Proactive Generation Redispatch to Enhance Power System Operation Resilience during Hurricanes

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***Abstract*—This paper proposes a proactive generation redispatch strategy to enhance the operational resilience of power grids during hurricanes. Enhancing the overall operation resilience is a mathematically involved problem accompanied with many challenges related to modeling and computation methods. Most previous resilience enhancement methods focus on reducing the amount of load curtailment during extreme events without proactively preparing the system for forecasted extreme events or considering the consequences after the occurrence of an event. Also, system operational cost is usually neglected resulting in higher costs for operational resilience enhancement strategies. In this paper, a multiobjective mixed integer linear programming optimization problem is formulated for generation redispatch to minimize load curtailments and operational costs for a one-day interval when a power system is subjected to a hurricane. System constraints (e.g., ramping rates, minimum up/down times, and transmission line constraints) and spatiotemporal properties of extreme events are considered in the optimization problem. The CPLEX solver is integrated with MATLAB to formulate and solve the optimization problem. Although the proposed method can be adapted to enhance power system resilience against different types of extreme events, the focus of this work is on improving the operational resilience of power grids against hurricanes. The IEEE 30-bus system is used to validate the proposed strategy under two levels of severity: low and extreme impacts. The results demonstrate the effectiveness of the proposed method in improving power grid operational resilience during the development of hurricanes.**

***Index Terms*—Extreme weather event, generation redispatch, hurricane, resilience.**

I. Introduction

The frequency and intensity of extreme weather events (e.g., hurricanes, earthquakes, and floods) have increased dramatically in recent years and have caused large and prolonged power outages and significant economic losses [1], [2]. For instant, the estimated economic losses due to extreme weather-related outages in the United States is more than $25 billions per year [3]. Also, around 200 million people have experienced power outages due to an ice storm in China in 2008 resulting in total direct economic losses of $2.2 billions [4]. As a result, the importance of enhancing the resilience of the power grid against extreme weather events has gained significant attention worldwide [5]. Specifically, resilience enhancement strategies of distribution systems have gained more interest than that of transmission systems due to several factors including the vulnerability of distribution systems to extreme events and lack of resources for black start support [6], [7]. Also, most of resilience enhancement strategies at the transmission level focus on emergency response strategies such as mobile energy storage devices, topology switching, and load shedding, which usually neglect the role of operational costs and generation dynamic constraints [1]. Several studies have focused on enhancing the resilience of the power grid during the extreme weather events while ignoring both the the impact of load variations and consequences of the implemented strategies after the system return to normal operation conditions [1]. Further, the impact of the attack time of extreme weather events (i.e., the instant at which an extreme event hits the system) on both system operation and enhancement strategies has not received much attention. Thus, implementing a resilience enhancement strategy at the transmission level that encounters operation cost, generation dynamic constraints, load variations, and extreme weather attack time has become more important than ever before.

A resilience enhancement framework presented in [8] assumes that power systems pass through three main stages when exposed to extreme event: prior to event, during the event, and after the event. Based on this concept, resilience enhancement strategies vary according to the targeted stage. Operational resilience enhancement focuses on providing an immediate solution based on the available assets to reduce the impacts of adverse events. In [9], a procurement plan with a minimal cost has been proposed to ensure the availability of sufficient black start support resources at optimal locations prior to an event, however, the spatiotemporal properties of extreme event have been neglected. Other strategies such as maintenance planning [10] and mobile energy storage allocation [11] have been studied to enhance power system resilience before extreme weather events. On the other hand, authors of [12] have provided a defensive islanding algorithm to split distribution grids into smaller and reliable microgrids considering non-dispatchable and dispatchable distributed generators. In [13], a proactive resilience enhancement strategy based on generation redispatch has been proposed to reduce the cost of load curtailment during hurricanes where the operational costs as well as the load variations have been ignored. Several restoration strategies have been proposed to restore the curtailed loads as fast as possible after extreme weather events have passed [14]. In [15], a three-step look-ahead load restoration strategy with a priority to critical loads has been developed utilizing synchronized distributed generators after major natural disasters.

This paper proposes a proactive generation dispatch strategy to enhance the operational resilience of power grids against hurricanes. Due to the sequential characteristics and spatiotemporal properties of a hurricane, the strategy considers

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the status of the power grid in the three main stages: prior, during, and after the event. As a result, the strategy takes in consideration system conditions and statuses of all system components right before an event and potential future statuses due to the event. The proposed strategy minimizes the overall operating cost of the power system through (a) minimizing or even eliminating load curtailments during hurricane and (b) minimizing fuel cost during normal operation. The effect of load variations has been considered over a period of 24 hours sampled in 5-minute intervals. The hurricane is assumed to take place during peak load in order to induce more severity to the system. In addition, several system dynamic constraints have been utilized 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 optimization problem is formulated using CPLEX solver integrated with MATLAB environment to solve for optimal generation redispatch for resilience enhancement and cost reduction. The proposed method is implemented on the IEEE 30-bus transmission system. Analysis and validation of the results are also provided.

The rest of the paper 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. Section IV illustrates the proposed approach on the IEEE 30-bus system and discusses the results. Section V provides concluding remarks.

II. The Concept of Proactive Generation Redispatch for Resilience Enhancement

This section describes the proposed resilience enhancement strategy for transmission systems against hurricane based on proactive generation redispatch. First, it describes hurricanes' progression and their impacts on the power grid components. Then, it explains the proposed generation redispatch algorithm.

Extreme weather events have been classified as high intensity and low probability events that result in catastrophic power outages in very short periods of time [16]. Impacts on the performance of power system vary according to the type of the event and vulnerability and preparedness of the system. For example, earthquakes have high impacts on underground cables whereas hurricanes result in failure of transmission poles and lines [17]. For each extreme weather event, a proper model is required to identify its propagation properties and spatiotemporal characteristics. Both probabilistic and deterministic approaches have been applied on historical data of extreme events to enhance weather events modeling [18]. Most resilience-based studies have focused on component failure modeling using probabilistic fragility curves due to the stochastic behavior of extreme weather events [18]. However, some studies have used predetermined sequential failure scenarios based on forecasting models or historical data [1].

Intensities of hurricanes change temporally and geographically with their progression trajectories, which can be used to identify their spatiotemporal properties [13]—various components in the system can be impacted at sequential time intervals. Fig. 1 shows a scenario where two system components are on the trajectory of a hurricane. At t_2, component A is subjected to potential failure resulting in noticeable disturbance in the system performance. Component B is expected to fail at t_4 imposing further impacts on system dynamics. Hurricanes are usually fast acting weather events that might impact more than one component at the same instant resulting in various system configurations. Also, it is usually difficult to restore failed elements during the hurricane time especially if maintenance crew dispatching is a must for the restoration process. In very severe hurricane conditions, maintenance of some failed components might extend from a few hours to a few days [13]. Therefore, at each time instant during the hurricane, the set of failed components will include the possible failed components from previous time intervals.

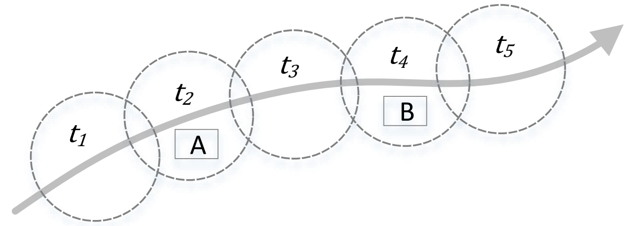

Fig. 1. Two components on the trajectory of a hurricane

Failure of system components results in noticeable changes in the performance of the power grid such as power flow between transmission lines, generators output level, and overall operating costs. When the number of failed elements increases, the severity of the situation arises dramatically. In some cases, power grid can withstand low impact failures but when it comes to fast sequential failure scenarios, some loads must be curtailed to maintain more resilient operation. Moreover, during extreme weather events, the priority should be given to the reduction of load curtailment rather than operational costs. However, some existing strategies ignore the future potential failures of system components. This leads to implementing a less resilient strategy and increasing the negative consequences on the system performance. For instant, if a generating unit is expected to be impacted by a hurricane at upcoming future time, it is preferable to reduce the utilization of this unit before the extreme weather event hits the system.

Proactive generation redispatch relies mainly on determining the optimal generation levels of each operating generator unit for a specific period of time given the current and forecasted future system conditions. During normal operation, minimum operating costs should be imposed whereas during abnormal conditions, load curtailments and their associated costs should be minimized. Integrating the two objectives for two different operation conditions (i.e., to minimize both generation costs and load curtailment costs) requires consideration of several system constraints and varying factors such as ramping rates, minimum up and down times, and forecasted hurricane progression. For example, load demand at each time instant has a direct role in generation output levels. Assurance of assets availability, such as generating units and transmission lines, during and after a hurricane is a vital constraint to maintain reliable operation of the system. On the other hand, restoring the curtailed load in a fast, efficient, and economical way, enhances the overall operational resilience level of the system. Also, the power grid could be split into several islanded microgrids where the generation level at each microgrid should be sufficient to supply all or most of its loads. Using generation redispatch, generator levels can be adjusted to meet the goal of each islanded microgrid.

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 reduce the fuel cost during normal operation conditions whereas the second objective is to minimize the cost of load curtailments during hurricane. Several system constraints are considered to maintain the feasibility and reliability of the proposed strategy. A DC power flow formulation is used to reduce the complexity of the problem.

A. Objective Function

The multiobjective objective function is expressed as follows.

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

where Ω_T^H represents the set of all time instants during hurricanes; Ω^N represents the set of all buses; $C(C_{n,t})$ represents the cost of load curtailment at n^{th} bus and time instant t; Ω_T represents the set of all time instants; Ω^G represents the set of all generators; and $C_f(P_{i,t}^G)$ is the fuel cost function of i^{th} generator at time t.

B. Constraints

Several constraints are considered as follows.

1) Power Balance:

The power balance at time t a bus n can be expressed as follows.

$$\sum_{i\in\Omega_n^G} P_{i,t}^G - (L_{n,t} - C_{n,t}) + \sum_{n'\in\Omega_n^N} P_{n,n',t}^L = 0 \;\forall n \in \Omega^N, \qquad (2)$$

where Ω_n^G represents the set of generators connected to bus n; $P_{i,t}^G$ is the i^{th} generator real power at bus n; $L_{n,t}$ is the amount of load in MW at bus n; $C_{n,t}$ is the amount of load curtailed at bus n ; Ω_n^N represents the set of all buses connected to bus n; and $P_{n,n',t}^L$ represents the power line flow from bus n to bus n' at time t.

2) Transmission Flow Limits:

The power flow through a specific line connected at bus n at any time t must be within the predefined limits as follows.

$$B_{n,n'}.(\theta_{n,t} - \theta_{n',t}) - P_{n,n',t}^L \le P_{n,n',t}^{Max} \;\forall n \in \Omega^N, \qquad (3)$$

$$B_{n,n'}.(\theta_{n,t} - \theta_{n',t}) - P_{n,n',t}^L \ge P_{n,n',t}^{Min} \;\forall n \in \Omega^N, \qquad (4)$$

where $B_{n,n'}$ represents the susceptance of the line connecting nodes n and n'; $\theta_{n,t}$ and $\theta_{n',t}$ are the voltage angles at buses n and n', respectively; and $P_{n,n',t}^{Max}$ and $P_{n,n',t}^{Min}$ are the maximum and minimum line flow ratings, respectively.

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 as follows:

$$0 \le C_{n,t} \le L_{n,t} \;\; \forall n \in \Omega^N \; \forall t \in \Omega_T^H. \qquad (5)$$

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

$$C_{n,t} = 0 \;\; \forall n \in \Omega^N \; \forall t \in \Omega_T^{NH}, \qquad (6)$$

where Ω_T^{NH} represents the set of all time instants excluding hurricane duration.

4) Ramping Rates of Generating Units:

The ramping rates of each generator should be satisfied as follows.

$$\begin{aligned} P_{i,t+1}^G - P_{i,t}^G \le{}& (2 - u_{i,t} - u_{i,t+1}).P_i^{G,Min} \\ &+ (1 + u_{i,t} - u_{i,t+1}).R_i^{UP} \;\; \forall i \in \Omega^G, \end{aligned} \qquad (7)$$

$$\begin{aligned} P_{i,t}^G - P_{i,t+1}^G \le{}& (2 - u_{i,t} - u_{i,t+1}).P_i^{G,Min} \\ &+ (1 - u_{i,t} + u_{i,t+1}).R_i^{DN} \;\; \forall i \in \Omega^G, \end{aligned} \qquad (8)$$

where $P_{i,t+1}^G$ is the i^{th} generator power time, $t+1$; $u_{i,t}$ and $u_{i,t+1}$ are the statuses of i^{th} generator at time t and time $t+1$, respectively; $P_i^{G,Min}$ is the minimum generation power of i^{th} generator; and R_i^{UP} and R_i^{DN} are the up and down ramping rates of the i^{th} generator, respectively.

5) Generators Minimum Up/Down Time:

During redispatch, minimum up and down times for each generator should be satisfied as follows.

$$\sum_{t-UT+1}^{t} T_{i,t}^{ON} \le u_{i,t} \;\; \forall t \in \{UT, \ldots, T\} \; \forall i \in \Omega^G, \qquad (9)$$

$$\sum_{t-DT+1}^{t} T_{i,t}^{OFF} \le 1 - u_{i,t} \;\; \forall t \in \{DT, \ldots, T\} \; \forall i \in \Omega^G, \qquad (10)$$

where $T_{i,t}^{ON}$ and $T_{i,t}^{OFF}$ are the turn on/off signals of i^{th} generator at time t, respectively; and UT and DT are the minimum up/down times for same generator, respectively.

6) Power Limits of Generating Units:

The generated power of each generator can be as expressed as follows.

$$P_i^{G,Min}.u_{i,t} \le P_{i,t}^G \le P_i^{G,Max}.u_{i,t} \;\; \forall i \in \Omega^G, \qquad (11)$$

where $P_i^{G,Min}$ and $P_i^{G,Max}$ are the lower and upper limits of i^{th} generator at time t.

7) Generators' Status:

The status of each generator at time t is represented by a binary number as follows.

$$u_{i,t} \in \{0, 1\} \;\; \forall i \in \Omega^G, \qquad (12)$$

where Ω^G is the set of all generators.

8) Voltage Angle Limits:

Voltage angle at bus n at time t can be expressed as follows.

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

where Ω^N is the set of all buses.

IV. Implementation and Results

The proposed approach is applied on the IEEE 30-bus system [13]. The computation are performed using CPLEX solver integrated with MATLAB. This section explains the implementation procedures, and discusses the results.

A. Hurricane Scenario

Since the optimization problem is solved at discrete time instants, the total duration of an extreme event is assumed to be 25 minutes sampled in set of 5 minutes. At each instant, some components may fail such as generators, transmission lines, and connected loads. Based on the trajectory of the hurricane, the potential impacted components are predetermined using the approach proposed in [13]. In order to test the severity of the hurricane, two scenarios are simulated; low and extreme impacts. The spatiotemporal properties of the hurricane on the IEEE 30-bus system is illustrated in Fig. 2. In low-impact scenarios, only one component can fail at each time instant whereas in extreme-impact scenarios, multiple components can fail—the list of impacted components at each time instant is provided in Table I.

TABLE I
List of Failure Components

Time Instant	Component No.	Component Description
t_1	–	–
t_2	C_1	Line 15-23
	C_2	Line 18-19
	C_3	50% Load 19
t_3	C_4	Line 16-17
	C_5	60% Load 17
t_4	C_6	G_6
	C_7	Line 4-6
t_5	C_8	G_2
	C_9	Line 2-6
	C_{10}	Line 2-5

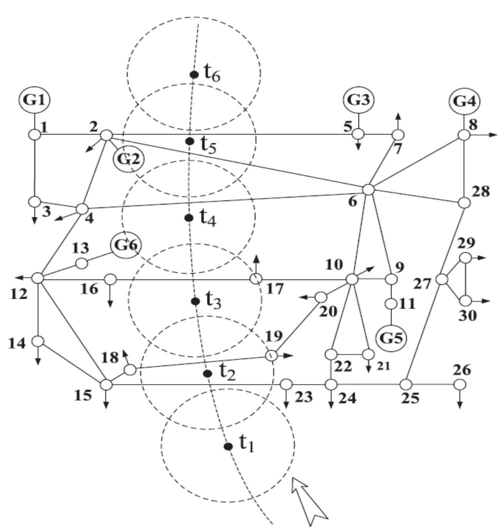

Fig. 2. Hurricane propagation on IEEE 30-bus system [13]

B. Case Studies

In order to validate the proposed method, several test cases are simulated. Due to the variation of load demand, the solution of the redispatch strategy will differ significantly. The impact of load variation is considered using 5-minute intervals load demand which are obtained from [19] as illustrated in Fig. 3. In order to match system load demand, the load scaling approach is applied on the obtained load profile. The 5-minute interval is used to match the same discrete instant during hurricane time. Although there is no control on the attack time of the hurricane, it is assumed to take place during peak load to create more severe circumstances for the generation redispatch strategy. The validation process is done under two possible cases as follows.

1) Low-impact Hurricane

In this case, the hurricane severity level is assumed to be low by assuming only one failure takes place at each time instant during the event. The optimal generation dispatch is solved for three main cases: (i) proactive generation redispatch is performed in response to a hurricane; (ii) no generation redispatch is perfomred while a hurricane occurs; and (iii) generation dispatch under normal conditions.

The total operating cost is determined for all cases and represented in Table II. It can be seen that the generation redispatch strategy achieves the same cost level as in normal operation of the system while minimizing load curtailment. In other words, the proposed strategy reaches same minimum cost level as if the system is operating normally. On the other hand, the operating cost increases significantly if no redispatching is applied due to the significant amount of load curtailment. Fig. 4 shows the real power output of all six generating units for 24 hours. The overall generation profile has changed due to the impact of the hurricane during the peak load period. In the

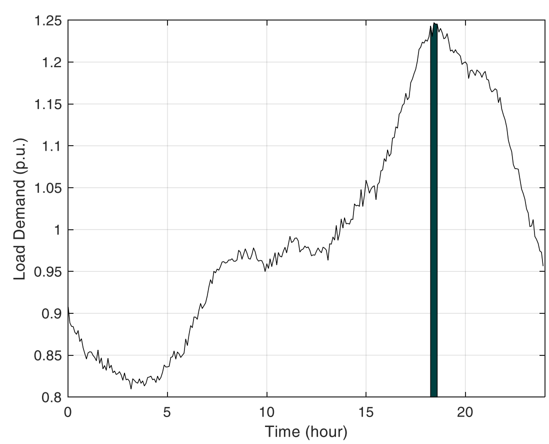

Fig. 3. Load profile with hurricane duration

TABLE II
Total Cost for Low-Impact Scenario

Strategy	Low Impact	
	Cost ($)	Total Load curtailment (p.u.)
Normal Operation	5448.96	–
Redispatch	5448.96	0
No Dispatch	7768.99	25.77

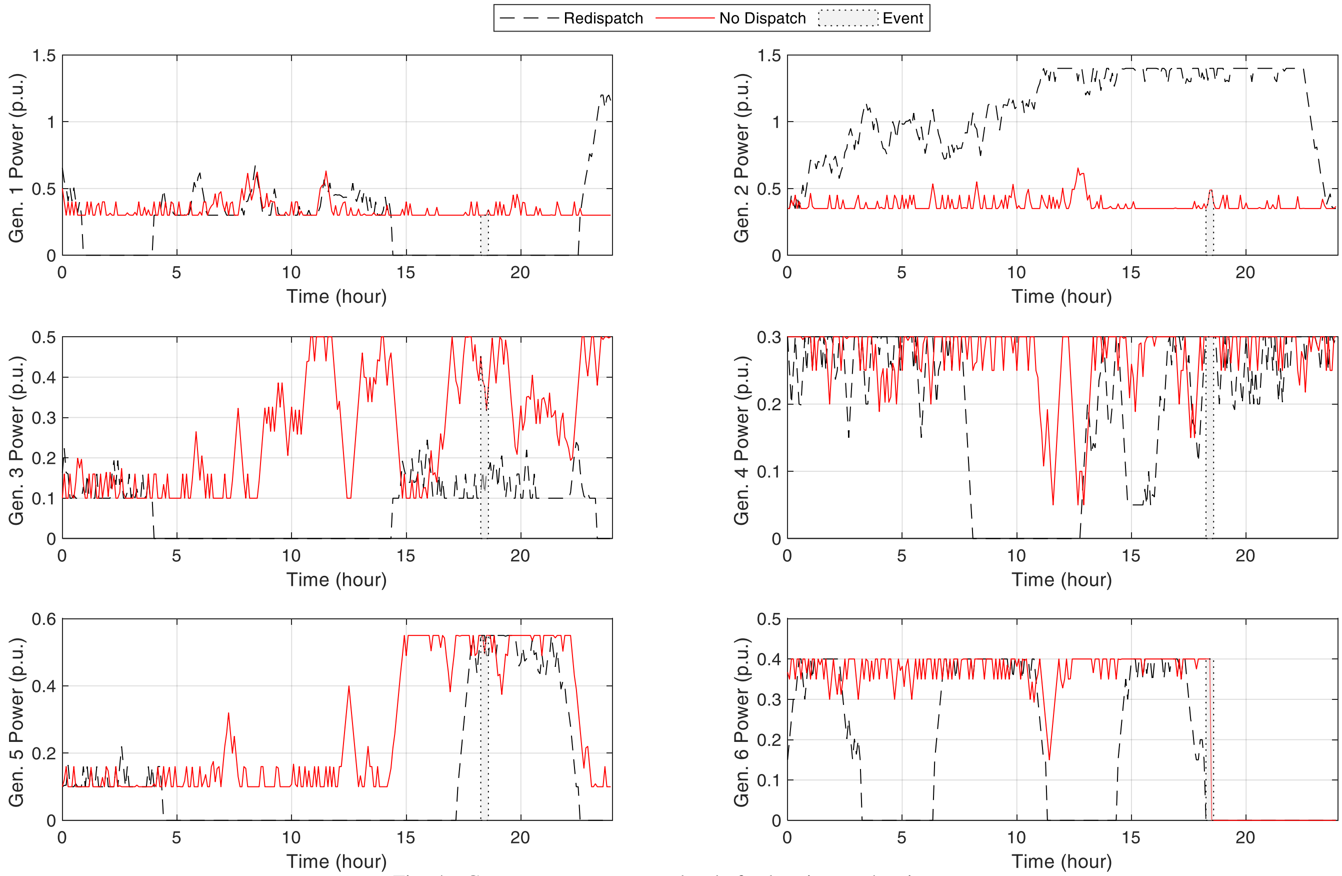

Fig. 4. Generator power output levels for low-impact hurricane

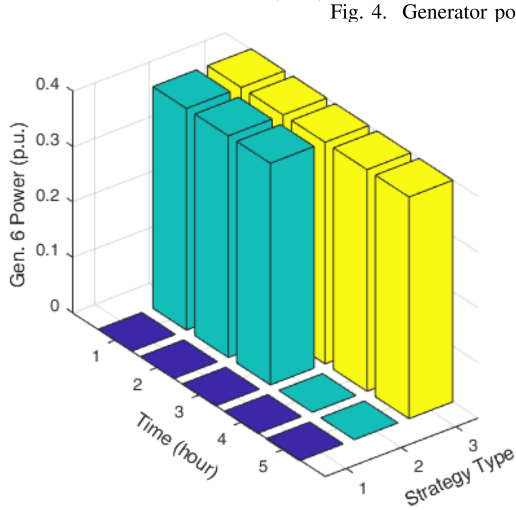

Fig. 5. Comparison between various strategies for G_6

scenario of no generation redispatch, all units are operating at their lowest operating costs unless any of them fails. In the redispatching scenario, all ramping up and down constraints have not been violated as well as the minimum up/down time. The results show very high reliance on G_2, which can be related to the consideration of future failure of G_6. When G_6 fails, several nearby loads with relatively high values need to be supplied resulting in high generation level of the nearest generating units, G_2 and G_1. To show this behavior, the generation output level of G_6 for the event duration is plotted in Fig. 5. The proposed strategy takes in consideration future failure of G_6 and shuts it down prior to the event. However, in case of no dispatching strategy, when G_6 suddenly fails, high load amount has to be curtailed.

2) Extreme-impact Hurricane

In this case, a more severe hurricane scenario is assumed resulting in splitting the system into two complete islanded systems by the end the of hurricane duration. Fig. 6 shows the generation level of all units with and without generation redispatch during the hurricane duration and the preceding 5 instants. Both cases are assumed to have same initial generation level prior to the event. In other words, generation redispatch will start at the first instant of the hurricane. In this case, G_1, G_3, and G_5 ramp up very fast in order to be able to compensate for the loss of G_6 at t_4 and G_2 at t_5. G_4 is operating at its maximum level starting at t_2. The amount of load curtailment for both strategies has been obtained and plotted against load variations as shown in Fig. 7. Although the load variation between t_4 and t_5 is very small, the amount of load curtailed is relatively large. Even with the very fast ramping response, the total generation level will not be sufficient at t_5 resulting in load curtailment. The proposed strategy shows less amount of load curtailments. Due to the sequential failure characteristics of hurricanes, failures taking place at t_5 create more severe situation resulting in isolating the largest generating units, G_1. Due to the islanding situation, G_3, G_4, and G_5 supply their maximum power levels for the load on the right island of the system whereas G_1 supplies all loads in the left island of the system. The proposed strategy is able to recover more than half of the curtailed load by t_6 providing a fast recovery rate (i.e., improving grid resilience).

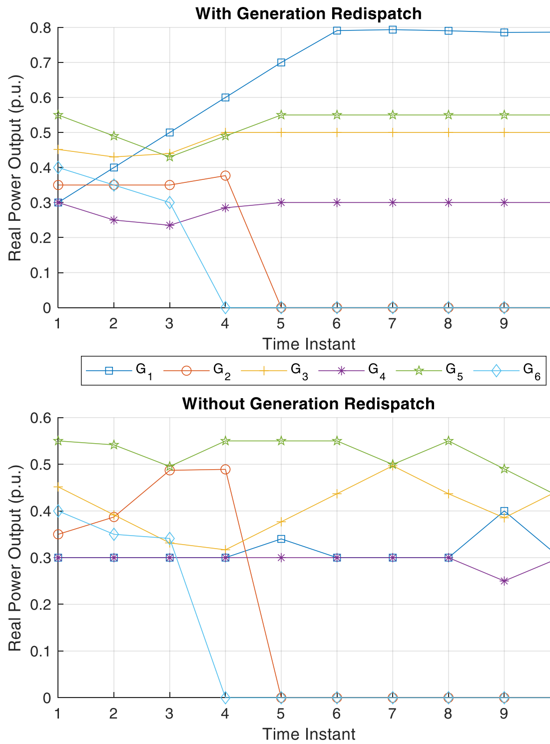

Fig. 6. Generators output levels during hurricane

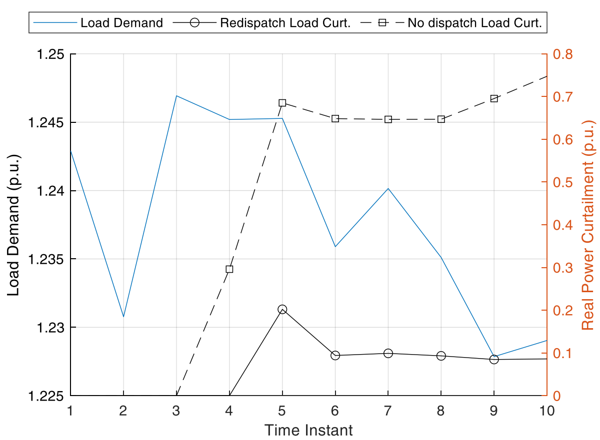

Fig. 7. Load curtailment during hurricane

V. Conclusion

This paper has presented a proactive generation redispatch strategy to enhance the operation resilience of power grid during hurricanes. The proposed method minimizes the operational costs of the system during normal operation as well as the amount of load curtailment during hurricane time. The proposed method was demonstrated on the IEEE 30-bus system under two severity levels of hurricane. The results showed that generation redisptatch strategy enhances the operational resilience of power grid against low-impact hurricanes and maintain the least operational costs. In addition, proactive redispatch considers the current and potential failures of system components. It also helps to have less amount of load curtailed due to severe hurricane conditions with high restoration rates. Generation redispatch strategy can also be integrated with mobile energy storage strategy for further resilience improvements.

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