Proactive Generation Redispatch to Enhance Power System Resilience During Hurricanes Considering Unavailability of Renewable Energy Sources

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***Abstract*—This article proposes a proactive generation redispatch strategy to enhance operational resilience of power grids during hurricanes considering unavailability and forced outages of renewable energy sources (RESs). Previous resilience enhancement strategies focus on utilizing available generation resources to enhance the performance of power grids during extreme events without proactively preparing the system for predicted events. Recent incidents have shown that unavailability and forced outages of RESs during extreme weather events can lead to catastrophic impacts. Due to spatiotemporal characteristics of hurricanes and rapidly varying component statuses, system operators need to initiate proactive actions early in time to avoid power outages and potential cascading failures. In this article, a mixed integer linear programming problem is formulated to minimize the amount of load curtailments and operational costs. The optimization problem considers the behavior of RESs and their forced outages during hurricanes. Operational generation constraints (e.g., ramping rates, minimum up/down times, and start-up/shut-down generation costs), transmission constraints (e.g., line capacity and line availability), and other system constraints (e.g., load and weather variation) are considered for the resilience enhancement approach. The importance of the proactive redispatch strategy is assessed under various penetration levels of RESs. The proposed strategy is tested on a modified version of the IEEE 30-bus system under diverse impact levels of a hurricane. The results show the effectiveness of the proactive and dynamic generation redispatch to improve power system resilience and the capability to reduce the load curtailments with limited generation resources during hurricanes by at least 40%.**

***Index Terms*—Extreme weather events, generation redispatch, hurricanes, renewable energy sources, resilience.**

Manuscript received July 31, 2021; revised November 16, 2021; accepted January 15, 2022. Date of publication February 14, 2022; date of current version May 20, 2022. Paper 2021-ESC-0892.R1, presented at the 2021 IAS Annual Meeting, Vancouver, BC, Canada, Oct. 10–14, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Energy Systems Committee of the IEEE Industry Applications Society. This work was supported by the U.S. National Science Foundation (NSF) under Grant NSF 1847578. *(Corresponding author: Michael Abdelmalak.) (Corresponding author: Michael Abdelmalak.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TIA.2022.3151313.

Digital Object Identifier 10.1109/TIA.2022.3151313

NOMENCLATURE

Indices and Sets

i	Index of generators
n, n'	Index of buses
t	Index of time instants
Ω^N	Set of all buses
Ω_n^N	Set of buses connected to bus n.
Ω^G	Set of all generators
Ω_n^G	Set of generators connected to bus n
Ω^T	Set of all time instants
Ω_H^T	Set of all time instants during hurricane event
Ω_{NH}^T	Set of all time instants excluding hurricane duration

Notation for Optimization Problem

b	Generator linear cost coefficient
$B_{n,n'}$	Susceptance of line between bus n and bus n'
C_su	Generator start-up cost
C_sd	Generator shut-down cost
$C(C_{n,t})$	Load curtailment cost at bus n at t
$C_f(P_{i,t}^G)$	Operational fuel cost of generator i at t
$C_{n,t}$	Load curtailment at bus n at time t
$L_{n,t}$	Amount of load in MW at bus n at time t
$P_{n,n,'t}^L$	Real power flow between bus n and bus n' at time t
$P_{n,n'}^{Min}, P_{n,n'}^{Max}$	Real power flow limits between bus n and bus n'
$P_{i,t}^G$	Real power of generator i at time t
$P_i^{G,Min}$	Minimum power rating of generator i
$P_i^{G,Max}$	Maximum power rating of generator i
P_t^S	Solar real power at time t
P_t^W	Wind real power at time t
R_i^{UP}	Ramp up rate of generator i
R_i^{DN}	Ramp down rate of generator i
$T_{i,t}^{ON}, T_{i,t}^{OFF}$	Turn ON/OFF signal of generator i at time t
$u_{i,t}$	Status of generator i at t
$u_{i,t+1}$	Status of generator i at $t+1$
UT, DT	Minimum up/down time
W_1, W_2	Optimization weighting factors
$\theta_{n,t}$	Voltage angle of bus n at time t
$\theta_{n,'t}$	Voltage angle of bus n' at time t
θ_n^{Min}	Minimum voltage angle of bus n
θ_n^{Max}	Maximum voltage angle of bus n

I. Introduction

EXTREME weather events have shown significant catastrophic impacts on the power system resulting in noticeable economic losses [1], [2]. More than $25 billions per year is the estimated economic losses due to extreme weather-related outages in the United States [3]. More than 147 million customers lost power due to weather-related events in the United States between 2003 and 2012 [4]. During the last two decades, more than 160 thousand customers per year are impacted by weather-related power outages in the United States [5]. Hurricanes and tornadoes have counted the most frequent number of occurrences as well as one of the most impactful extreme weather events on electric power grids [1]. The deployment of renewable energy sources (RESs) alleviates several concerns related to their stochastic behavior and output variability on power system resilience [6], [7]. A few studies have assessed the role of high penetration levels of RESs on power system resilience performance [8]. On the other hand, several resilience enhancement strategies have been studied based on corrective and restorative approaches giving less interest to proactive strategies [9], [10]. Also, resilience enhancement strategies of distribution systems have gained more interest than that of transmission systems due to the high vulnerability levels of distribution systems to extreme events [9], [10]. Some system dynamic constraints are not explicitly considered in resilience-based studies to reduce modeling complexities [11]. Impacts of load and renewable energy variations, future potential failures, event attack time, and enhancement implementation time have not been extensively studied yielding less realistic problem formulation [12]. Thus, it has become indispensable to implement a resilience enhancement strategy that accounts for operational cost, generation dynamic constraints, load variations, uncertainties of renewable energy sources, and extreme weather spatiotemporal characteristics.

Resilience enhancement strategies can be classified into planning-based and operational-based methods [13]. Planning-based methods assess the current system resilience level, study strengthening strategies, and improve the system resilience characteristics against future extreme events. On the other hand, operational-based methods utilize the current available assets to reduce/eliminate the impacts of occurring extreme weather events on system performance [14], [15]. Operational-based approaches provide a set of immediate solutions and actions to maintain a minimal acceptable level of performance of the power grid and avoid any further tightly operational constraints that might lead to a cascading failure or blackout [12]. Operational-based resilience enhancement strategies can be classified into proactive, corrective, and restorative based on the study period [16]. Proactive strategies tend to prepare the system in advance, whereas corrective strategies provide immediate actions after the occurrence of an event. Restorative strategies retain failed components or curtailed loads in a stable and reliable manner.

Various operational-based resilience enhancement strategies have been studied. A procurement plan has been studied to ensure the availability of sufficient black start resources prior to an event under minimal operating costs ignoring propagation patterns of extreme events in [17]. In [18], a decision-making framework based on analytical hierarchy process has been proposed to evaluate possible locations of solar panels and battery energy storage systems for multiple contingencies to improve resilience and reduce operational costs in distribution systems. A maintenance planning and rescheduling strategy [19]–[21] and a mobile energy storage allocation strategy [22], [23] have been studied to enhance power system resilience prior to adverse events. A framework that splits distribution systems into self-adequate microgrids for resilience enhancement has been provided in [24]. Also, the role of demand response to improve operational resilience of microgrids has been studied in [25]. In [26], resilience enhancements have been quantified using a graph theory-based approach integrated with Choquet integral to maintain power supply to critical loads at the distribution level. An event-driven resilience-based unit commitment model has been proposed in [27] considering simultaneous failures of system components due to a predefined hurricane event. In [28], a proactive sequential generation redispatch strategy has been proposed to reduce the cost of load curtailments during hurricanes without including operational costs and load variations. In [11], a multiobjective optimization problem has been formulated to reduce both operational costs and curtailment costs for a day-head interval during hurricane events; however, the role of RESs and their accompanied uncertainties have not been considered. A discrete Markov decision process has been provided in [29] and [30] to improve resilience of transmission systems during wildfires. Also, the role of dynamic decision process considering economic valuation during extreme events has been provided in [31].

The high penetration levels of RESs has introduced significant uncertainties in the operation and control of power systems especially during extreme weather events. Assessing the impacts RESs on power system response to extreme events has become a key factor for modern power operation especially for resilience-based studies. Authors of [32] have proposed a stochastic programming approach to determine the optimal utilization of RESs when the main feeder in a distribution system is impacted by a wildfire. In [33], a two stage optimization function has been solved to minimize the costs for both dispatchable and nondispatchable renewable generating units, and load curtailment of microgrids. The role of RESs to provide voltage support for resilience-based autonomous microgrid formation after disturbances has been studied in [34] and [35]. The time-varying demand and renewable energy levels have been integrated into a probabilistic extreme event model to quantify the resilience level for planning purpose in [36]. Although several studies have focused on the role of RESs to improve the resilience of distribution systems, only a few studies have focused on transmission systems [1]. Also, the 2021 Texas ice storm has raised concerns about the capability and availability of RESs during extreme events [37]; and hence, the impacts of RESs on the resilience of transmission systems require further investigation.

This article proposes a proactive generation redispatch strategy to enhance the operational resilience of power grids during hurricanes considering the role of RESs. This article advances the work presented in [38]. Due to the spatiotemporal propagation characteristics of hurricanes, the status of each component in the power grid might vary, which can be classified into three main stages: prior, during, and after the event. The proposed strategy takes into consideration varying conditions of system components as well as the variability and intermittency of RESs. The strategy minimizes the overall operating cost of the power system through (1) minimizing or even eliminating load curtailments during hurricanes and (2) minimizing the operating cost of both conventional generators and RESs during normal operation. Also, the effect of both load variations and availability of RESs are considered over a period of 24 h sampled in 5-min intervals. To induce more severity to system conditions, two hurricane scenarios are simulated at different attack times—at peak RES generation and at peak load demand. For realistic system modeling, several system dynamic constraints have been considered such as power balance, transmission limits, load curtailment limits, generation limits (e.g., power output limits, ramping rates, and up/down times), and generator statuses. A mixed integer linear programming (MILP) optimization problem is formulated to determine optimal generation utilization and cost reduction and minimal load curtailments using CPLEX solver integrated with MATLAB environment. The proposed method is tested on a modified version of the IEEE 30-bus system for validation.

The contribution of this article is summarized as follows.

1) Integrate the spatiotemporal characteristics of hurricanes into sequential failure behavior of power grid components.
2) Develop an MILP optimization problem considering dynamic system constraints, load variations, and spatiotemporal fragility model.
3) Assess the role of RESs during hurricane events for resilience enhancement.
4) Provide extensive simulation results via standard test systems to validate the efficiency and accuracy of proactive generation redispatch considering insufficient RESs generation.

The rest of the article is organized as follows. Section II describes the proactive generation redispatch strategy. Section III explains the main proposed algorithm for minimum load curtailments during extreme weather events and overall operation costs under consideration of RES. Section IV illustrates the proposed method on the IEEE 30-bus system and discusses the results. Section V concludes this article.

II. Concept of Proactive Generation

This section describes the proposed resilience enhancement strategy for transmission systems against hurricanes. First, it describes the propagation behavior of hurricanes through a power grid. Then, it explains the proposed generation redispatch algorithm under the unavailability of RESs.

A. Spatiotemporal Impacts of Hurricane

Extreme weather events, also known as high-impact-low-probability events, can cause catastrophic impacts and sometimes prolonged power outages [39]. Even in a very short period of time, the performance of a power system varies dramatically according to the type of event and vulnerabilities of system components. For instance, wildfires reduce the capacity of over head transmission lines due to high heat convection and radiation losses, whereas hurricanes result in failure of transmission towers and lines as well as generation resources [40]. A proper propagation model is required to simulate the spatiotemporal characteristics of extreme weather events based on the event type. Probabilistic and deterministic weather event models have been proposed and applied in resilience-based studies [41]. Fragility curves are the most commonly used failure models to determine component failures based on a specific weather parameter. Additionally, some studies have used either real weather events or predetermined sequential failure scenarios based on forecasting models of extreme weather events [1].

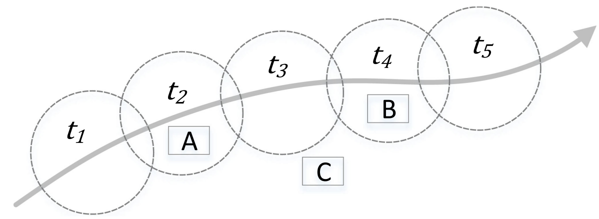

Fig. 1. Three components on the trajectory of a hurricane.

Hurricanes are rapidly propagating weather events with unique spatiotemporal characteristics. Their intensities vary temporally and geographically with their progression trajectories [28]. Power system components are impacted based on their relative position to a hurricane trajectory. Also, several components can be impacted at sequential time intervals. In [42], a detailed spatiotemporal fragility model has been provided to simulate the impact of a typhoon on power grid components. Fig. 1 shows impacts of a hurricane scenario on three system components. At t_2, component A is subjected to potential failure resulting in a noticeable disturbance in the system performance. Component B is expected to fail at t_4 imposing further impacts on system dynamics. Also, component C will not be impacted since it lies outside the impact region of the hurricane. As components fail sequentially, the configuration and topology of the system change dramatically resulting in different system operating conditions. On the other hand, restoring failed components usually requires some time after the hurricane event to make sure that no further failures are encountered. Under severe hurricane conditions, restoration of failed components may extend to a few days especially if maintenance crew dispatching is a must [28]. Therefore, the sets of failed and restored components varies based on the time instant. During a hurricane event, the sets of failed components include all failed components from previous time instants till the current instant. After the hurricane passes the system, the set of restored components includes all restored components till the current instant.

B. Proactive Generation Redispatch

Sequential failures of power system components result in significant changes in the performance of power grids such as power flow in transmission lines, output levels of generators, and overall operating costs. As the number of failed components increases, impacts of the event increase dramatically. Priority is always given to reduction of load curtailments during and post hurricane events to maintain an acceptable level of grid performance, whereas minimal operating costs is usually the objective for the period before the hurricane and after the restoration period. In severe situations, some loads must be curtailed to maintain the stability of power systems and to avoid larger potential load curtailments in future time instants. However, some existing strategies ignore the future potential failures of system components resulting in less resilient strategies and increased negative consequences. For instance, it is preferable to reduce the utilization of conventional generators that are expected to be impacted by a hurricane at a future instant. In some cases, the power grid could be islanded into multiple grids and thus the generation level at each islanded grid should be sufficient to stably supply its loads and avoid load curtailments. Moreover, curtailed loads should be recovered as soon as possible to improve the overall resilience of power systems.

Proactive generation redispatch focuses on determining the optimal generation level of each operating generator for a specific period of time under varying system conditions due to extreme weather events. During normal operation, minimum operating costs of both generators as well as RESs should be imposed. On the contrary, during abnormal circumstances, load curtailments should be avoided or minimized, if necessary. Also, the behavior of RESs should be considered during extreme weather events for realistic system representation. For example, solar power may have much less generation level due to high cloud formulation and reduced solar irradiance level during hurricane events. Also, operating wind turbines during high speed hurricane events is accompanied with high risks. System constraints and proper varying factors should be considered in the optimization problem such as ramping rates, minimum up and down times, and forecasted hurricane progression. Assurance of assets availability, such as generators and transmission lines, during and after a hurricane is a vital constraint to maintain reliable operation of power systems.

III. Multiobjective Optimization Formulation

This section introduces the formulation of the mulitobjective optimization problem to minimize the overall operating costs. The first objective is to minimize the cost of load curtailments during and after the hurricane period whereas the second objective is to reduce the operational costs of conventional generators and RESs. Various system constraints are considered to maintain reliable operation of the power grid. A dc power flow formulation is used for system modeling which has been commonly used in studies that require repetitive solutions of optimization problems such as power system reliability and resilience studies [43]–[45].

A. Objective Function

The multiobjective function is expressed as follows:

$$\min\ W_1 \sum_{t\in\Omega_T^H} \sum_{n\in\Omega^N} C(C_{n,t}) + W_2 \sum_{t\in\Omega_T} \sum_{i\in\Omega^G} C_f(P_{i,t}^G). \quad (1)$$

Values for W_1 and W_2 are chosen such that their summation equals to one. Pareto analysis method can be used to determine their proper values. In this article, W_1 is selected to be 0.9 to make sure that the algorithm prioritize reducing load curtailment over operational costs during the event [11], [12].

B. Constraints

For a feasible problem formulation, several constraints are considered as follows.

1) Power Balance: During any time instant, the amount of power supplied by generators and RESs should be equal to required load consumption as well as system losses. The power balance at bus n and at time t can be expressed as follows:

$$\begin{aligned} &P_{n,t}^S + P_{n,t}^W \\ &+ \sum_{i\in\Omega_n^G} P_{i,t}^G - (L_{n,t} - C_{n,t}) + \sum_{n,n'\in\Omega_n^N} P_{n,n,'t}^L = 0\,. \end{aligned} \quad (2)$$

2) Transmission Flow Limits: The power flow through a specific line connected to bus n at any time t must be within the predefined line capacity limits as follows:

$$B_{n,n'}.(\theta_{n,t} - \theta_{n,'t}) - P_{n,n',t}^L \leq P_{n,n'}^{\text{Max}}\ \forall n \in \Omega^N \quad (3)$$

$$B_{n,n'}.(\theta_{n,t} - \theta_{n,'t}) - P_{n,n',t}^L \geq P_{n,n'}^{\text{Min}}\ \forall n \in \Omega^N. \quad (4)$$

3) Load Curtailment Limits: During the hurricane, the amount of load curtailment at each bus should be less than or equal the total amount of load at the same bus. In other words, the maximum load curtailment at a specific bus should not exceed the sum of all loads at the same bus, which can be expressed as follows:

$$0 \leq C_{n,t} \leq L_{n,t} \quad \forall n \in \Omega^N \quad \forall t \in \Omega_H^T. \quad (5)$$

During normal operating conditions, the amount of load curtailment should be zero

$$C_{n,t} = 0 \quad \forall n \in \Omega^N \quad \forall t \in \Omega_{NH}^T. \quad (6)$$

4) Status of Generating Units: The status of each generator at time t is represented by a binary number as follows:

$$u_{i,t} \in \{0,1\} \quad \forall i \in \Omega^G. \quad (7)$$

5) Ramping Rates of Generators: The ramping behavior of each generator is governed by its current status, future status, current power generation, and future power generation. When a generator is fired up, it should supply power more than or equal its minimum capacity. If a generator is supplying power and requested to ramp down, it cannot supply power less than its minimum capacity. Also a generator can ramp up till its maximum capacity. The ramping rates of each generator are expressed as follows:

$$\begin{aligned} &P_{i,t+1}^G - P_{i,t}^G \leq (2 - u_{i,t} - u_{i,t+1}).P_i^{G,\text{Min}} \\ &+(1 + u_{i,t} - u_{i,t+1}).R_i^{UP} \quad \forall i \in \Omega^G \end{aligned} \quad (8)$$

$$\begin{aligned} &P_{i,t}^G - P_{i,t+1}^G \leq (2 - u_{i,t} - u_{i,t+1}).P_i^{G,\text{Min}} \\ &+(1 - u_{i,t} + u_{i,t+1}).R_i^{DN} \quad \forall i \in \Omega^G. \end{aligned} \quad (9)$$

6) Generators Minimum Up/Down Time: During redispatch, minimum up and down times for each generator should be satisfied as follows:

$$\sum_{t-UT+1}^{t} T_{i,t}^{ON} \leq u_{i,t} \quad \forall t \in \{UT, \ldots, T\} \quad \forall i \in \Omega^G \tag{10}$$

$$\sum_{t-DT+1}^{t} T_{i,t}^{OFF} \leq 1 - u_{i,t} \quad \forall t \in \{DT, \ldots, T\} \quad \forall i \in \Omega^G. \tag{11}$$

In (10), there should be at most one instant of turn-ON signal for a duration of UT prior to t whereas in (11), there should be at most one instant of turn-OFF signal for a duration DT prior to t when the generator's status changes into 0.

7) Power Limits of Generators: The generated power of each generator can be expressed as follows:

$$P_i^{G,\text{Min}}.u_{i,t} \leq P_{i,t}^G \leq P_i^{G,\text{Max}}.u_{i,t} \quad \forall i \in \Omega^G. \tag{12}$$

8) Voltage Angle Limits: The voltage angle at bus n at time t can be expressed as follows:

$$\theta_n^{\text{Min}} \leq \theta_{n,t} \leq \theta_n^{\text{Max}} \quad \forall n \in \Omega^N \tag{13}$$

where θ_n^{Min} and θ_n^{Max} are the minimum and maximum voltage angle levels for the nth bus, respectively.

The proposed proactive generation redispatch algorithm considering unavailability of RESs is illustrated by the flowchart shown in Fig. 2.

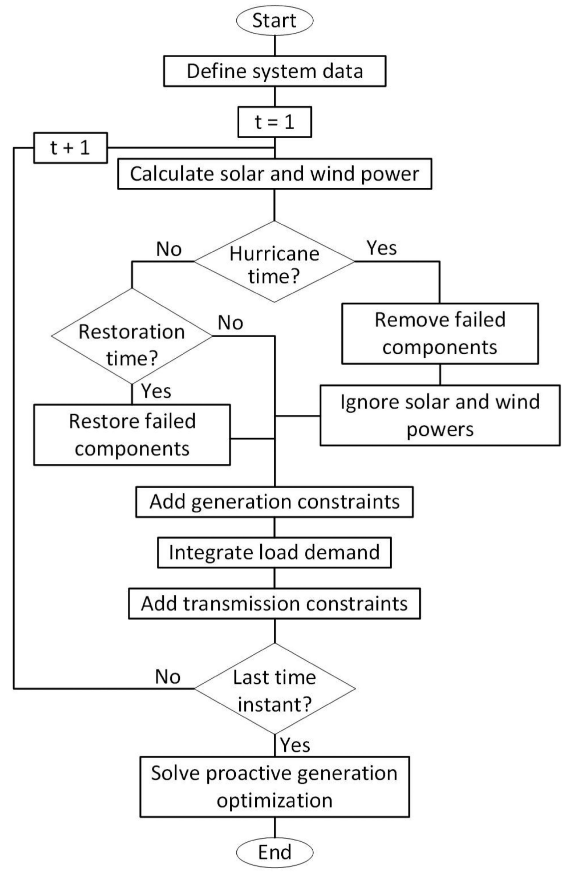

Fig. 2. Proposed proactive generation redispatch algorithm considering unavailability of RESs.

IV. Implementation and Results

The proposed approach is applied on modified versions of the IEEE 30-bus system. The CPLEX solver is integrated with MATLAB environment to solve the MILP optimization problem. This section explains the implementation procedures and discusses the results. Test cases are simulated to validate the accuracy and effectiveness of the proposed method as well as assess the impact of RESs penetration level on proactive redispatch strategy.

A. Modified IEEE 30-Bus System

To accommodate the role of RESs in the proposed strategy, solar and wind energy sources are added to the IEEE 30-bus system. G_5 is replaced by a solar power plant with total power capacity of 25 MW, whereas G_6 is replaced by a wind power plant with maximum capacity of 30 MW. The parameters of both solar and wind energy are obtained from [42]. The curves of solar and wind power, shown in Fig. 3, are calculated based on historical data from [46]. Generators data are provided in Table I. The generators' ramping rates (MW/hour) are assumed to be 10% of the maximum power capacity. All generators are assumed to have minimum up/down time of 15 min. The impact of load variation is considered using 5 minute intervals load demand obtained from [47] as shown in Fig. 4.

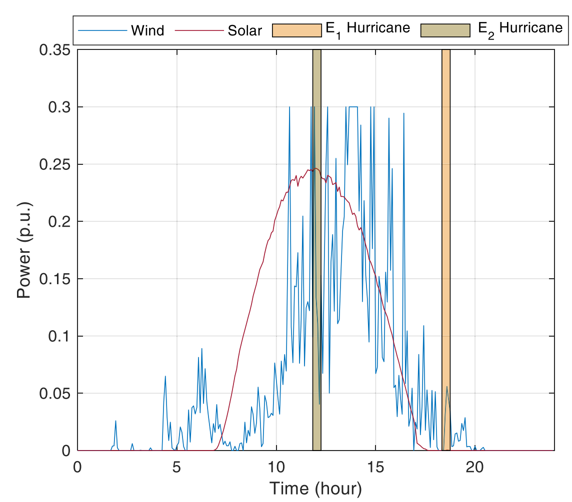

Fig. 3. Solar and wind real power output.

B. Hurricane Scenario

In this work, a hurricane scenario is assumed to propagate across the IEEE 30-bus system as shown in Fig. 5. The total time for the hurricane to cross the system is assumed to be 25 min. The hurricane period is sampled in sets of 5 min to discretize their propagation behavior. The set of failed components at each

TABLE I
GENERATOR PARAMETERS

Unit	Cost ($)			Power (MW)	
	b	C_{su}	C_{sd}	P_{min}	P_{max}
G_1	1.75	70	176	30	120
G_2	2	70	176	35	140
G_3	2	70	176	10	50
G_4	2.25	70	176	5	30
G_5	0.75	0	0	10	25
G_6	0.75	0	0	15	30

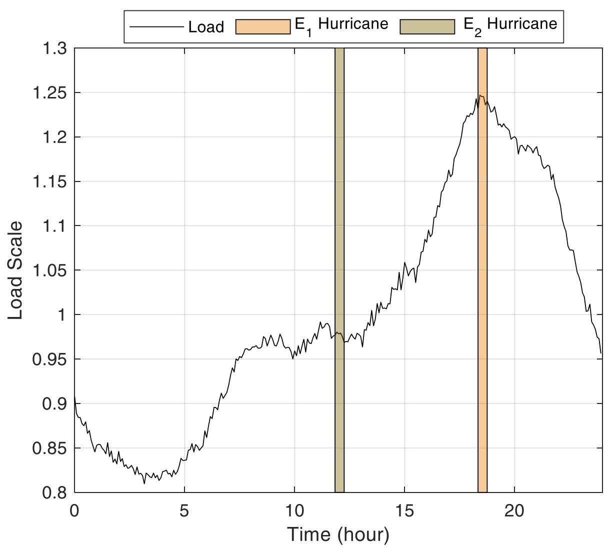

Fig. 4. Load scaling profile.

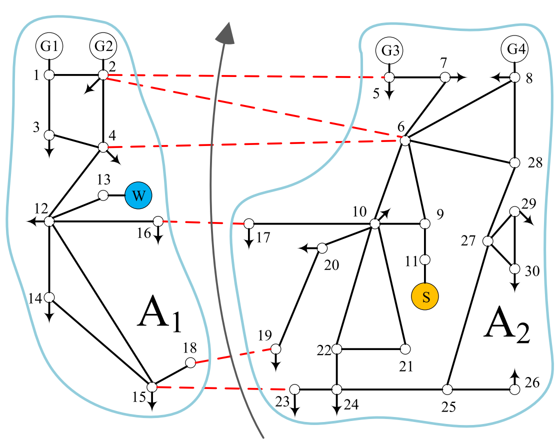

Fig. 5. Hurricane propagation on IEEE 30-bus system.

time instant is provided in Table II based on the trajectory of the hurricane using the approach proposed in [28] and [42].

C. Validation of the Proposed Algorithm

The accuracy and effectiveness of the proposed algorithm are tested through several test cases. The performance of the redispatch strategy relies on numerous factors such as the hurricane impact time, the severity of the hurricane, the preparedness strategy execution time, the duration of the event, and the scale of the system. In this work, two factors are considered: the hurricane impact time and the strategy execution time. Also, it is assumed that all failed components will be fully restored after one-hour period from the hurricane end instant. All test cases are validated through comparisons between the proposed proactive redispatch strategy and corrective redispatch strategy. In the corrective strategy, no prior redispathcing is applied before the hurricane impact time; however, dispatching is readjusted at each time instant to encounter the failed components and fulfill the current system operational constraints.

TABLE II
LIST OF FAILURE COMPONENTS

Time Instant	Component No.	Component Description
t_1	–	–
t_2	C_1 C_2	Line 15-23 Line 18-19
t_3	C_3	Line 16-17
t_4	C_4	Line 4-6
t_5	C_5 C_6	Line 2-6 Line 2-5

TABLE III
SIMULATED HURRICANE EVENTS

	Impact period	Start time	End time
E_1	During peak load demand	18:25	18:50
E_2	During peak solar generation	11:55	12:20

1) Hurricane Impact Time: Within the context of this article, a hurricane impact time is the instant when a hurricane lands and its impacts are being realized on power grid components. Since a hurricane can occur at different times during a day, the realization of its impact will vary based on system operational conditions at the impact time. In this article, two hurricane events are simulated: E_1-hurricane occurs during peak load demand and E_2-hurricane occurs during peak solar generation. Table III summarizes the two simulated hurricane events.

(a) During peak load period

During normal operation, generators and RESs supply the full load demand; but, during a hurricane, RESs are forced to shut down due to their uncertain generation behavior. In this case, E_1-hurricane lands at 18:25 during which neither solar nor wind will have noticeable input, as shown in Fig. 3. Therefore, the dependence on conventional generators will increase significantly.

Fig. 6 shows the real power output of all four conventional generators for 24 h. In a normal day, all generators are utilized at almost 50% of their capacities. The occurrence of the hurricane imposes a corrective redispatch to adjust the generation based on the new system state. This is noticed at G_1 and G_2 where a ramp down behavior is realized to maintain operational constraints. The generation profiles have changed completely due to applying the proposed proactive generation redispatch. Prior to the hurricane, higher utilization of G_1 is noticed to compensate

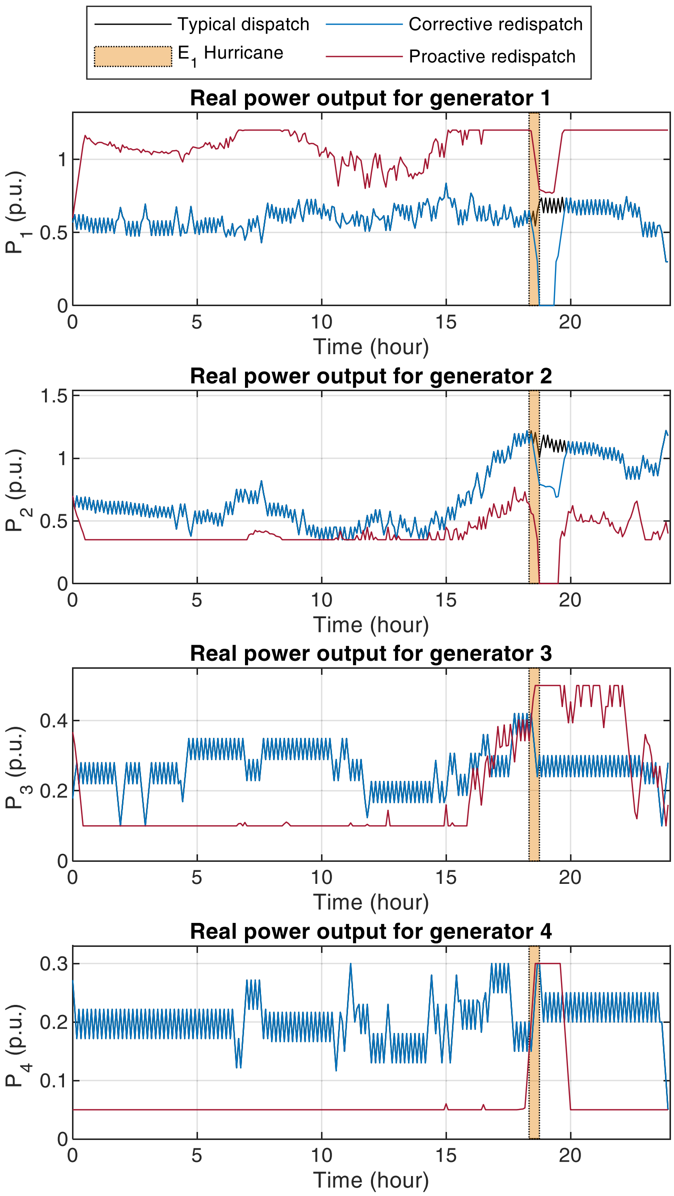

Fig. 6. Real power output of all conventional generators with and without proactive redispatch strategy during E_1 hurricane [case 1(a)].

for the less utilization of G_3 and G_4. During the hurricane, G_3 and G_4 ramp up to match the required load demand and compensate the ramping down of G_1 and G_2. Also, G_2 comes to a complete shutdown at 18:50. After the restoration of system components (1 h post hurricane end time), G_1 and G_2 ramp up to benefit from their low operational costs. G_3 operates at almost the full capacity to maintain high load demand; whereas G_4 ramps down to reduce overall operational costs. Generally, the proactive redispatch provides a better preparedness of the system.

The failure of system components on the hurricane trajectory results in splitting the power system into two islands. Most of the load spots exist in A_2; while the two largest generators exist in A_1. Insufficient generation resources at a specific area yields non-avoidable load curtailments. Fig. 7 shows the amount

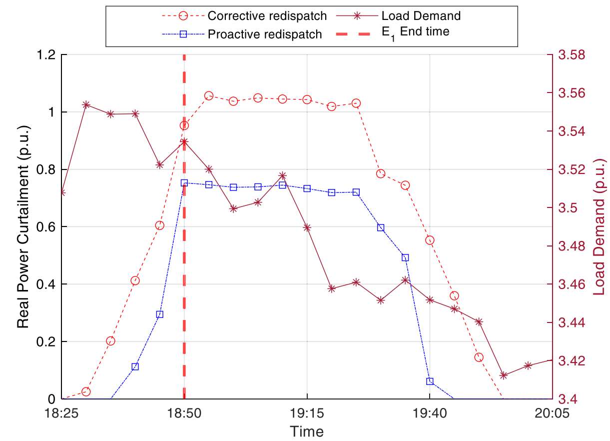

Fig. 7. Load curtailments with and without proactive redispatch strategy during E_1 hurricane [case 1 (a)].

of load curtailments with and without the proactive redispatch strategy. The proactive redispatch shows less load curtailments compared to the corrective redispatch. At the first few instants during a hurricane, the proactive redispatch has avoided any load curtailments. Afterward, the proposed algorithm has shown at least 30% reduction in load curtailments. At 18:50, the amount of load curtailments is still growing momentarily under the corrective strategy. After the restoration of failed components, the proactive redispatch provides faster recovery of curtailed load.

(b) During peak solar generation period

Since RESs are forced to shut down during the hurricane because of their uncertain behavior, this case assesses the proactive redispatch algorithm when the hurricane lands during high generation supply from RESs. E_2–hurricane lands at 11:55 during which RESs have high generation, as shown in Fig. 3. Since reliance on conventional generators will increase, the capabilities of the proactive redispatch strategy can be realized.

Fig. 8 compares the real power output of all conventional generators with and without proactive redispatch. Although the proposed algorithm is applied for a whole day, Fig. 8 shows a view for a two-hour period starting at the hurricane impact time. Overall, the generation profiles vary based on the applied redispatch strategy. In a typical day with normal operating conditions, the power supplied from RESs will yield less utilization of conventional generators. This is clearly noticed in the corrective strategy results of Fig. 8. Applying the proactive redispatch strategy encourages the system to rely on G_1 due to its high capacity and low operational costs. Also, G_3 and G_4 ramp up during the hurricane to match the required load demand. On the other hand, G_1 ramps down very fast to maintain all dynamic constraints post islanding behavior.

The significant impact of the redispatch strategy is the capability to minimize load curtailments even with unavailability of RESs as shown in Fig. 9. It is worth noting that the proactive redispatch resulted in no curtailments during the hurricane period and prior to islanding. At 12:20, the proactive redispatch has much lower load curtailments compared to corrective redispatch

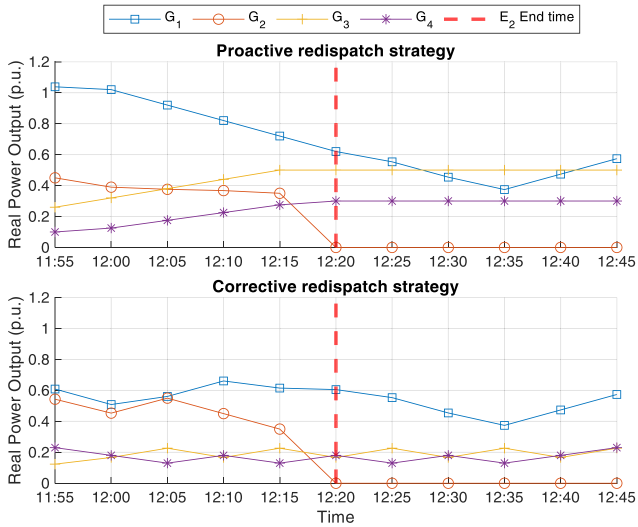

Fig. 8. Real power output of all conventional generators with and without proactive redispatch strategy during E_2 hurricane [case 1(b)].

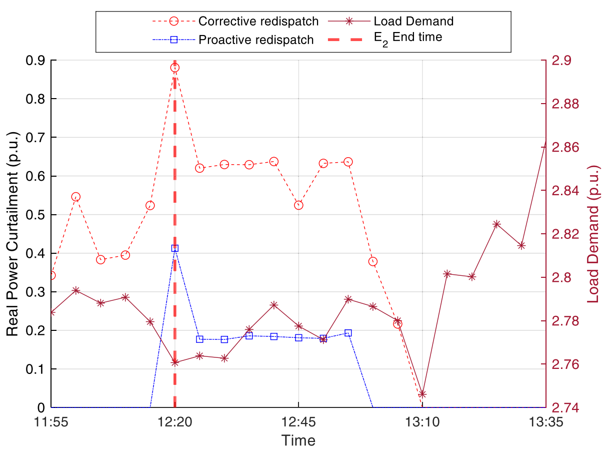

Fig. 9. Load curtailments with and without proactive redispatch strategy during E_2 hurricane [case 1 (b)].

by almost 60%. After the hurricane, the curtailed load under proactive redispatch is due to islanding behavior and insufficient generation in A_2. The increase in load demand starting at 12:30 does not impose further stress conditions on the proactive redispatch strategy. On average, proactive redispatch reduced the amount of load curtailment by 70% post the hurricane period.

2) Strategy Execution Time: Due to high uncertainties in hurricane's temporal and geographical progression and high possibility of changing its trajectory, it may not be essential to apply the redispatch strategy for the whole day resulting in overall high operational costs. The proposed algorithm can be executed at any instant prior to the hurricane; however, diverse generation levels and costs are encountered. In this case, the impact of execution time of the proposed strategy is tested by comparing two scenarios: (i) 60-min interval; and (ii) 120-min interval prior to the hurricane.

Fig. 10 shows the real power output of all conventional generators for the two scenarios during E_2–hurricane. When

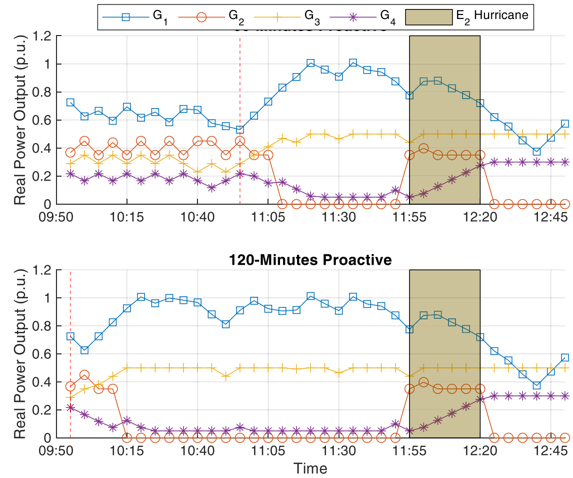

Fig. 10. Generation profile under different implementation time.

TABLE IV
MODIFIED GENERATOR PARAMETERS

Unit	G_1	G_2	G_3	G_4	G_5	G_6
b	1.8	2	1.8	2.2	1.9	1.6
C_{su}	70	75	80	65	60	70
C_{sd}	30	40	35	25	30	40
Unit	S_1	S_2	S_3	W_1	W_2	W_3
b	0.9	1	0.9	1.1	1	0.8

the proactive redispatch strategy is executed earlier, operational costs are reduced and the utilization of reliable generators is achieved. For instance, G_1 ramps up as soon as the proactive strategy is being implemented while G_2 ramps down to complete shutdown. This implies the capability of the proactive redispatch strategy to prioritize low-operational cost generators over high-operational cost generators. Also, G_4 is pushed to maintain low generation level prior to the hurricane for further cost reduction. Although same load curtailment level is observed for both scenarios, different costs are encountered. The total operational costs for scenario (i) and (ii) are $\$940,297.7$ and $\$937,629.7$, respectively.

D. Effect of RESs Sizing

In this case, further analysis is conducted to assess the impacts of varying penetration levels of RESs on the resilience of power systems and overall operational costs. The standard IEEE 30-bus system is modified to include solar power plants at buses 3, 6, and 10, and wind power plants at buses 12, 15, and 25. The generation cost coefficients for all units are modified to create a diverse cost profile as summarized in Table IV. All conventional generators are assumed to have 15 min minimum up/down time. E_2–hurricane is considered in this case. Simulations are run on the system with varying RESs levels under proactive redispatch and corrective redispatch strategies. For the validation purpose, the initial generation level of all units is obtained from optimal power flow solution for a normal day—no hurricane is expected.

Fig. 11 shows that the operational cost decreases smoothly as the size of RESs increases when using the proposed proactive

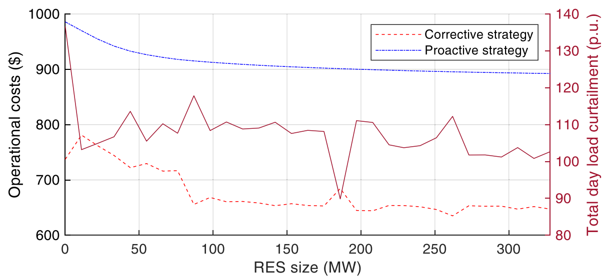

Fig. 11. Variation between RES size and operational costs and total load curtailments.

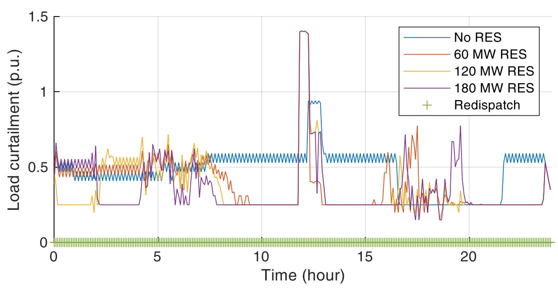

Fig. 12. Variation between RES size and load curtailments.

redispatch algorithm. Ignoring the proactive redispatch results in less operational costs due to the low utilization of conventional generators. Also, increasing the size of RESs without retiring conventional generators can reduce the total amount of load curtailments, which highlights the importance of integrating RESs to resilience enhancement of power systems. At the beginning of the day, higher load curtailments may be observed compared to the end of the day due to the very tight operating conditions. Even with high generation capacities, the power flow for some transmission lines hits the maximum threshold yielding further burdens on system operation.

Fig. 12 shows the relationship between load curtailment and time under various RESs penetration levels. For each penetration level, the generation redispatch is solved with and without the proposed proactive strategy. It is noticeable that for all RESs penetration level, the proactive redispatch has avoided load curtailments. Without employing proactive generation dispatch similar to the proposed approach, load curtailments cannot be avoided regardless of RES sizes. As the RES sizes increase, the load curtailment profile changes based on the weather data and the total amount of load curtailments decreases. Due to the very tight operating conditions, load is curtailed even with zero penetration level of RESs.

V. Conclusion

This article has proposed a proactive generation redispatch strategy to enhance the operation resilience of power grids during hurricanes considering unavailability of RESs. The proposed method minimizes load curtailments and operational costs considering system operational constraints and hurricane spatiotemporal characteristics. An MILP is formulated to determine the optimal generation redispatch under a predefined sequential failure of system components. The proposed method was demonstrated on a modified version of IEEE 30-bus system. The results showed that the proactive generation redisptatch strategy is able to reduce the total amount of load curtailment by 60% in many cases and avoided load curtailments for a hurricane taking place at high RESs generation period. Also, the role of execution time of the proposed proactive redispatch has been assessed. The earlier the execution is, the less load curtailment will be. The results has also shown that the proactive redispatch strategy can avoid load curtailments regardless the penetration level of RESs in the specified system. The proposed algorithm provides system operators with possible solutions to reduce the impacts of hurricanes on transmission systems via utilization of available generation resources. This algorithm facilitates the decision process during a fast evolving hurricane event. It provides system operators with a preliminary dispatch solution that considers forced outages of RESs during hurricane. Also, it paves a framework for system planners to determine proper upgrade and hardening requirements for resilient power grids. In the future, the role of large-scale energy storage systems integrated into proactive generation redispatch shall be considered. Also, the scalability of the proposed algorithm to larger systems will be studied.

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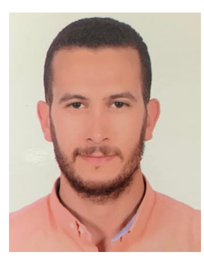

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