Security-Constrained Transmission Outage Scheduling and Feasibility Assessment

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***Abstract*—The increasing volume of transmission outage requests poses significant challenges to maintaining operational flexibility and system reliability. Traditional outage coordination relies on manual evaluations that demand extensive engineering expertise and computational resources, making the process time-consuming, reactive and iterative. This paper introduces a security-constrained DC optimal power flow (DCOPF) framework formulated as a multi-period mixed-integer linear programming (MILP) model to streamline transmission outage scheduling within an operational planning horizon. The objective function seeks to maximize the number of scheduled outages, while satisfying scheduling, generation, and network constraints under both normal and N-1 contingency conditions. To ensure practical applicability, the optimized outage schedule is subjected to AC feasibility analysis, verifying voltage and thermal limits under normal and contingency conditions. The proposed approach aims to reduce analytical workload, enhance decision-making efficiency, and transform outage planning from a reactive process into a proactive one. The framework has been validated using the IEEE 39-bus test system.**

***Index Terms*—Transmission Outage Coordination, Mixed-Integer Linear Programming (MILP), N-1 Contingency Analysis, Reliability Assessment, AC Feasibility, Outage Scheduling.**

I. Introduction

The electric power industry is experiencing a steady increase in transmission outage requests, driven by capital projects, frequent maintenance activities, and other operational requirements aimed at ensuring grid reliability and resiliency. Coordinating these outages within an operational planning horizon remains highly resource-intensive. Engineers perform detailed analyses, incorporating forecasted load profiles, generation schedules, and concurrent outages, to ensure that planned outages do not compromise operational security. Traditionally, these evaluations have relied on manual processes and single-point load flow studies; however, the growing complexity of modern grids and the integration of variable generation resources demand more comprehensive approaches, including multi-contingency and seasonal assessments.

Recent surveys, including the *EPRI Outage Coordination Survey* conducted in 2024, highlight emerging challenges: increasing outage volumes, declining workforce expertise, and the need for more detailed analyses to address evolving system conditions and extreme events [1]. Research in outage scheduling has explored mathematical optimization, heuristics, and machine learning (ML) techniques to improve efficiency and decision-making [2]–[12]. While optimization-based approaches primarily focus on minimizing operational and maintenance costs, they often lack sufficient emphasis on system reliability under normal and contingency conditions [2]–[7]. ML and heuristic methods offer potential for proactive outage planning and scenario screening, but practical implementation remains limited by data availability, computational burden, and existing operational structures [8]–[12]. These gaps underscore the need for advanced frameworks that reduce analytical workload while ensuring compliance with reliability standards.

To address these challenges, this work presents a security-constrained outage scheduling optimization framework based on DC power flow and formulated as a multi-period mixed-integer linear programming (MILP) model. The objective is to maximize the number of transmission outages scheduled within an outage planning horizon, while satisfying scheduling, generation, and network constraints under both normal and N-1 contingency conditions. To ensure practical applicability, the optimized schedules are validated through AC power flow analysis to confirm operational feasibility. Other key features of the proposed approach include:

- **Reliability-focused optimization:** Incorporates N-1 contingency constraints to maintain system security.
- **Multiple elements per outage ticket:** Allows grouping of multiple transmission components within a single request, reflecting real-world practices.
- **AC feasibility validation:** Assesses if the optimized schedule is AC-feasible.
- **Industry relevance:** Tested on the IEEE 39-bus system, demonstrating strong potential for practical implementation.

The details of the proposed framework are presented in the following sections.

II. Outage Scheduling Optimization

Optimal outage scheduling is formulated as a multi-period MILP problem. The objective is to maximize the number of scheduled transmission outages within an outage planning horizon, subject to scheduling and generation constraints, DC power flow, and nodal balance requirements etc., while accounting for both normal and N–1 contingency conditions [4],

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[13]. Since the optimization is based on DC power flow, the resulting solution is subsequently assessed for AC feasibility.

TABLE I
NOTATION USED IN THE OUTAGE OPTIMIZATION MODEL

Symbol	Description
Sets	
T	Time periods ($t \in T$)
I	Outage tickets ($i \in I$)
G	Generators ($g \in G$)
C_G	Generator contingencies ($c \in C_G$)
C_T	Branch contingencies ($c \in C_T$)
C_0	Base case ($c \in C_0$)
B	Buses ($j \in B$)
L	Branches not in outage tickets ($l \in L$)
L'	Branches in outage tickets ($l' \in L'$)
Parameters	
W_i	Weight of outage ticket i
TD_i	Duration of outage ticket i
$(P_{g,c})_{\max}, (P_{g,c})_{\min}$	Max/min capacity of generator g under contingency c
$N1_{g,c}$	0 if generator g experiences contingency c, 1 otherwise
$\theta_{\max}, \theta_{\min}$	Angle limits
$(P_{l,c})_{\max}, (P_{l,c})_{\min}$	Thermal capacity of branch l under contingency c
$N1_{l,c}$	0 if branch l experiences contingency c, 1 otherwise
$(P_{l'})_{\max}, (P_{l'})_{\min}$	Thermal rating of branch $l' \in L'$
$a_{l',i}$	1 if branch l' belongs to outage ticket i, 0 otherwise
$d_{j,c,t}$	Load at bus j during time t and contingency c
B_l, $B_{l'}$	Susceptance of branch l or l'
M	Big-M constant
Decision Variables	
$x_{i,t}$	1 if outage ticket i starts at time t, 0 otherwise
$y_{i,t}$	1 if outage ticket i ends at time t, 0 otherwise
$z_{i,t}$	0 if outage ticket i is active during time t, 1 otherwise
$P_{g,c,t}$	Generation from generator g at time t under contingency c
$\theta_{j,c,t}$	Angle at bus j at time t under contingency c
$P_{l,c,t}$	Flow in branch l at time t under contingency c
$P_{l',c,t}$	Flow in branch l' at time t under contingency c
$S_{l',i,t}$	0 if branch l' is out of service with outage ticket i active at time t, 1 otherwise

A. Objective function

$$\max \sum_{t\in T} \sum_{i\in I} W_i \, x_{i,t} \tag{1}$$

The objective function aims to schedule as many outages (with higher weights) as possible within the operational planning period. The weights can be assigned to outages based on factors such as the number of elements in the outage ticket, the voltage level at which the outage is to be implemented, and the nature of the outage (maintenance, repair, or capital projects) etc.

High-voltage and multi-element outages pose greater operational risk and therefore receive a higher weight, while routine maintenance on lower-voltage equipment can be assigned a lower weight. Repair outages typically carry a high weight because they are urgent and harder to reschedule. For example, a 345-kV repair involving multiple branch elements would have a higher weight than a single-element 115-kV maintenance outage.

B. Constraints

Scheduling Constraints:

$$\sum_{t\in T} x_{i,t} \le 1 \quad \forall i \in I \tag{2}$$

Equation (2) ensures that each outage ticket can start only once within the planning horizon.

$$z_{i,t-1} - z_{i,t} = x_{i,t} - y_{i,t} \quad \forall i \in I,\ t \ge 2 \in T \tag{3}$$

$$1 - z_{i,1} = x_{i,1} - y_{i,1} \quad \forall i \in I \tag{4}$$

Equation (3) defines the relationship among the variables $x_{i,t}$, $y_{i,t}$, and $z_{i,t}$. Equation (4) is a modified form of equation (3) for the time period $t = 1$ [4]. At $t = 0$, no outage ticket is active, and all associated elements are assumed to be in service. Table II illustrates the relationship among $x_{i,t}$, $y_{i,t}$, and $z_{i,t}$ for an example in which outage ticket i remains active from period 2 through period 4.

TABLE II
ILLUSTRATION OF $x_{i,t}$, $y_{i,t}$, AND $z_{i,t}$ FOR AN OUTAGE ACTIVE FROM PERIOD 2 TO 4.

t	1	2	3	4	5	6	7
$x_{i,t}$	0	1	0	0	0	0	0
$y_{i,t}$	0	0	0	0	1	0	0
$z_{i,t}$	1	0	0	0	1	1	1

$$\sum_{t\in T} (1 - z_{i,t}) = TD_i \quad \forall i \in I \tag{5}$$

Equation (5) sets the duration of outage tickets.

$$x_{i,t} + y_{i,t} \le 1 \quad \forall i \in I,\ t \in T \tag{6}$$

The above constraint prevents an outage ticket from starting and ending in the same period.

$$S_{l',i,t} = \begin{cases} z_{i,t}, & a_{l',i} = 1 \quad \forall\, l' \in L',\ i \in I,\ t \in T \\ 1, & a_{l',i} = 0 \quad \forall\, l' \in L',\ i \in I,\ t \in T \end{cases} \tag{7}$$

In equation (7), $S_{l',i,t} = 0$ if branch l' is out of service when outage ticket i is active; otherwise $S_{l',i,t} = 1$.

$$S_{l',t} \le S_{l',i,t} \tag{8}$$

The above constraint determines the operational status of branch l' at time t.

Generator Constraints:

$$(P_{g,c})_{\min} \cdot N1_{g,c} \le P_{g,c,t} \le N1_{g,c} \cdot (P_{g,c})_{\max} \quad \forall g \in G,\ c \in C_G,\ t \in T \tag{9}$$

This constraint ensures that the output of generator g at time t under contingency c remains within its operating limits [13]. If generator g is experiencing contingency c, then $N1_{g,c} = 0$, which forces $P_{g,c,t} = 0$. Otherwise, $P_{g,c,t}$ is bounded between its minimum and maximum limits.

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Angle Constraints:

$$\theta_{r,c,t} = 0 \quad \forall c \in (C_0 \cup C_G \cup C_T),\ t \in T,\ r: \text{ref} \tag{10}$$

$$\theta_{\min} \leq \theta_{j,c,t} - \theta_{k,c,t} \leq \theta_{\max} \quad \forall j,k \in B,\ c \in (C_0 \cup C_G \cup C_T),\ t \in T \tag{11}$$

Equation (10) sets the voltage angle at the reference/slack bus to zero. Equation (11) restricts the voltage angle difference across branches within specified limits (optional).

Thermal Limit Constraints:

$$(P_{l,c})_{\min} \cdot N1_{l,c} \leq P_{l,c,t} \leq N1_{l,c} \cdot (P_{l,c})_{\max} \quad \forall l \in L,\ c \in (C_0 \cup C_G \cup C_T),\ t \in T \tag{12}$$

$$(P_{l'})_{\min} \cdot S_{l',i,t} \leq P_{l',c,t} \leq S_{l',i,t} \cdot (P_{l'})_{\max} \quad \forall l' \in L',\ c \in (C_0 \cup C_G \cup C_T),\ i \in I,\ t \in T \tag{13}$$

Equation (12) ensures that branch $l \in L$ respects thermal limits under contingency c [13]. If $N1_{l,c} = 0$, then $P_{l,c,t} = 0$. Equation (13) applies similar limits to branches $l' \in L'$ linked to outage tickets. If $S_{l',i,t} = 0$, then $P_{l',c,t} = 0$.

Node Balance Constraints:

$$\sum_{(j,k)\in l' \to j} P_{l',c,t} - \sum_{(j,k)\in l' \leftarrow j} P_{l',c,t} + \sum_{(j,k)\in l \to j} P_{l,c,t} - \sum_{(j,k)\in l \leftarrow j} P_{l,c,t} + \sum_{g@j\in G} P_{g,0,t} = d_{j,c,t}, \quad \forall j \in B,\ c \in (C_0 \cup C_T),\ t \in T \tag{14}$$

$$\sum_{(j,k)\in l' \to j} P_{l',c,t} - \sum_{(j,k)\in l' \leftarrow j} P_{l',c,t} + \sum_{(j,k)\in l \to j} P_{l,c,t} - \sum_{(j,k)\in l \leftarrow j} P_{l,c,t} + \sum_{g@j\in G} P_{g,c,t} = d_{j,c,t}, \quad \forall j \in B,\ c \in C_G,\ t \in T \tag{15}$$

Equation (14) maintains nodal balance for base case and branch contingencies with fixed generator dispatch. Equation (15) maintains nodal balance for generator contingencies, allowing generator dispatch to vary [13].

DC Power Flow Constraints:

$$P_{l,c,t} - B_l \cdot (\theta_{j,c,t} - \theta_{k,c,t}) - M \cdot (1 - N1_{l,c}) \leq 0 \quad \forall l \in L,\ c \in (C_0 \cup C_G \cup C_T),\ t \in T \tag{16}$$

$$P_{l,c,t} - B_l \cdot (\theta_{j,c,t} - \theta_{k,c,t}) + M \cdot (1 - N1_{l,c}) \geq 0 \quad \forall l \in L,\ c \in (C_0 \cup C_G \cup C_T),\ t \in T \tag{17}$$

$$P_{l',c,t} - B_{l'} \cdot (\theta_{j,c,t} - \theta_{k,c,t}) - M \cdot (1 - S_{l',t}) \leq 0 \quad \forall l' \in L',\ c \in (C_0 \cup C_G \cup C_T),\ t \in T \tag{18}$$

$$P_{l',c,t} - B_{l'} \cdot (\theta_{j,c,t} - \theta_{k,c,t}) + M \cdot (1 - S_{l',t}) \geq 0 \quad \forall l' \in L',\ c \in (C_0 \cup C_G \cup C_T),\ t \in T \tag{19}$$

Equations (16) and (17) apply B-θ relationship for branches $l \in L$ under contingencies, active only when $N1_{l,c} = 1$. Equations (18) and (19) apply B-θ relationship for branches $l' \in L'$ linked to outage tickets, active only when $S_{l',t} = 1$.

III. AC Feasibility Analysis

To ensure system security and reliability, an AC feasibility check is applied to the schedule from outage optimization. This step involves formulating and solving AC Optimal Power Flow (ACOPF) problems representing normal and N-1 contingency conditions across all time periods, after applying outages from the scheduling results. The inputs to the AC feasibility check include network topology, contingency lists, outage schedules, generator dispatch plans, and voltage angle references obtained from the outage optimization. Fig. 1 illustrates the AC feasibility check process.

A. Objective Function and Variables

ACOPFs are solved to minimize deviations from reference operating points while satisfying AC network constraints. The objective function for each scenario and time period is expressed as:

$$\min \textstyle\sum_{c\in(C_0\cup C_G\cup C_T)} \sum_{t\in T} w\|v(c,t) - v_{\text{set}}(c,t)\|_2^2 \tag{20}$$

Where v represents variables, including bus voltage magnitudes and angles, slack generator real power outputs, and reactive power outputs of regulators such as generators, switched shunts, and condensers etc. The vector v_{set} denotes the corresponding reference values, derived from voltage magnitude midpoints, scheduled generator outputs, and prior outage optimization results. The penalty terms weighted by w regulate deviations in voltage magnitudes, voltage angles, slack generator MW outputs, and reactive power outputs of regulators, normalized where applicable by their allowable ranges. These soft constraints provide controlled flexibility while minimizing excessive deviations from scheduled operating points.

B. Constraints and Solution Process

The constraints enforce AC power balance at each bus, variable bounds, variable fixing (for e.g., fixed susceptance values for discrete shunt devices) and power factor regularization constraints for HVDC components etc.:

$$\begin{aligned} &P(v(c,t)) = 0 \\ &Q(v(c,t)) = 0 \\ &v^{min} \leq v(c,t) \leq v^{max} \end{aligned} \tag{21}$$

If infeasibilities occur during the solution process, a hierarchical relaxation strategy is applied. The procedure begins by relaxing voltage limits, followed by easing slack generator constraints, and finally employing alternative optimization solvers to improve convergence. This iterative approach enhances the likelihood of finding a feasible solution while highlighting any violations for operators to review.

C. Feasibility Analysis Output

The AC feasibility analysis produces a comprehensive summary indexed by time period, including solver status, warnings on voltage or generator limit relaxations and branch thermal violations etc. Additionally, it provides ticket approval recommendations based on base-case feasibility. These insights can help system operators to refine outage schedules and

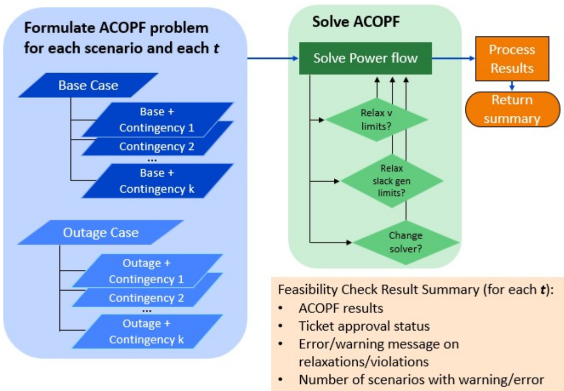

Fig. 1. AC feasibility check process.

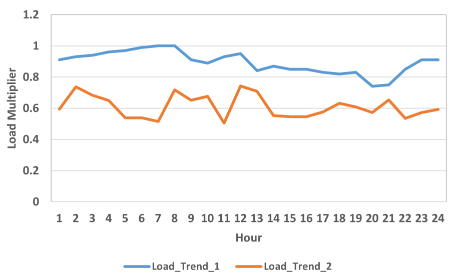

Fig. 2. Load multipliers used to create study cases.

adjust control settings, ensuring secure and reliable network operation under both normal and contingency conditions.

IV. Results

The integrated framework with outage scheduling optimization and AC feasibility analysis was implemented using EPRI's Grid Analysis Toolkit (GAT) [14] and validated on the IEEE-39 bus system. To model load variability across an outage planning horizon with 24 time periods, two sets of 24 cases (PSS/E .raw format) were generated by applying multipliers from the load trends shown in fig. 2 to the original case loads.

The following two sets of N-1 contingencies were created to be considered for the outage optimization:

- **Contingency Set 1:** Circuit 1 of branch between buses 16–21 open, Circuit 1 of branch between buses 3–18 open.
- **Contingency Set 2:** Circuit 1 of branch between buses 16–21 open, Circuit 1 of branch between buses 3–18 open, and Generator with ID 1 at bus 30 out.

Tables III and IV show two sets of outage ticket information used during the validation process. Each table includes the following attributes:

- **Outage Ticket**: Ticket identifier.
- **Weight**: Assigned outage weight based on factors such as the number of elements, voltage level, and outage type (maintenance, repair, or project).
- **Outage Duration**: Outage duration in time periods.
- **Elements in Outage Ticket**: The branches included in the outage ticket, specifying the from-bus and to-bus numbers.
- **Branch Id**: Circuit identifier for each branch.

Outage optimization followed by AC feasibility analysis were performed for the following study scenarios:

- **Scenario-1**: Snapshot cases modeling load trend-1, contingency set-1, and outage ticket set-1.
- **Scenario-2**: Snapshot cases modeling load trend-2, contingency set-1, and outage ticket set-1.
- **Scenario-3**: Snapshot cases modeling load trend-1, contingency set-2, and outage ticket set-1.
- **Scenario-4**: Snapshot cases modeling load trend-1, contingency set-2, and outage ticket set-2.

All computational runs were performed on a standard computing system equipped with an i7 processor (2.20 GHz) and 32 GB of RAM. Figure 3 illustrates the outage schedules generated for scenarios 1, 2, and 3. In all these scenarios, the transmission outage tickets were successfully scheduled within the outage planning horizon, and the resulting schedules were verified to be AC-feasible. Additionally, the schedules also exhibited sensitivity to factors such as system loading levels and the contingencies modeled.

Figure 4 shows the outage schedule for scenario-4. The schedule failed to maintain AC feasibility due to voltage violations during time periods 16 and 17, which coincided with the scheduling of ticket 5 involving two branch elements (from table IV). In a small network such as the IEEE 39-bus system, achieving feasibility for an N-3 scenario (two elements in outage ticket and one N-1 contingency) under high loading conditions could be challenging. Moreover, the current framework lacks a feedback mechanism to adjust outage optimization based on AC feasibility checks. As a result, while the approach performed well under normal operating conditions, it might not produce AC-feasible schedules in highly stressed situations.

TABLE III
Outage Ticket Information Set-1

Outage Ticket	Weight	Outage Duration	Elements in Outage Ticket	Branch Id
Ticket 1	2	5	Branch 11–12	1
Ticket 2	4	2	Branch 28–29	1
Ticket 3	5	2	Branch 14–15	1
Ticket 4	1	3	Branch 16–17	1
Ticket 5	3	2	Branch 26–28	1

TABLE IV
Outage Ticket Information Set-2

Outage Ticket	Weight	Outage Duration	Elements in Outage Ticket	Branch Id
Ticket 1	2	5	Branch 11–12	1
Ticket 2	4	2	Branch 28–29	1
Ticket 3	5	2	Branch 14–15	1
Ticket 4	1	3	Branch 16–17	1
Ticket 5	3	2	Branch 5–6, Branch 26–28	1, 1

Table V shows solution times for outage optimization and AC feasibility analysis across the study scenarios. As system conditions became more complex through variations in load trends, contingency sets, and outage ticket combinations, solution times changed accordingly. Scenario-1 had the shortest solution time, while scenario-2 showed a moderate increase with a different load trend. In scenario-3, the solution times

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increased as the schedule was generated and evaluated under a larger set of contingencies. Scenario-4 had the longest solution times, specifically for AC feasibility analysis, where the process explored several parameter relaxations to reach feasibility. However, the schedule was AC-infeasible due to the combined challenges of the expanded contingency set and stricter outage requirements, with ticket 5 involving two branch elements.

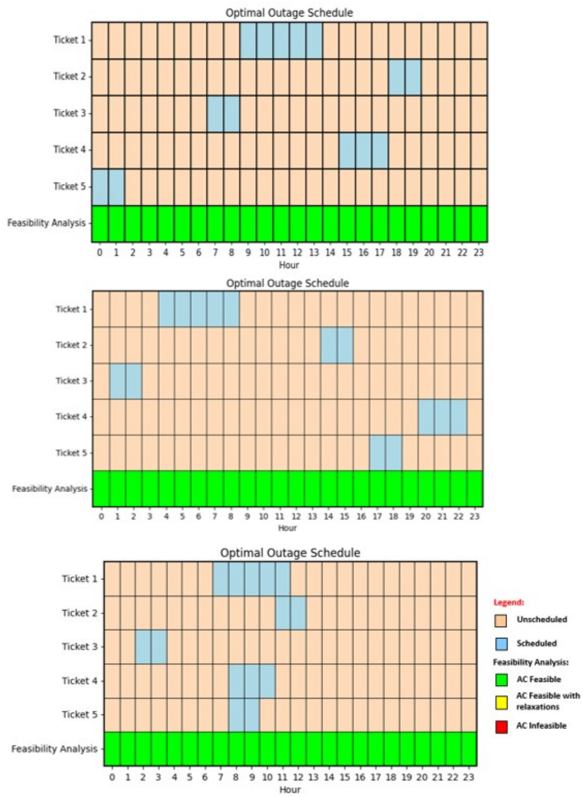

Fig. 3. Transmission outage schedules for scenarios 1 (top), 2 (middle) and 3 (bottom).

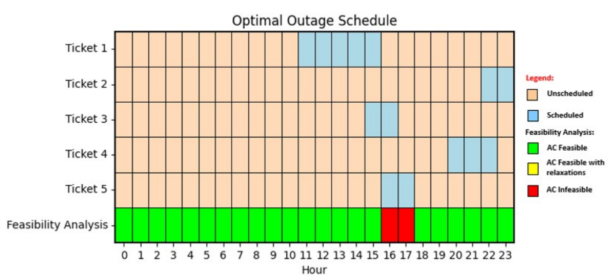

Fig. 4. Transmission outage schedule for scenario 4.

TABLE V
SOLUTION TIME - OUTAGE OPTIMIZATION & AC FEASIBILITY ANALYSIS

Scenario	**Solution Status**	**Solution Time - Outage Optimization**	**Solution Time - AC Feasibility Analysis**
Scenario-1	AC Feasible Schedule	35 sec	49 sec
Scenario-2	AC Feasible Schedule	42 sec	54 sec
Scenario-3	AC Feasible Schedule	47 sec	67 sec
Scenario-4	AC Infeasible Schedule	52 sec	132 sec

V. CONCLUSION

Outage coordination is increasingly complex due to rising outage requests, workforce attrition, and a more dynamic and less predictable power system. This study introduced and tested a security-constrained DCOPF-based outage scheduling methodology on the IEEE 39-bus system, supplemented by an AC feasibility check. Results indicated that optimized schedules are sensitive to modeling parameters and may not always satisfy AC feasibility. Future work will focus on refining the proposed approach by incorporating AC-feasibility feedback into the optimization process to produce AC-feasible schedules. Additional efforts will include validating the methodology on a larger system case to assess scalability, followed by extending the framework to include generation outages for more comprehensive outage planning.

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