A Resilient Integrated Resource Planning Framework for Transmission Systems: Analysis Using High Impact Low Probability Events

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***Abstract*—This paper presents a Resilient Integrated Resource Planning (IRP) framework for transmission systems, specifically focusing on the analysis of High Impact Low Probability (HILP) events. The framework addresses the need to assess and enhance the resilience of transmission networks in the face of extreme events. Conventional reliability-based planning methods typically average the impact of various outage durations, whereas resilience-oriented studies prioritize the analysis of events with significant consequences. Therefore, this work adopts a metric based on the proximity of outage lines to generators to select HILP events. The base resilience of the system is evaluated by calculating load curtailment in various network components resulting from HILP outage events. The transmission network is represented as an undirected graph, and graph theoretic technique is employed to identify islands with or without generators, which can potentially form microgrids. Expected Load Curtailment and Expected Critical Load Curtailment are introduced as metrics to measure the system's resilience. The framework also enables the re-evaluation of system resilience by incorporating additional resources to achieve desired resilience levels. Case studies on the IEEE 24-bus system demonstrate the capabilities of the proposed framework. Overall, the resilient IRP framework proposed in this paper provides valuable insights for optimizing resource placement and planning decisions, enhancing the robustness and resilience of transmission networks.**

***Index Terms*—High Impact Low Probability Events, Integrated Resource Planning, Load Curtailment, Resilience, Resilience Metrics, Transmission Systems.**

I. Introduction

Modern power systems face significant challenges in maintaining reliable electricity access and availability in the face of extreme weather events and other high-impact low-probability (HILP) disruptions. These events can have severe consequences, leading to widespread power interruptions and incurring substantial costs. For instance, Winter Storm Uri in Texas, United States, in February 2021 caused widespread power interruptions that left 4.5 million customers without power supply [1]. Moreover, during the year 2022 alone, there were 18 weather-related disasters in the United States, each costing more than $1 billion [2]. These incidents underscore the urgent need for tools to measure resilience and planning strategies using these measures that can lead to strategies to enhance the grid's ability to withstand and recover from such events.

Resilience enhancement strategies for electric power supply have gained significant interest in recent years due to the increasing reliance on electricity access and the rising frequency and intensity of extreme weather events. These strategies aim to bolster the resilience of power systems, employing both planning-based and operation-based approaches [3]. Operation-based strategies focus on optimizing the deployment of existing resources to efficiently mitigate the impact of extreme events and subsequent outages. In contrast, planning-based strategies concentrate on expanding electricity infrastructures to fortify them against potential future events, prioritizing the selection of investments that ensure reliable and resilient power supply to end-use customers. Planning-based strategies may include the installation of underground cables, energy storage planning, and other measures.

Existing research has explored various planning-based strategies to enhance the resilience of power systems. Nazemi et al. [4] formulated an optimization problem using linear programming to plan energy storage deployment for earthquake resilience. They developed a new metric that quantifies the resilience of distribution networks considering uncertainties (e.g., location, duration, and level of impact) associated with extreme events, utilizing fragility curves to assess the potential impacts of earthquakes on distribution system components. Huang et al. [5] proposed a resilience-oriented planning strategy for optimal configuration of urban multi-energy systems, comprehensively analyzing impacts from the supply, network, and demand sides. They developed a comprehensive energy storage model and used linear modeling to evaluate the effects of energy redistribution and combined heat and power. In [6], a planning-oriented resilience assessment framework was developed to assess the resilience of the power system against typhoon disasters and determine its weak points. By analyzing the impacts of various potential typhoon disasters on each transmission corridor, the resilience of the power system could be comprehensively investigated, and the weak points of the system fully determined. Additionally, the framework could further guide the resilience enhancement measures to strengthen the weak points, such as expanding or upgrading the vulnerable transmission corridors. The paper by Ranjbar et al. [7] has presented a joint transmission system and Distributed Energy Resource (DER) planning model for improving power system resiliency, considering both the normal and emergency operating situations and the duration of each situation. Moreover, the emergency condition was modeled by a set of damage scenarios based on three damage states, i.e., moderate damage, severe damage, and complete damage for transmission system components. While these studies have significantly enriched the field of power system resilience planning, there remains a notable research gap. Specifically, there is a need for a holistic framework that not only identifies vulnerable points in the system but also quantifies resilience, and enables integrated resource planning to achieve desired resilience levels.

In this paper, we present a Resilient Integrated Resource Planning (IRP) framework specifically tailored for transmission systems, focusing on the analysis and evaluation of HILP events. Our framework aims to assess and enhance the resilience of transmission networks by considering the proximity of outage lines to generators as a metric for selecting HILP events. Through the generation of numerous random line outage scenarios, we selectively analyze HILP events to evaluate the system's base resilience. Additionally, we incorporate additional generating resources in the framework to re-evaluate system resilience based on desired levels. By quantifying load curtailment and introducing resilience metrics such as Expected Load Curtailment (ELC) and Expected Critical Load Curtailment (ECLC), our framework provides a comprehensive assessment of system resilience. To demonstrate the effectiveness of our proposed framework, we conduct case studies on the IEEE 24-bus system, showcasing its capabilities and potential for optimizing resource placement and planning decisions. By advancing the field of resilient power system planning, our research contributes to the development of more robust and resilient transmission networks capable of withstanding and recovering from disruptive events.

The rest of the paper is arranged as follows. Section II describes the proposed framework and solution approach. Section III validates the proposed work through case studies. Section IV provides concluding remarks.

II. Proposed Framework

This section presents the proposed framework for the IRP of resilient transmission systems. The framework provides a comprehensive approach to address the unique challenges posed by HILP events. By incorporating three distinct stages, the framework offers a systematic process to evaluate the base case resilience of the system, selecting HILP events, and re-evaluate resilience with the addition of new resources. Each stage contributes to a holistic understanding of the system's resilience and facilitates informed decision-making in integrated resource planning.

The transmission network, consisting of generators, loads, buses, transmission lines, and transformers, is modeled as a graph using graph theoretic techniques. In this graph representation, buses are represented as nodes, and lines/transformers are represented as edges. By linking generator and load information to the respective buses, the need to model them separately in the graph is eliminated. Under node information,

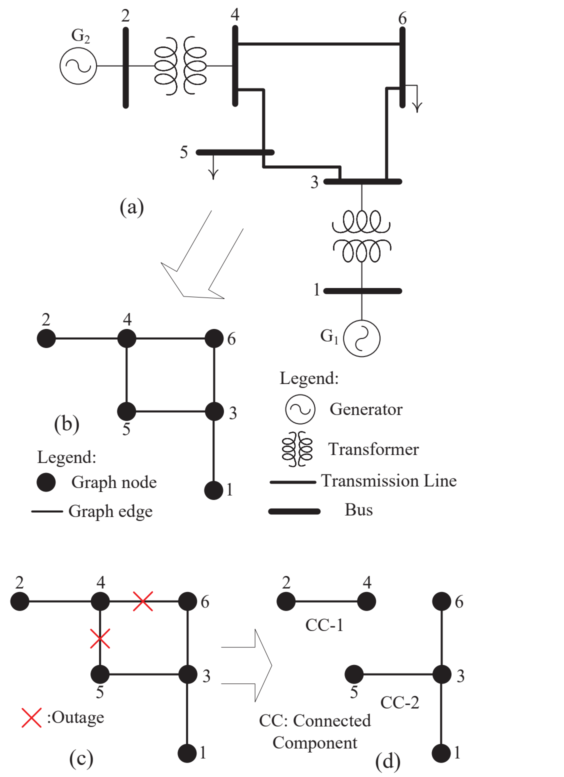

Fig. 1. (a) Hypothetical 6-bus transmission network, (b) Graph theoretic representation of the network, (c) Outage of lines 4-5 and 4-6 in the network, (d) Formation of two connected components (or islands) as a result of the outage

all connected generators and load information associated with a particular bus can be obtained. Fig. 1.(b) shows the graph theoretic representation of a hypothetical 6-bus transmission network (Fig. 1.(a)).

The transmission network is represented by an undirected graph denoted as $\mathcal{G} = (\mathcal{N}, \mathcal{E})$, where $\mathcal{N}$ represents the set of nodes (or vertices), and $\mathcal{E}$ represents the set of edges (or branches). This graph model provides a clear visualization and mathematical representation of the interconnected components of the transmission system.

Furthermore, the concept of connected components from graph theory is leveraged in this work. A connected component of an undirected graph is defined as a maximal set of nodes where each pair of nodes is connected by a path [8]. In other words, within a connected component, there is a direct or indirect path between any two nodes. Connected components play a crucial role in understanding the system's behavior and resilience as they represent distinct networks within the transmission system. By identifying and analyzing these connected components, insights can be gained into the system's structural integrity, load distribution, and vulnerability to disruptions. Fig. 1.(d) shows the formation of two connected components in the hypothetical 6-bus transmission network after the outage of lines 4-5 and 4-6 (shown in Fig. 1.(c)). The first connected component (CC-1) comprises of nodes 2 and 4, and the second connected component (CC-2) comprises nodes 1, 3, 5, and 6.

By incorporating graph theoretic modeling and leveraging

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the concept of connected components, the proposed framework provides a robust analytical foundation for assessing and enhancing the resilience of transmission systems. The subsequent subsections delve into the details of each stage, outlining their objectives, methodologies, and contributions towards a comprehensive understanding of the system's resilience.

A. Outage Data Generation and Selection of HILP Events

The first stage of the proposed framework involves the generation of outage data and the selection of HILP events. To comprehensively assess the resilience of the transmission system, a large number of randomly generated line outage scenarios are generated from a uniform distribution. These scenarios represent a wide range of potential disruptions that the system may encounter. By considering a diverse set of outage scenarios, the framework aims to capture the full spectrum of potential multiple line outages that can impact the system's resilience.

In order to select HILP events from the randomly generated line outage scenarios, a metric based on the proximity or closeness of the outage lines to the generators, referred to as proximity index (PI), is employed. The rationale behind this metric is rooted in the understanding that when outages occur in close proximity to generators, the likelihood of experiencing a higher curtailment of loads within the system increases. By assessing the proximity of outage lines to generators, the framework identifies events that have a higher probability of causing significant disruptions and load curtailments. The PI of the i^{th} scenario is mathematically expressed as follows:

$$PI_i = \sum_{k=1}^{N_i} C_{ik} \tag{1}$$

where N_i is the total number of outaged lines in the i^{th} scenario and C_{ik} is a binary variable that equals 1 if the k^{th} line of the i^{th} scenario is connected to a generator and 0 otherwise.

A threshold is set to determine whether an event qualifies as an HILP event. This threshold ensures that the number of line outages surpasses a certain level, indicating that the event has a substantial impact on the system. By setting an appropriate threshold, the framework focuses on events that have a relatively low probability of occurrence but can have a severe impact when they do occur. This approach aligns with the resilience-oriented perspective, as it allows for a targeted analysis of events that are most likely to challenge the system's resilience. The binary condition expressed in (2) is used for selection of an HILP event.

$$\text{HILP Selection:} \begin{cases} \text{HILP Event} & \text{if } PI_i \geq PI_{th} \\ \text{Not HILP Event} & \text{otherwise} \end{cases} \tag{2}$$

where PI_{th} is the threshold of the PI, which is set to six in this study.

B. Evaluation of the Base Case Resilience of the System

The second stage of the proposed framework focuses on evaluating the base case resilience of the transmission system. This evaluation is conducted without introducing any additional generating resources into the system. Instead, the analysis centers around leveraging the inherent capabilities of the existing system, such as the formation of microgrids, to enhance resilience.

During an HILP outage event, the transmission system may be divided into multiple connected components (or islands), some of which may contain generators while others may not. Graph theoretic techniques are applied in this stage to identify these connected components within the system. By identifying the distinct networks of connected components, it becomes possible to assess the impact of the outage on each network and quantify the resulting load curtailment.

The evaluation of base case resilience involves calculating the load curtailment for each network of connected components. This assessment provides valuable insights into the system's ability to withstand and recover from disruptive events. By quantifying the amount of load curtailment, a realistic picture of the system's performance under various HILP outage scenarios can be obtained.

Two key resilience metrics are introduced in this stage: Expected Load Curtailment (ELC) and Expected Critical Load Curtailment (ECLC). ELC represents the expected value of the total load curtailments across all HILP outage scenarios considered. It provides an aggregate measure of the system's resilience, taking into account the probability and magnitude of curtailed loads. ECLC, on the other hand, focuses specifically on the curtailment of critical loads during the computation. Critical loads refer to those essential for maintaining critical functions or services within the system. By considering the curtailment of critical loads, ECLC provides a more targeted measure of the system's ability to sustain essential operations during disruptive events. ELC and ECLC are calculated as follows:

$$ELC = \sum_i P_i \times LC_i \tag{3}$$

$$ECLC = \sum_i P_i \times CLC_i \tag{4}$$

where P_i represents the probability of the i^{th} HILP event, LC_i is the amount of load curtailed during the i^{th} HILP event, and CLC_i is the amount of critical load curtailed during the i^{th} HILP event.

C. Re-evaluation of System Resilience with Additional Resources

In the earlier stages, the outage scenarios were generated and the system's base case resilience was assessed. Building upon these foundational assessments, the third and final stage of the proposed framework focuses on re-evaluating the system's resilience after incorporating additional resources. This stage allows for the assessment of how the introduction of these resources impacts the system's ability to withstand and recover from HILP events.

In this stage, various resources can be added to the system based on the desired level of resilience. These resources may include renewable energy sources, energy storage systems,

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microreactors, or other options (e.g., reclosers, microgrid, strengthening of infrastructures, etc.) that enhance the system's capacity and flexibility. The selection and placement of these resources are guided by the insights gained from the previous stages of the framework.

By strategically incorporating additional generating resources, the framework aims to improve the system's resilience by reducing load curtailment and enhancing the ability to meet demand during HILP events. The placement of these resources takes into account the identified vulnerabilities and critical points of failure in the system. The goal is to optimize the allocation and utilization of resources to achieve the desired level of resilience.

Once the additional generating resources have been integrated into the system, a re-evaluation of the system's resilience is conducted. This evaluation involves repeating the analysis performed in the previous stages with the updated system configuration. The performance of the system under HILP outage scenarios is assessed, taking into account the capabilities and benefits offered by the added generating resources.

III. Case Studies and Discussion

In this section, we present case studies conducted on the IEEE 24-bus system [9], also known as the Reliability Test System (RTS). Our aim is to showcase how the proposed resilient IRP framework works. The IEEE 24-bus system is commonly used as a benchmark in power system analysis. It comprises 24 interconnected buses linked by transmission lines and transformers, which provides a simplified but realistic representation of an actual power system. Within this context, the system includes 11 generator buses (including the slack bus), 13 load buses, 5 transformers, and 29 lines (including 4 double-circuit lines which have been treated as single lines). We create an undirected graph, treating buses as vertices and branches (lines and transformers) as edges in the graph. This graph theory-based approach helps us visually understand and study the system's structure and connections, forming the basis of our case studies. The Python package "pandapower" [10] is employed to conduct power flow analyses within both the primary network and isolated network segments.

To demonstrate the framework's effectiveness, we explore a wide range of 10,000 randomly generated multiple line outage scenarios within the IEEE 24-bus system. We evaluate each scenario to determine if it falls into the category of an HILP event, based on our proposed proximity index-based criteria. This index calculates the number of outage lines that are close to the generator buses, allowing us to identify scenarios that could lead to significant disruptions. We then focus our attention on the HILP events, as they provide valuable insights into the system's resilience. By utilizing the introduced resilience metrics, we quantitatively assess how the system responds to these HILP scenarios.

Illustrative figures play a pivotal role in conveying the details of our case study findings. Fig. 2 and Fig. 3 depict two representative outage scenarios selected from the 10,000 randomly generated instances. In scenario 1, the outage involves a set of six transmission lines: 2-6, 3-9, 7-8, 11-13, 16-17, and 20-23. Conversely, scenario 2 encompasses the outage of lines 2-6, 7-8, 11-13, 15-21, 16-17, and 20-23, with the sole distinction being the substitution of line 3-9 from scenario 1 with line 15-21. Although both scenarios entail six line outages, only the latter, scenario 2, is classified as an HILP event. This classification is based on the proximity index (PI), which evaluates the direct connections between outaged lines and generator buses. Please note that the PI for scenario 2 is six, surpassing the PI threshold of six, while the PI for scenario 1 is five, which falls just below the PI threshold.

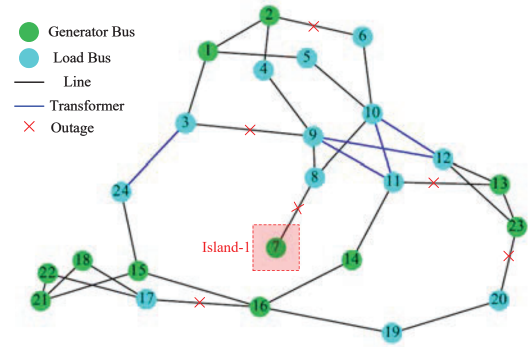

Fig. 2. Analysis of outage scenario 1 showing an island formed in the IEEE 24-bus system

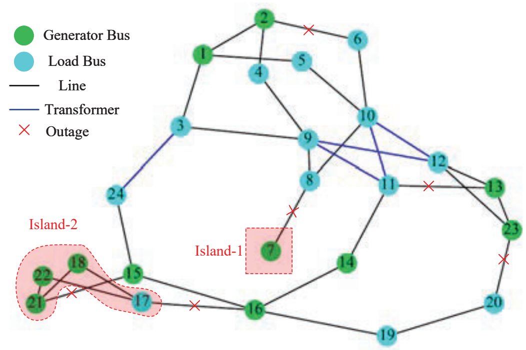

Fig. 3. Analysis of outage scenario 2 showing islands formed in the IEEE 24-bus system

Delving deeper into the analysis of each line outage scenario, we delve into the computation of the total load curtailment. Scenario 1 illustrates a situation where bus 7 becomes isolated, leading to the formation of an isolated island. Remarkably, within Island-1, comprising bus 7, the total load of 125 MW is less than the total available generation of 300 MW, resulting in an absence of load curtailment. The remainder of the primary network similarly showcases the total available generation of 3105 MW, surpassing the total load of 2725 MW, thus avoiding the need for load curtailment. Consequently, scenario 1 turns out to have zero total load curtailment.

In contrast, scenario 2 introduces a more intricate scenario,

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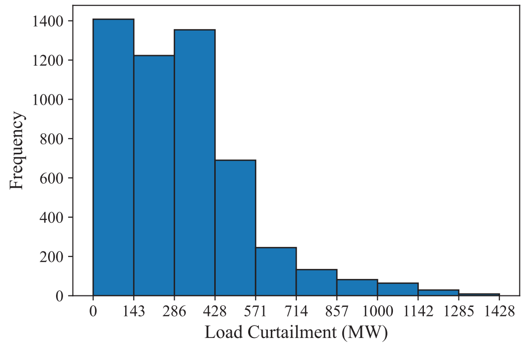

Fig. 4. Distribution of load curtailment in HILP scenarios

where two islands are formed. Island-1, resembling the isolated island from scenario 1, once again experiences no load curtailment. Island-2 consists of three generator buses (18, 21, and 22) and a load bus (17). With a total generation capacity of 1100 MW exceeding the load demand of 333 MW, Island-2 remains free from curtailment. However, the disconnection of these islands from the primary network results in the load curtailment. The total load of 2392 MW within the primary network necessitates a generation capacity of 2447.37 MW, yet the available capacity remains confined to 2005 MW, leading to a load curtailment of 442.37 MW. Therefore, the total load curtailment is 442.37 MW in scenario 2.

The analysis of these scenarios reinforces the rationale behind selecting HILP events, with scenario 2 showcasing a more pronounced disruption due to its higher load curtailment. This justifies the HILP classification approach based on the proximity index. Building on this analysis, we advance to the second stage, where we assess the base case resilience of the system by computing ELC and ECLC based on load curtailments and critical load curtailments for each identified HILP scenario. Out of 10,000 randomly generated multiple line outage scenarios, there were 5,237 HILP scenarios. The distribution of load curtailment in HILP scenarios is shown in Fig. 4. We obtained an ELC of 304.35 MW and an ECLC of 135.42 MW, assuming all loads in buses 2, 3, 4, 7, 18, and 19 are critical loads. Subsequently, the third stage follows a similar course, involving a reevaluation of these resilience metrics. This stage entails the incremental addition of supplementary resources until the desired level of resilience is achieved. For the desired values of ELC=198 MW and ECLC=85 MW, one possible solution is the installation of DERs at buses 2, 7, and 19, each having a capacity of 100 MW.

IV. Conclusion and Future Work

In this paper, we have presented a resilient Integrated Resource Planning (IRP) framework for transmission systems, which addresses the challenges posed by High Impact Low Probability (HILP) events. The framework encompasses three stages: Outage Data Generation and Selection of HILP Events, Evaluation of Base Case Resilience, and Re-evaluation of System Resilience with Additional Resources. By leveraging graph theoretic modeling and considering connected components, the framework offers a systematic approach to evaluate, enhance, and optimize the system's resilience.

Through the application of the proposed framework, we gain valuable insights into the vulnerabilities and behavior of the transmission system under HILP events. The evaluation of base case resilience provides a benchmark for measuring system performance, while the selection of HILP events focuses on disruptive events with significant impacts. The subsequent re-evaluation stage allows us to assess the effectiveness of additional resources in improving system resilience. By quantifying resilience metrics such as Expected Load Curtailment (ELC) and Expected Critical Load Curtailment (ECLC), the framework facilitates informed decision-making in resource allocation to enhance the system's ability to withstand and recover from disruptions.

In future research, a potential avenue to explore is the determination of the optimal placement of generating resources, such as renewable energy sources, energy storage systems, or microreactors, considering the resilient planning of the transmission system. This involves developing advanced optimization models that take into account various factors, including cost-effectiveness, reliability, and environmental sustainability. By incorporating these factors into the decision-making process, we can identify the most effective locations for deploying generating resources to enhance the system's resilience.

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