Simulating Impacts of Extreme Events on Grids with High Penetrations of Wind Power Resources

Preprint

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Simulating Impacts of Extreme Events on Grids with High Penetrations of Wind Power Resources

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***Abstract*—As extreme weather events become more frequent and intense, the demand for connecting grid operation and infrastructure planning with extreme event models will increase as well. We present a methodology for creating damage contingencies and scenarios for electric transmission grids during a hurricane strike. Using WIND Toolkit meteorological data in conjunction with fragility curves for various electric grid elements, we generate stochastic damage scenarios that can be used for short- and long-term planning problems, e.g., emergency asset management. Included is an example case study: Hurricane Dolly damaging a synthetic 2000-bus test system during its landing in Southern Texas. We perform statistical analysis of damages and discuss topological effects on the example synthetic grid. Also, we include a cursory evaluation impacts using simplified operational models. Finally, we discuss how our method can be extended to use even higher-fidelity meteorological data sets and suggest directions for future work.**

***Index Terms*—Transmission grid planning, risk quantification, fragility curve, hurricane damages, contingencies, data-driven forecasting, scenario-based optimization**

I. Introduction

Resiliency of transmission and distribution power grids has recently become a focus of research in the power systems community [1]–[4]. One of the drivers of this interest is extreme weather events such as hurricanes, fires, and floods, and ensuring that the electric grid can withstand and recover from these events. For example, a recent report [2] finds offshore wind power in the Gulf of Mexico to be economically feasible in the near future, but also advises more rigorous resilience studies for hurricane events. The analysis of resilience to these events requires realistic examples of infrastructure damage. Failure to properly explore the damage scenarios and their consequences can lead to power grids being hardened against unlikely or low-impact events or, worse, being woefully unprepared for certain high-impact events that were not considered. Therefore, generating quality scenarios for resiliency studies must include quantifying the probability of events as well as assessing their consequences. In this paper, we focus on generating the hurricane damage scenarios to grids with high penetrations of wind power but also include a cursory evaluation impacts using simplified operational models.

A classic approach in operations is to use $(N-1)$ security constraints, where the power grid is ensured to be secure if any single element (line or generator) fails. In effect, the method generates scenarios by supposing that any one component of the electric grid may fail but that more than one failure is unlikely in the context of normal operations. This idea is successful in ensuring reliability of the electric grid and can be extended to multiple, k, damaged elements. However, this extension leads to a combinatorial growth in the number of scenarios. While guaranteed to generate high-impact scenarios, it provides no ability to quantify the likelihood of these scenarios. Decisions based on such an $(N-k)$ model could potentially result in a robust yet over-built electric power grid leading to greater construction and operational costs. For example, it is unlikely that a hurricane damages transmission lines a significant distance from its path but leaves those in its path undamaged.

In this paper, we outline a method that combines fragility curves with high-fidelity data sets to generate a user-specified number of realistic damage scenarios for a synthetic power grid with high penetration of renewables. These scenarios are realistic in the sense that they are likely to occur and have plausible impacts on the power grid. While our methodology leverages domain expertise in the form of fragility curves for the components of the power grid it is easily used in software

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to create scenarios. We demonstrate our method in the context of a hurricane, but note that the method has a straightforward extension to other natural disasters such as floods, fires, and earthquakes.

The rest of the paper is as follows: In section II we introduce the application of fragility curves in conjunction with meteorological data sets to simulate damages. We demonstrate our results by looking at Hurricane Dolly landing in Southern Texas and damaging a 2000-bus synthetic transmission grid from [5], denoted as ACTIVSg2000 for the rest of the paper. In sections III and IV we show a number of additional investigations that follow and discuss applications that could benefit greatly from our method. Finally, we expand on what can be improved and suggest possible future work directions in section V.

II. Background

Fragility curves define infrastructure component damage probabilities given the intensity of hazardous conditions such as high wind speeds or flood levels, and are often used in Monte-Carlo simulations for evaluating grid resilience [4]. The derivation of fragility curves for estimating stochastic damage of grid infrastructure is outside the scope of this paper [6], [7], and in this paper we mostly focus on their application. As wind power is central in our study, we demonstrate the application of fragility curves using an example based on Hurricane Dolly landing in Southern Texas in 2008 and damaging the ACTIVSg2000 synthetic transmission grid with use-specified amount of renewables on it. A visualization of our experimental setup is included in Fig. 1 which shows the entire path of Hurricane Dolly (July 20-27, 2008) and the ACTIVSg2000 grid. Employing NREL's flagship WIND Toolkit (WTK) [8] wind speed data and the fragility curve method [9] for various elements of the transmission grid, we estimate the damages and impacts to the operation of the electric grid. The novelty of using high-fidelity WTK data in this research is important as it allows seamless integration of damages with various levels of wind power production on the entire grid [10].

A. Wind Turbines

Given the maximum wind speed an element of the grid experiences during a hurricane and the element's fragility curve, we estimate the probability of damage. A schematic of the procedure for generating stochastic damages to turbines within wind plants due to high wind speeds is shown in Fig. 2. To simulate stochastic damage to n wind generators based on the fragility curve, we draw n samples from uniform zero-one distribution and, based on the experienced wind speed, decide whether the turbine is operational or damaged (see Fig. 2). In case of wind turbines, the fragility curve is given by the graph of Fisk Cumulative Distribution Function (CDF):

$$F(u;\alpha,\beta)=\frac{(u/\alpha)^{\beta}}{1+(u/\alpha)^{\beta}}, \quad (1)$$

with parameters α and β that depend on the type of the turbine [11]. For example, if we allow the turbine to yaw during the

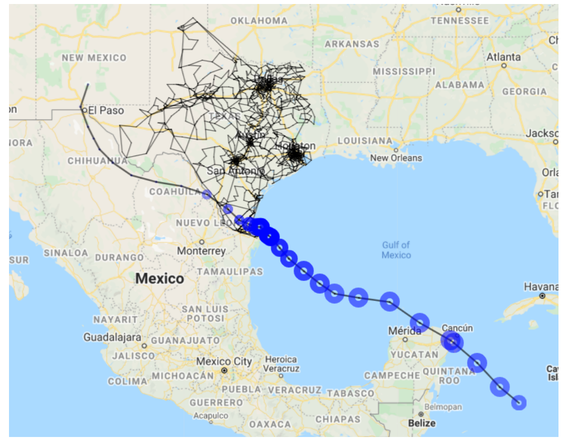


Fig. 1: The path of Hurricane Dolly (July 20-27, 2008) and synthetic 2000-bus transmission grid. Size of the blue circles corresponds to hurricane's radii and their color intensity correspond to maximum wind speed.

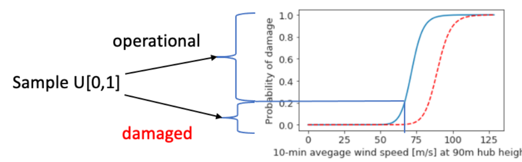


Fig. 2: Schematic diagram of fragility curve application to generate MC damages to a wind turbine: non-yawing (blue) and yawing (red dashed).

hurricane, i.e., face the wind at the right angle fast enough, probability of damage decreases significantly.

We use NREL's WTK data to estimate maximum hurricane wind speeds, but we remark that there exist other techniques and data sets, e.g. hurricane best-track data [12]. WTK contains multiple years of high-quality wind speed and other meteorological data that includes at least 18 tropical storm events evaluated using high-fidelity models. Furthermore, a central benefit of using WTK data for producing damage scenarios is that the same data set is used for wind power production on the entire grid. These benefits are not present in other methods for estimating hurricane wind speeds and is crucial for understanding how grids with high penetrations of wind power will function during extreme events. Fig. 3 shows WIND Toolkit wind speed field at 100 meters above ground during Hurricane Dolly's landing in Texas in 2008.

B. Other Components

We augment the fragility curve method used in [9] for simulating damage to substations and transmission lines by using high-fidelity WTK data for maximum wind speed estimation. The ACTIVSg2000 transmission network has 1125 substations, i.e. buses with load on them, and to simulate their damage we use the procedure in Fig. 2 with fragility curve derived in [13].

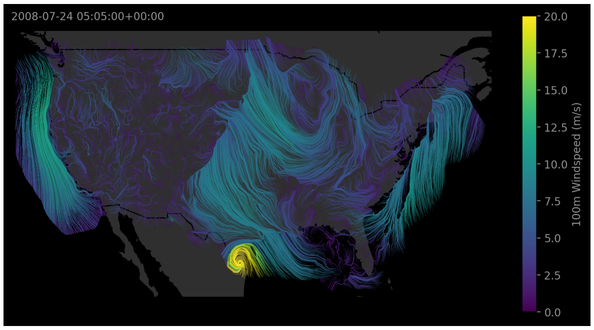


Fig. 3: Hurricane Dolly visualization: NREL's WIND Toolkit wind field at 100 meters above ground.

To simulate the stochastic damage of the transmission lines we use fragility curves of transmission towers and assume that a transmission line gets damaged if even one tower is damaged. A fragility curve for transmission towers within 50 miles of the Texas coast is derived empirically in [14] using 10 years of information gathered by ERCOT utility companies. Also, based on [14], we assume that towers are located on average every 0.16 km and we consider the straight line distance between two connected buses. We note that transmission line damage analysis can be further improved using fragility curves derived in e.g., [6] and [3].

III. Numerical Experiments

A. Statistics

In our experiments using the ACTIVSg2000 grid, three wind plants with a total of 317 turbines were within a close distance of the hurricane track and experienced damage due to high wind speeds. We performed 1000 Monte Carlo (MC) simulations whose statistics are summarized in Table I. Fig. 4 shows the realization when the maximum number of turbines were damaged, and Fig. 5 shows power production time series at three separate wind plants near the path of Hurricane Dolly. At 6 pm on July 23rd wind speeds reach the cut-out value and all turbines shut down. After the hurricane passes, power production resumes but not at the same level because a number of damaged turbines do not come back online. We remark that in real world operation, wind turbines might stay off for the entire hurricane period without turning on briefly as hurricane eye passes by them.

TABLE I: Damage Statistics of 1000 MC Simulations

	Number of structures damaged			
Structure	Mean	Std	Max	Min
Wind Turbine	53.5	6.5	75	34
Substation	2.5	1.0	6.0	0.0
Pole	69.5	8.1	95	47
Line	20.9	2.3	28	14

Fragility curve methodology was also applied to substations, and the resulting damage statistics are included in Table I. We assume that once the substation is damaged the corresponding load disappears until the end of the simulation (that is, no repairs are being made). Fig. 6 shows how load time series were modified to reflect the substation damage: real and reactive load at each bus is set to zero once the substation is damaged.

Finally, we remark on transmission line damage shown in Fig. 7. ACTIVSg2000 network has 2346 lines between buses and total of approximately 300K towers. Damage statistics of 1000 MC simulations are displayed in Table I. Fig. 4 shows one realization when maximum number of branches were damaged: damaged transmission towers are shown as

Fig. 4: 3 wind farms (heat map) composed of individual wind sites (eight wind turbines per site). Sites that have at least one damaged turbine are shown as black dots.

Fig. 5: Power production at 3 damaged wind plants.

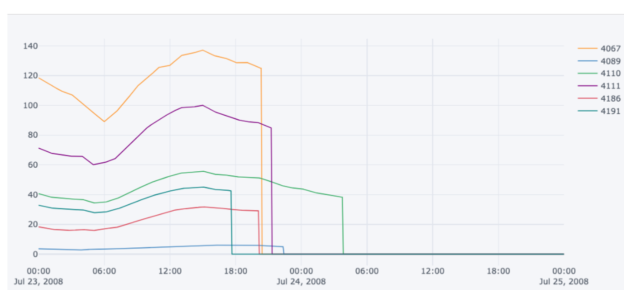


Fig. 6: Resulting load time series at damaged substations.

black dots and damaged lines are shown in red.

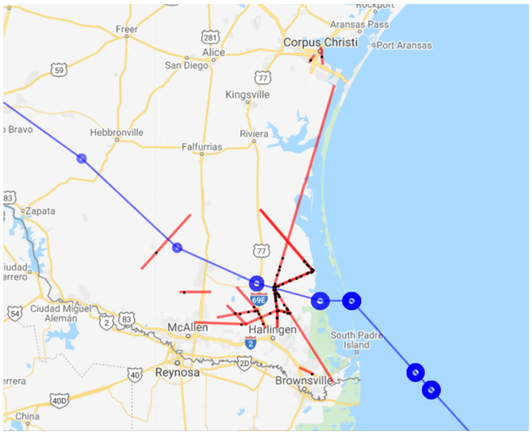


Fig. 7: Realization of transmission tower (black) and line (red) damage.

B. Topology

An interesting consequence of line damages is the resulting topology of the resulting network. These results motivate the following questions: how often does the network stay connected or what are the resulting sub-graph sizes if the network does get disconnected? In our experiments, all 1000 simulations resulted in a disconnected graph. For example, one realization results in the following sub-graph sizes: [1985,10,2,2,1], thus creating four small islands. Furthermore, counting the number of small sub-graphs (less than 20 buses) resulting from 1000 simulations show that there is a noticeable chance of getting a disconnected sub-graph of size about 10 to 13 nodes (see Fig. 8). This can be explained by one node in Dolly's path that is comprised of ten buses and several possible combinations of broken lines that leave this node disconnected from the rest of the grid.

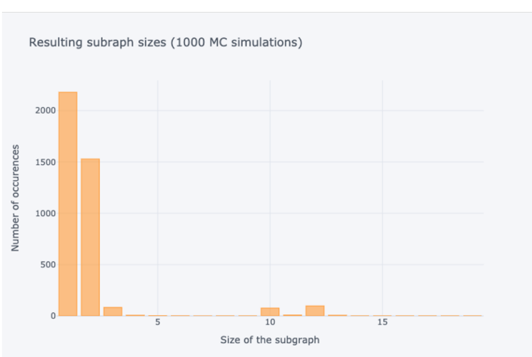


Fig. 8: Count of sub-graphs of size less than 20 resulting from 1000 MC simulations.

IV. Applications

Next we discuss a few possible applications and initial results obtained using our generated contingency scenarios.

A. Economic Dispatch

To better understand the consequences of grid damage scenarios, we run a deterministic economic dispatch (ED) simulation using an AC optimal power flow (OPF). We consider first two days during which Hurricane Dolly travels over land. Fig. 9 shows loss of load when transmission lines, substations, and wind turbines are damaged. We observe that total loss of load on the grid is not very large, since demand is also lost due to damaged substations. However, although brief, large fluctuations of real or reactive loss of load will lead to voltage and frequency violations. In total, we observed 8 buses experiencing real and reactive overload or loss of load events.

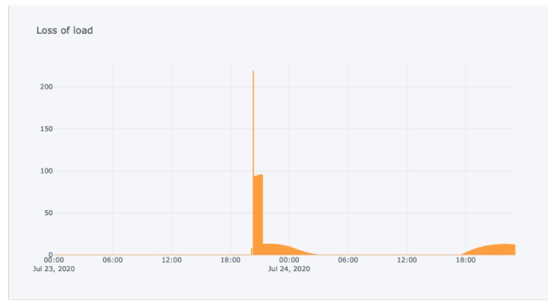


Fig. 9: Real loss of load when transmission lines, substations and wind plants get damaged.

B. Voltage Violations

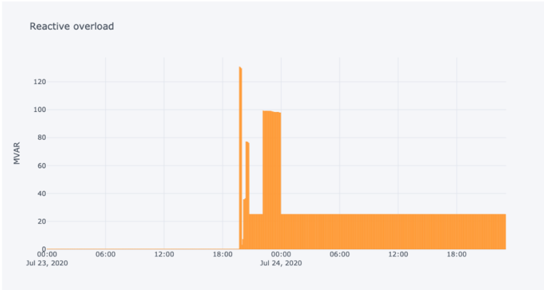
In the second experiment we relax voltage bounds in our AC OPF formulation, accepting .6 to 1.4 pu. Results of this experiment demonstrate how reactive power overload in Fig. 10a causes voltage violations in buses of zone 4 of ACTIVSg2000 grid as shown in Fig. 10b. These voltage violation scenarios can be then used to test and improve real-time voltage control algorithms, e.g., Ripple-Type control [15].

C. Emergency Asset Positioning

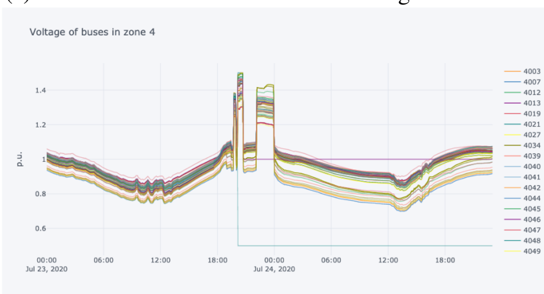
Yet another application of the created damage scenarios is in emergency response (e.g. battery placement) through stochastic optimization [16], [17]. Using our approach we can easily generate a user-specified number of multi-period damage scenarios at the 5-min temporal resolution looking several hours into the future. Then those scenarios can be used in the expectation term of stochastic optimization while hedging against possible damages leaving certain buses disconnected or against sudden wind power loss with significant after-event nameplate reduction. We are currently working on such problem formulations and will address it another paper in the near future.

V. Conclusions and Future Work

In this paper, we outline a method that combines fragility curves with high-fidelity data sets to generate realistic damage scenarios and demonstrate their application to grid planning problems. In the future, we plan on investigating the use



(a) Reactive overload that leads to voltage fluctuations.



(b) Voltage fluctuations in zone 4 of the grid.

Fig. 10: Reactive overload that leads to voltage fluctuations

of other high-fidelity wind speed data sets. For example, we plan on continuing our study with new WTK ensemble data sets that can be used to obtain different tracks of a hurricane. Also, since NREL's WTK data is not specifically designed to represent extreme-events, our next steps will involve investigating extreme-event specific simulation tools. One such tool is high-fidelity and high-resolution NOAA's hurricane weather research and forecasting experimental modeling system HWRFx [18]. We remark that although HWRFx is computationally expensive, compute time can be reduced by restricting space and time domain. Also, further study is needed to determine how accurate HWRFx generated data is for generating wind power output in the domain at a large distance away from the tropical storm. In addition, we will further investigate other natural hazards such as floods, earthquakes, and extreme temperatures. For example, in case of flooding, we would use a fragility curve of the structure that is a function of the flood level instead of a function of wind speed. Finally, we plan on continuing our study into damages of various other transmission grid elements, especially ones that are within NREL's domain, e.g., PV arrays and modern offshore wind turbines. For general structures, such as buildings or transmission towers, we plan on using FEMA's HAZUS [7] framework to obtain fragility curves while for various renewable technologies, such as wind turbines and PV arrays, we will use results of recent studies performed at NREL e.g., [19].

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