

Creating precise mathematical models that accurately represent the primary design, building, operation, and maintenance processes is crucial to the successful integration of digital twin technology. The development of a synchronized digital duplicate of the physical system is based on these models.

The core concept of a digital twin is to represent the physical environment P within a digital space $\mathcal{D}$. This relationship can be formally expressed as:

$$\mathcal{D}(t) = f(\mathrm{P}(t), S(t), C(t)). \tag{1}$$

This function f(·) encapsulates the data fusion and transformation processes that maintain alignment between the digital and physical systems.

Subsequently, system behavior over time can be modeled through state-space equations:

$$dx(t) = Ax(t) + Bu(t)y(t) = Cx(t) + Du(t). \tag{2}$$

In the following sections, we will extract and analyze key formulas that govern the digital twin model, illustrating their significance in enhancing the precision and effectiveness of the 3D substation design and management process.

II. C. Real-time data update model

For the digital twin system to accurately reflect the current state of the physical substation, it must continuously incorporate real-time data updates. This dynamic update process ensures synchronization between the digital model and its physical counterpart.

The data update at time step t can be mathematically expressed as:

$$\mathbf{D}(t) = \mathbf{D}(t-1) + \Delta\mathbf{D}(t). \tag{3}$$

This increment $\Delta\mathbf{D}(t)$ can be further detailed as a function of sensor measurements $\mathbf{S}(t)$ and system events $\mathbf{E}(t)$:

$$\Delta\mathbf{D}(t) = g(\mathbf{S}(t), \mathbf{E}(t)), \tag{4}$$

where g(·) represents the data processing and integration function, which may include filtering, validation, and fusion operations.

In practical applications, this formula enables the digital twin to continuously refine its state, supporting accurate monitoring, diagnostics, and decision-making throughout the substation's lifecycle.

II. D. Multi-objective design optimization model

The 3D design process of substation infrastructure involves balancing multiple objectives simultaneously, making it a classic multi-objective optimization problem. The general formulation of this optimization problem can be expressed as:

$$\min_{\mathbf{x}} \quad \mathbf{F}(\mathbf{x}) = (f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_k(\mathbf{x})), \tag{5}$$

subject to the constraint:

$$mg_j(\mathbf{x}) \leq 0, \quad j = 1, 2, \ldots, m, \tag{6}$$

where, $\mathbf{x}$represents the design variable vector, encompassing parameters such as spatial coordinates, component configurations, and wiring layouts, $f_i(\mathbf{x})$are the objective functions to be minimized (or maximized), which may include factors like construction cost, spatial efficiency, safety margin, and maintenance accessibility, $g_j(\mathbf{x}) \leq 0$denote the constraint functions that ensure design feasibility, compliance with engineering standards, and physical limitations.

In order to give decision-makers a range of ideal trade-offs, the solution to this multi-objective optimization aims to identify a Pareto-optimal collection of designs that balance conflicting objectives. Through the methodical integration of numerous criteria and limitations into the optimization process, this framework facilitates effective and efficient substation 3D design.

II. E. Vulnerability assessment

Every system component underwent a thorough vulnerability evaluation during the suggested framework's implementation phase. Conditional probabilities obtained from fragility functions, which characterize the probability of failure at different hazard intensities, are used to quantify the risk level associated with each component.

The probability of failure $P_f$of a physical component can be expressed as:

$$P_f = F(V_w, \theta_w, V_f, H_s, H_w, H_p, t_p, A_c). \tag{7}$$

A parametric vulnerability function specifically developed for wooden utility poles integrates these factors. This function models the fracture limit states corresponding to different pole classes (Class 3, 4, and 5), incorporating the soil rigidity coefficient α\alpha$\alpha$ to ω [reference]. The fragility function F captures the probability that the pole exceeds its structural capacity under given environmental loads.

The survival probability $P_s$for each power grid element is then calculated as the complement:

$$P_s = 1 - P_f. \tag{8}$$

Figure 2(a) illustrates a multidimensional fragility surface, showing how varying wind speed v_w, wind direction θ_w, surge height H_s, and wave height H_w influence the failure probability, while other parameters remain constant.

This vulnerability analysis facilitates risk-informed decision-making in power network management and allows for a probabilistic understanding of system resilience. Substations may be less directly affected by wind damage, but they are especially susceptible to flooding from hurricanes and strong rains. Certain vulnerability curves, derived from FEMA recommendations and supported by current research, define the susceptibility of substations to flood events. The flood water height F (in meters) is the primary intensity parameter used to evaluate the impact of flooding (see Table 1). Figure 2(c) illustrates the substation flood vulnerability curve, which measures the likelihood of damage rising with flood height.

For transmission lines—comprising components such as poles or towers—the overall probability of damage P_L can be computed once the individual vulnerability functions for each of the n elements along the line are known. The combined damage probability is given by:

$$P_L = 1 - \prod_{i=1}^{n} (1 - P_i), \tag{9}$$

where P_i is the failure probability of the i-th element in the transmission line.

This formula assumes statistical independence between element failures and calculates the probability that at least one component fails, thereby causing damage to the entire line.

Table 1: Brittleness Functional Coefficients for Wooden Utility Poles ([17])

Pole class	Soil rigidity coefficient $\boldsymbol{\alpha}$	WindSpeed threshold $V_{w,th}$ (m/s)	Age factor t_p (years)	Fracture Limit F_l (kN·m)
Class 3	0.85	30	20	150
Class 4	0.90	35	15	180
Class 5	0.95	40	10	210

Notes: A : Soil rigidity coefficient affecting pole stability. $V_{w,th}$: Critical wind speed beyond which brittleness sharply increases. t_p: Age of the pole, accounting for material degradation. F_l: Fracture limit indicating the maximum bending moment the pole can withstand before failure.

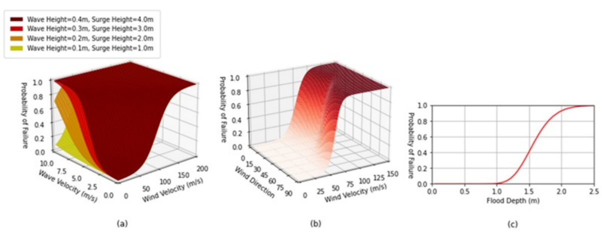

Figure 2: Structural and Functional Vulnerability of Power Infrastructure Under Extreme Weather Conditions

III. Application case study

III. A. implementation of a digital twin-based test platform

This section uses a case study that simulates a hurricane impact scenario in Guangzhou to show how the suggested Digital Twin (DT) framework can be used in practice. The local electric power network (EPN), which consists of substations, transmission towers, utility poles, and client buildings, was the subject of an extensive data collection effort. About 22,500 residential buildings, 2,900 commercial buildings, and 400 industrial facilities make up the improved EPN dataset. Ten substations, 55 transmission towers, and 14,000 utility poles are examples of infrastructure components. The DBSCAN clustering algorithm was used, balancing cluster size and accuracy, with a maximum clustering radius of 35 meters to improve computational efficiency and model fidelity. 260 industrial clusters, 1,200 commercial clusters, and 2,000 residential clusters were the end results.

Disconnected leaf nodes at the ends of distribution lines were pruned and consolidated to streamline the network. The finalized DT-based EPN model consists of 2,750 distribution lines, 1 major transmission line, and 10 substations (see Figures 3–5).

Figure 3 illustrates the network topology on Guangzhou Island, while Figures 3(a) and 3(b) present the EPN before and after clustering respectively.

Assuming component failures X_i follow independent Bernoulli distributions with failure probabilities p_i, the expected number of failures $\mathbb{E}[F]$for each component type is calculated as:

$$\mathbb{E}[F] = \sum_{i=1}^{n} p_i, \tag{10}$$

where n is the total number of components of the specific type.

The vulnerability function $p_i = f(hazard, intensity)$is derived from prior fragility analyses.

Simulation results reveal that utility poles are most affected, with an estimated 230 failures, whereas transmission towers experience minimal impact, with approximately 12 expected failures. Among the 10 substations, flooding impacted 5 sites, and their failure probabilities exhibited a strong positive correlation with flood height levels F (in meters), modeled by:

$$p_{substation} = 1 - e^{-\beta F}, \tag{11}$$

where $\beta$is a fitted parameter reflecting flood sensitivity.

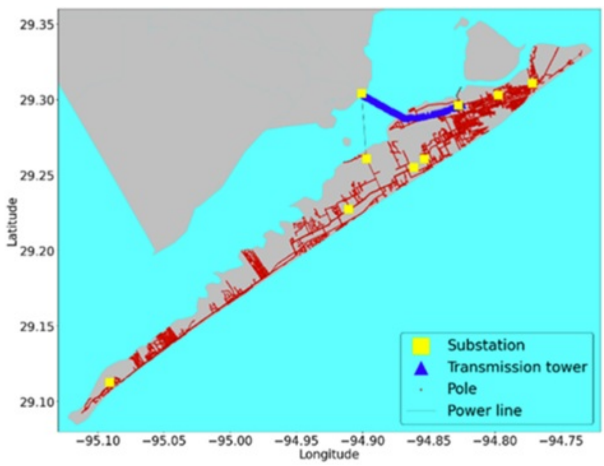

Figure 3: An illustration of how the Guangzhou Island EPN is incorporated into the DT model

A Bayesian Network (BN) model comprising 8,200 nodes of the electric power network (EPN) was created using specialized software in accordance with the process shown in Figure 6(a). The Environmental Vulnerability Function (EVF) and associated algorithms were used to estimate the likelihood of consumer power interruptions. According to the model, power outages are anticipated to affect about 94.8% of subscribers. The estimated outage rates for residential, commercial, and industrial buildings are 95.1%, 94.5%, and 92.7%, respectively, and decision-makers can modify weights according to various land use types and building functions.

Stakeholders are especially interested in outages that happen right after repairs because substations usually need regular maintenance. The recovery phase was replicated by updating the BN with repair status information. The findings displayed in Figure 6(b) demonstrate that, even when the power supply has been restored in certain areas, the model still emphasizes the possibility of extensive outages brought on by distribution pole failures, assuming that all substations have been fully restored.

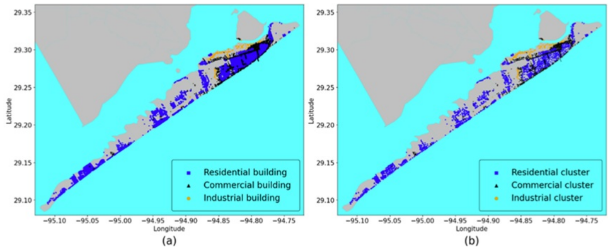

Figure 4: Construction of formwork

Figure 5: The estimated likelihood that an EPN element will fail

According to historical data, Hurricane Ike caused disruptions that affected over 3.2 million consumers in nine states, damaging about 210 transmission towers, 350 substations, and 9,000 utility poles. The transmission system in the Houston metropolitan region was mainly unharmed, although the majority of the damaged transmission towers were located in East Texas and Louisiana. Houston's outages were mostly caused by damage to substations and distribution lines, necessitating the replacement of about 7,800 utility poles.

Four substations on Guangzhou Island also experienced floods; three of them were fixed in three days, but one needed to be replaced entirely. The day after the hurricane, Guangzhou Island and the Bolivar Peninsula saw practically complete blackouts, with customer outage rates approaching 98%, according to reports from major power providers serving the Houston area. Near-total outages are predicted by the Digital Twin model for a large portion of Guangzhou Island, which closely resembles historical data (see Figure 6(a)). Additionally, the model predicts increased failure rates for utility poles and substations but relatively low failure probabilities for transmission towers.

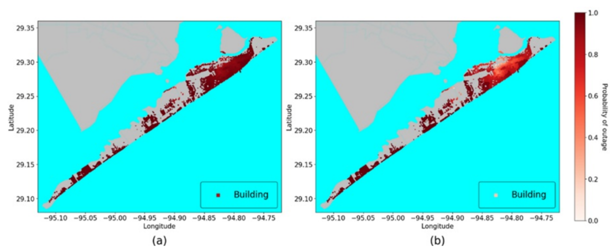

Figure 6: (a) Architecture of the EPN on Guangzhou Island before and after building clustering; (b) Predicted power outage restoration status after substation repairs based on the DT

III. B. Practical implementation example

This study confirms the feasibility and effectiveness of the proposed solutions by implementing and continuously improving an innovative digital management strategy for power grid infrastructure projects using the 220 kV Forest Power Transmission and Transformation Project as a real-world case study.Throughout the design process, the adage "what you see is what you get, and what you get is what you build" is applied. First, using Autodesk Revit software, detailed 3D models of the electrical and civil components are created utilizing the 2D design drawings as a basis.

By directly connecting construction activities to features in the 3D model, the platform facilitates the idea of "completion where displayed" during the building process. As seen in Figure 7, the system dynamically visualizes progress along a timetable and automatically confirms that the construction procedure is reasonable. With each 3D object reflecting a corresponding physical construction entity, this user-friendly interface allows project managers to track the progress of building activities in real time.

Lastly, the system manages progress payments by putting the idea of "what is constructed is recorded, and what is recorded is paid" into practice. Payment details can be submitted and connected to work progress because each created entity correlates to a 3D model item. This partnership enhances the openness and precision of project financial tracking by giving stakeholders direct access to payment details through the 3D model on the digital management platform.

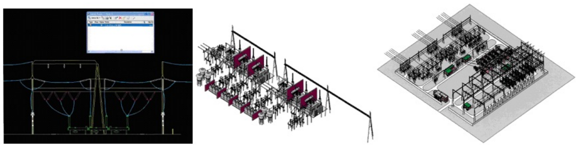

Figure 7: Dynamic visualization of construction progress and task monitoring on the digital management platform based on the 3D substation model

IV. Conclusion

This study assesses a comprehensive 3D digital twin-based design framework for substation engineering infrastructure using a real-world case study on Guangzhou Island. A comprehensive and precise EPN model is created by utilizing digital twin technology for power system modeling, incorporating essential elements such substations, transmission and distribution networks, and end consumers. Power system design and operational management are improved by using a loop-free, connected directed network structure in conjunction with multinomial trees, which maximizes computing efficiency and modeling accuracy. The study offers a thorough evaluation of failure probabilities across different power system components through the extensive use of vulnerability functions and BN modeling. The findings show that poles, substations, and transmission towers all differ significantly in their vulnerability, with poles and substations failing more frequently than transmission towers.

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