Enhancing Reliability and Resilience via Optimal Transmission Project Scheduling

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***Abstract*— This paper introduces a novel approach for optimizing the selection and scheduling of a portfolio of transmission projects proposed to enhance transmission system reliability and resilience. The methodology focuses on selecting and scheduling transmission projects across the various geographic zones to improve system reliability and resilience after the projects are completed while minimizing potential customer and critical load interruptions during the construction phase. The proposed optimization model aims to achieve or exceed reliability and resilience targets during the planning horizon while accommodating budgetary constraints and limitations on crew availability. A case study demonstrates the approach's effectiveness in simultaneously improving reliability metrics and resilience impact.**

Keywords—project scheduling, critical load, noncritical load, reliability, resilience, optimization

I. Introduction

A. Background and Motivation

The modern power grid is constantly evolving, driven by integrating renewable energy sources, changing demand patterns, and the need for enhanced operational efficiency [1-2]. As these dynamics reshape the power system landscape, ensuring its reliability and resilience remains paramount. On the other hand, extreme weather-related occurrences like hurricanes, earthquakes, and floods are intensifying in island regions vulnerable to these threats, necessitating strategies to strengthen the reliability and resilience of the electrical infrastructure supporting the power system of these areas [3]. As shown in Fig. 1, the Puerto Rico (PR) power system contains about 1,134 miles of transmission lines, 1,549 miles of sub-transmission lines, 279 38 kV substations, and 61 115 kV substations [5]. Several major and exceptional events occurred near the PR region in recent years. For example, Hurricane Irma approached PR closely with Category 5 winds, causing considerable flooding, extensive power outages, and interruptions to the water supply on September 6, 2017. Fourteen days later, Hurricane Maria (Category 4) hit PR, causing widespread power outages, severe flooding, mudslides, and extensive infrastructure damage [6-7]. In addition, the storm severely disrupted water service throughout the island. Such high-impact catastrophes generate long-duration outages, significantly affecting the island regions' economies, social welfare, and public health. Electric utilities must offer their consumers with power that is safe, affordable, and dependable. A large number of new transmission and sub-transmission projects were proposed to improve the reliability and resiliency of the PR electric transmission system. The projects can be classified into four categories:

1) Hardening for reliability and resilience
2) New line for resilience
3) New line for N-1 reliability improvement
4) Line rebuild for N-1 reliability improvement

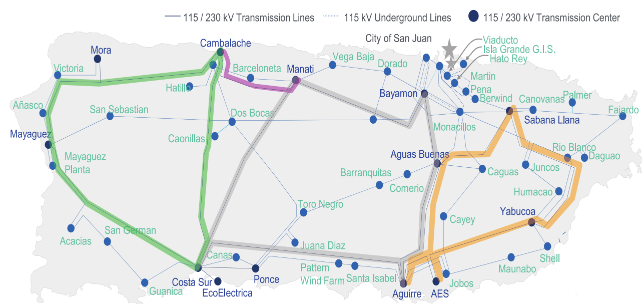

Fig 1. Puerto Rico Transmission Network [4]

These new transmission line projects are pivotal in fortifying the grid against contingencies and enhancing system reliability and resilience. When many transmission line projects are proposed to be built in one area or a relatively small power grid, the impact of the transmission line outages and their sequence during the construction phase need to be optimized to reduce adverse impacts on customer service reliability, while meeting overall program objectives and constraints. These include program scheduling horizon, available budget, and crew.

B. Contribution of this Paper

This paper proposes an innovative optimization approach that aligns transmission project scheduling with the twin objectives of enhancing reliability and resilience. The core idea is to utilize an analytical optimization approach to select and schedule projects that maximize system reliability and resilience benefits without sacrificing customer reliability during the construction phase, and while meeting schedule, budget, and

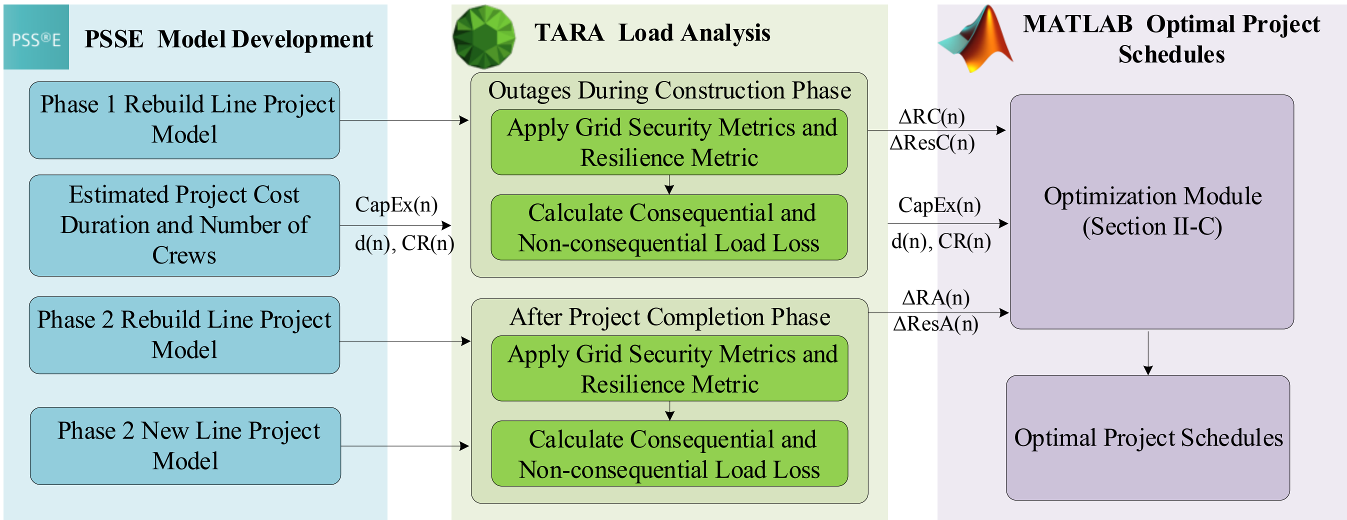

Fig. 2 Optimizing Transmission/Sub-Transmission Project Schedules

crew availability. The proposed approach can optimize amongst a large number of proposed transmission projects in a systematic and consistent manner.

The rest of the paper is structured into two main sections. In the first section, we cover the methodology behind this innovation, discussing the optimization approach and how we model reliability and resilience metrics. The second section provides a practical application of the approach through a detailed case study.

II. Project Schedules Optimization Methodology

This section proposes the optimization approach of transmission project schedules to enhance transmission system reliability and resilience while accommodating crew availability and total budget. The overall structure of the proposed project scheduling method is shown in Fig.2. The approach consists of three parts: 1) project modeling, 2) project impact analysis in terms of consequential load and non-consequential load loss, and 3) project schedule optimization.

A. Model Development

Transmission system reliability network upgrade (RNU) projects are typically proposed to strengthen the grid's reliability against potential contingencies to mitigate line overloads or voltage violations and enhance the system resilience and restoration speed against severe high-impact events. These projects are modeled in PSS/E 35.4 as change files and then analyzed using PowerGEM TARA for their consequential and non-consequential load drop and security-constrained dispatch analysis. As the projects will upgrade long miles of transmission and sub-transmission lines, the project conductor parameters (e.g., impedance, rating, etc.) were modeled from circuit breaker to circuit breaker. Total cost of each project was estimated based on the transmission line lengths, voltage levels, and conductor types.

Each project schedule is divided into two phases:

1) Phase 1: Project Construction
2) Phase 2: Project Post-completion

In Phase 1, the transmission/sub-transmission line will be de-energized for the rebuild, while in Phase 2 the project will be assumed in service.

The impact of each project is analyzed in phase 1 and phase 2 and quantified as consequential load drop and non-consequential load drop. Furthermore, the criticality of the load is taken into account.

B. Consequential Load and Non-consequential Load Loss Analysis

Proper metrics should be selected to realistically characterize the reliability and resilience of the power system. In this subsection, grid security metrics and resilience metrics are introduced.

- **Grid Security Metrics**

Two metrics are used to determine the grid security impact of capital projects: 1) the consequential and 2) the non-consequential load drop. Consequential load drop is defined as the loss of load as a direct result of a contingency event. For instance, if a load is isolated due to an event or the power-carrying capability of the system is insufficient to serve the load, this is recorded as the consequential load drop. Non-consequential load dropis the minimum amount of load shed required to be enacted to secure the transmission system to probable future contingencies (See NERC non-consequential load drop definition). A security-constrained dispatch is performed to calculate the non-consequential load drop.

- **Resilience Metric**

The resilience metrics can be summarized into two categories: 1) performance-based and 2) non-performance-based metrics

[8-9]. This paper proposes a performance-based resilience metric. The N-0-T consequential load drop is caused by taking the project out of service. The historical outage frequency data of the specific transmission line addressed by project T is measured, and an estimate of the project's impact on the outage frequency is assessed. The resilience benefit is then defined as the product of the change in outage frequency caused by project T and the N-0-T load drop.

C. Project Scheduling Optimization

This section provides a comprehensive overview of the mathematical formulation underlying the transmission line project scheduling problem. The Mixed Integer Linear Programming (MILP) approach, used in resource scheduling optimization, has been borrowed to determine the optimal project schedule [10-11]. The primary objective of this formulation is to maximize the overall reliability and resilience benefits throughout the designated planning horizon. To achieve this, an intricate set of decision variables and constraints are employed, ensuring a robust and effective approach to the transmission project scheduling optimization.

- **Objective Function**

This optimization is rooted in enhancing the power grid's reliability and resilience. These vital characteristics are achieved by minimizing the potential load drop under contingencies while considering various project attributes and constraints. The independent decision variables in this optimization problem are the scheduling status of each transmission line project during discrete time intervals. Each decision variable is binary, where a value of 1 signifies that the project is scheduled to commence at the commencement of that interval. This binary encoding facilitates a flexible and efficient representation of project scheduling decisions, allowing for optimal allocation of resources while minimizing load disruptions. The following equation (1) illustrates the multi-objective function:

$$\max_{S} \sum_{t=1}^{T} \Big(W_{rel} \sum_{n=1}^{N} [\Delta RC(n) \times c(n,t) + \Delta RA(n) \times a(n,t)] + W_{res} \sum_{n=1}^{N} [\Delta ResC(n) \times c(n,t) + \Delta ResA(n) \times a(n,t)] \Big) \qquad (1)$$

Here, the variables *c(n,t)* and *a(n,t)* take on binary roles, signifying the status of project "*n*" during interval "*t*" Specifically, *c(n,t)=1* indicates that project "*n*" is actively in the construction phase within interval "*t*" while *a(n,t)=1* denotes the completion of project "*n*" in or before interval "*t*". $\Delta RC(n)$ and $\Delta RA(n)$ respectively show the total impact of the project "*n*" on the expected load drop (both consequential and non-consequential) during the construction phase and after completion, while $\Delta ResC(n)$ and $\Delta ResA(n)$ represents the impact on resilience. W_{rel} and W_{res} are weighting factors and show the relative importance of each objective in the scheduling problem.

Each transmission line project is characterized by a set of attributes, including estimated capital expenses *CapEx(n)*, anticipated construction duration *d(n)*, and the requisite number of crews during construction *CR(n)*. Moreover, implementing a project triggers impacts on both consequential and non-consequential load drops during the construction phase and post-completion.

- **Reliability Constraints**

The expected load drop per contingency for critical loads must not surpass a predefined threshold value to uphold the system's overall reliability. This threshold, an essential parameter, is factored into the optimization process as a critical constraint, ensuring that the transmission line projects effectively safeguard the power grid's reliability under all contingencies. Mathematically, the reliability constraints are expressed as:

$$R_0(l,t) - \sum_{n=1}^{N} [RC(n,l) \times C(n,t) + RA(n,l) \times a(n,t)] \le Rel_{Cr}^{Th} \qquad \forall\, t, l \epsilon L_{cr} \quad (2)$$

$$R_0(l,t) - \sum_{n=1}^{N} [RC(n,l) \times C(n,t) + RA(n,l) \times a(n,t)] \le Rel_{N}^{Th} \qquad \forall\, t, l \epsilon L_{N} \quad (3)$$

Where $R_0(l,t)$ denotes the currently expected load drop for the load "*l*". L_{cr} and L_N represent the set of critical and noncritical loads, respectively, while "Rel_{Cr}^{Th}" and "Rel_{N}^{Th}" show the threshold value for the maximum allowable load drop for critical and noncritical loads.

- **Budget Constraints**

The total expenses associated with constructing and deploying transmission line projects are constrained by an annual budget limit (2). This fiscal constraint introduces a real-world dimension to the optimization problem, emphasizing the need to balance reliability improvements with budgetary constraints.

$$\textstyle\sum_{n=1}^{N} \sum_{t=1}^{T} s(n,t) \times CapEx(n) \le Budget \ (4)$$

Where "$s(n,t)$" is a binary variable, and the value of 1 signifies that the project "*n*" is scheduled to commence at the beginning of interval "*t*".

- **Crew Availability Constraints**

The availability of construction crews is another pivotal aspect of this scheduling paradigm.

$$\textstyle\sum_{n=1}^{N} c(n,t) \times CR(1,n) \le Ca(t) \quad \forall\, t \quad (5)$$

$Ca(t)$ represents the number of crews available at the beginning of interval "*t*".

- **Binary Variable Constraints**

To ensure that only one of the binary variables (s, c, and a) can be active within each interval, the subsequent mathematical constraints are imperative:

Equations (7), (8), and (9) ensure that project "n" transitions into the construction phase after its initiation and before its completion, fostering a coherent project timeline.

$$\sum_{t=1}^{T} s(n,t) \leq 1 \quad \forall n \quad (6)$$

$$a(n,t) - a(n,t-1) = s\big(n,t - d(n)\big) \;\; \forall n, t\epsilon\{d(n) + 1, \dots, T\} \quad (7)$$

$$a(n,t) = 0 \;\; \forall n, t\epsilon\{1,2,,\dots,d(n)\} \quad (8)$$

$$c(n,t) - c(n,t-1) = s(n,t) - \big(a(n,t) - a(n,t-1)\big) \;\; \forall n,t \quad (9)$$

III. Illustrative Example

The PR power system model is used as a simulation network. An illustrative example is presented in this section to provide practical insights into the effectiveness of the proposed optimization methodology. The case study centers on the optimal scheduling of a set of 83 proposed transmission projects. As mentioned in Section II, each project schedule includes two phases. The model of the lines will be set to out-of-service for the rebuild in Phase 1. For example, the project assumed that the existing 230 kV line from Cambalache to Manati would be out-of-service when the line was under construction. Phase 2 modeled the new line and rebuild project in the case study by applying the new conductor parameters. For example, this paper tested a 230kV new line project from Costa Sur to Mayaguez, and the project will only be modeled in Phase 2. Table 1 summarizes the information related to these 83 projects.

Table 1. Project Information

Project Type	*Project Count*	*Length (Mile)*	*Project System*
Hardening for reliability and resilience	47	845	Transmission / sub-transmission
New line for resilience	14	419	Transmission
New line for N-1 reliability improvement	10	103	Transmission / sub-transmission
Line rebuild for N-1 reliability improvement	12	47	Transmission / sub-transmission

This illustrative case demonstrates how the integrated consideration of system reliability, grid security, budget constraints, and crew availability culminate in an optimal project scheduling solution that simultaneously enhances multiple performance metrics. Additionally, the study assesses the influence of weighting factors on scheduling outcomes, reflecting the relative significance of reliability and resilience criteria. The analysis encompasses Scenarios 1-5, each incorporating distinct weighting approaches. Notably, Scenario 1 emphasizes reliability as the sole critical factor, while Scenario 5 accentuates resilience. Scenarios 2-4 balance reliability and resilience, with Scenario 2 favoring reliability and Scenario 4 prioritizing resilience. In Scenario 3, equal importance is assigned to both reliability and resilience. Fig. 3 presents the number of scheduled projects and the total expenses over a 20-year planning horizon across these scenarios.

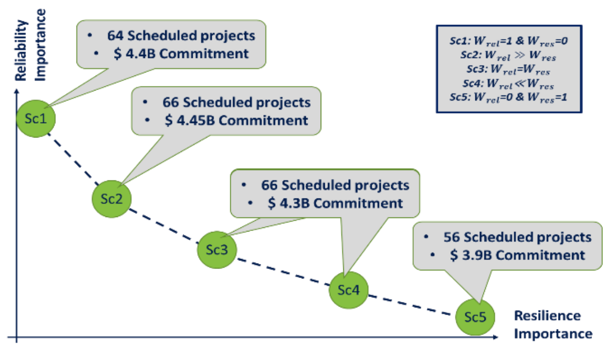

Fig. 3. Results of Different Scenarios

The following table summarizes the scheduling status of 8 sample projects.

Table 2. Project Scheduling Status (8 sample projects)

Project Name	**Reliability Benefit**	**Resilience Benefit**	***Is the project scheduled? (Yes [Y] or No [N])***				
			Sc1	**Sc2**	**Sc3**	**Sc4**	**Sc5**
P 1	None	High	*N*	*Y*	*Y*	*Y*	*Y*
P 2	None	High	*N*	*Y*	*Y*	*Y*	*Y*
P 3	None	Med	*N*	*N*	*Y*	*Y*	*Y*
P 4	Low	Med	*N*	*N*	*Y*	*Y*	*Y*
P 5	Med	None	*Y*	*Y*	*N*	*N*	*N*
P 6	Med	None	*Y*	*Y*	*N*	*N*	*N*
P 7	Med	None	*Y*	*Y*	*Y*	*Y*	*N*
P 8	High	None	*Y*	*Y*	*Y*	*Y*	*N*

As Table 2 illustrates, projects with no reliability value are not scheduled in Scenario 1. Similarly, projects with no resilience value are not scheduled in scenario 5.

IV. Conclusion

In conclusion, this paper introduces an innovative optimization methodology that harmonizes system reliability, grid resilience, budget constraints, and crew availability for optimal transmission project scheduling. The case study involving 83 PR transmission projects demonstrates the approach's capability to enhance reliability and resilience metrics concurrently. Through the assessment of varied weighting factors, a demonstration of the model's adaptability to different priority scenarios is provided. This work provides a valuable foundation for refining transmission project optimization strategies, addressing evolving challenges, and shaping a more reliable and resilient energy landscape for the future.

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