A Data Generation Engine and Workflow for Power Network Damage and Loss Estimation under Hurricane

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Abstract—**Regional power network reliability analysis is crucial for decision-making when nature hazard attacks. However, the data are scattered due to the sparse geospatially distributed power network components. Therefore, a data generation engine is needed to collect and process the data efficiently. Additionally, the scientific workflow specified to perform power network damage, and loss estimation under hurricane events is limited. This paper proposed a novel data generation engine and a scientific workflow for power network reliability analysis. The data generation engine contains three modules: the power infrastructure module, the hurricane module, and the structural analysis module. The logic and the usability of the proposed framework are validated through a benchmark problem.**

Keywords—Power network reliability, hurricane, fragility curves, workflow, data generation engine

I. INTRODUCTION

The reliability analysis of regional power networks under extreme events is prevalent due to the crippling social impacts and substantial economic losses caused by bulk power outages. Hines et al. [1] collected 933 causes of large blackouts from 1984 to 2006. The data revealed that the scale of the affected customers is hundreds of thousands. Therefore, the reliability analysis of the power network under extreme events is in demand.

Based on the nature, the extreme events can be grouped into (i) physical attacks, which lead to the damage of the physical components of the power system; (ii) cyber-attacks, which cause chaos in power delivery [2]. The reliability analysis of the power network under cyber-attack involves the optimization of power network topology and improving the network securities [3]. However, from the data collected by [1], the recurrence of a power network by cyber-attack is low, and the impacted customer size is small relative to physical attacks. Consequently, the reliability analysis of regional power networks under natural hazards is prior.

Structure performance assessment provides valuable information for reinforcing the structures and predicting the potential damages and losses before the natural hazard attacks. Hence, it is vital to develop a tool that can be utilized for rapid system-level performance assessment. Federal Emergency Management Agency (FEMA) developed a commercial off-the-shelf loss and risk assessment software Hazus to predict the probability of different structural damage levels under user-defined hazard intensities [4]. Bocchini et al. developed Probabilistic Resilience Assessment of Interdependent Systems (PRAISys) to evaluate the post-event resilience analysis of communities. The resilience analysis is achieved by epidemic modeling or DC power modeling with cascaded failure models [5]. SimCenter developed another popular regional hazards workflow which contains a variety of natural hazards utilizing both observed data and numerical simulation to perform both component-level and system-level reliability analysis [6, 7]. However, the tools mentioned above are not suitable for the power network reliability analysis under hurricane events due to: (i) the sparse geospatially scattered transmission tower inventories; (ii) the failure dependence between the transmission line and tower; (iii) the connection between the spatially and temporally variated hurricane loadings and the power network numerical model.

To fill the gaps, in this paper, a novel data generation engine and a scientific workflow are developed to investigate the performance of the power network during hurricane events. The objective is to efficiently collect and process the scattered data by the data generation engine and logistically link the power grid and hurricane model to achieve rapid power network damage and loss evaluation. The rest of the paper is organized as follows: Section II explains the data generation engine development and the workflow formulation. In section III, a benchmark case is studied to verify the logistics and feasibility of the proposed framework. In section IV, conclusions are drawn.

II. DATA GENERATION ENGINE AND SCIENTIFIC WORKFLOW DEVELOPMENT

The data generation engine aims to distribute different data types into the modules. Each module collects and processes the associated data type. We first categorize the data into loadings and structural components to achieve the goals. The Hurricane module handles the transmission tower loadings, and the power infrastructure module processes the transmission tower component model. Then, the proposed workflow gathers and streams the processed data into the structural analysis module. After the failure probability of the transmission lines is obtained, the power network damage and loss evaluation can be performed.

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Power Infrastructure module

The critical components of the power network include the substations, generators, transmission lines with different voltage levels, and transmission towers designed according to the basic wind speed and line voltage levels. In general, the realistic distribution of the power network key components is unavailable due to security; alternatively, validated synthetic power network models are distributed in platforms [8-10]. In the synthetic power network model, the transmission line is assumed to be a straight line that connects the two end substations; hence, the angle of the transmission line is calculated by the two end substations coordinates. Moreover, the towers along a line in the synthetic models are assumed to be an equal distance [11]. Thus, the distribution of the towers along the line can be determined. Consequently, with the assumptions in the synthetic power network models, the power infrastructure module is comprised of calculating and locating the transmission towers in the synthetic power grid.

Hurricane Module

The functionalities of the hurricane module are to extract the parameters from the hurricane model and map the hurricane parameters to each tower. The definition of the hurricane parameters coincided with the input parameters to evaluate the failure probability of the transmission towers. However, in engineering, the mean wind speed and the angle at 10m height of the wind profile are commonly used to describe hurricane properties. Hence, instead of the complete wind profiles in the hurricane model, only the wind speed and angle at 10m height are needed; consequently, the size of hurricane loading feeds into the workflow is significantly reduced. Another critical aspect is efficiently assigning the tower with the associated wind profile. The most straightforward method is calculating the distance between the tower and all the wind profiles in the numerical model. The associated wind profile is the one with the smallest distance. In the numerical hurricane models, millions of wind profiles exit leading to the high computational burden that limits the rapid evaluation of the damages and loss of the power network. A nearest neighbor search algorithm is implemented where the mapping efficiency can be guaranteed. [12].

Structural Analysis Module

The structural analysis module calculates the failure probability of the transmission towers and lines each time the hurricane attacks the region of interest. In the synthetic power network model, the towers are assumed to be homogenous, which means that the tower failure mechanism is identical. For regional power network reliability analysis, surrogate models of the transmission towers are used for rapid transmission tower failure probability evaluation under the hurricane. Among which, the fragility curves describe the failure probability of the transmission tower under the hurricane loading are prominent [13-15]. With the hurricane loading and the transmission tower fragility curves, the failure probability of the transmission tower can be calculated. The failure of the transmission towers causes damage to the transmission lines. Hence, a proper mathematical model that describes the failure dependence between the transmission tower and line is needed. The transmission line and the transmission tower are connected in series. Each transmission line is considered safe only if all the transmission towers in the line survive under the imposed loading. Therefore, the time-independent failure probability of the transmission line is calculated as:

$$P^k[FL] = 1 - P^k[SL] = 1 - \prod_{n=1}^{N_T}(1 - P[ST;\theta]) \quad (1)$$

where, $P^k[FL]$ is the k_{th} line failure probability; $P^k[SL]$ is the k_{th} line survive probability; $P[ST;\theta]$ is the failure probability of the tower conditioned by loading parameters θ; N_T is the total number of towers in k_{th} line.

Moreover, the hurricane event is a continuous stochastic process. The failure of the transmission line is dependent on the status of the line in the previous timesteps $(i-1)_{th}$. Therefore, the time-dependent failure probability of the k_{th} line failure probability at i_{th} the time step is conditioned by:

$$P_i^k[FL] = P_{i-1}^k[FL] + (1 - P_{i-1}^k[FL])P[FL] \quad (2)$$

In summary, the structural analysis module utilizes the tower surrogate models to perform the failure probability analysis of the transmission towers and lines.

Scientific Workflow

The data generation engine targets to gather the scattered power network and hurricane data into modules so that the data are compact and representative. The scientific workflow logistically assembles and transfers the data in each module to the main information stream and efficiently performs the power network damage and losses estimation.

Fig.1 illustrates the assembling of the data generation modules. First, in the power infrastructure module, the geographic information of the synthetic power network buses and branches is processed to calculate the coordinate of the towers for each transmission line. Then in the hurricane module, the hurricane loading parameters needed for structural failure analysis are calculated, and using the nearest neighbor search algorithm, the hurricane loading parameters for each tower will be assigned. The transmission tower failure probability in the structural analysis module will be calculated by feeding the hurricane loading parameters into the tower structure surrogate model. Finally, the failure probability of each transmission line will be calculated to assess the power grid damage and loss.

In the power network, thousands of transmission lines exited; hence instead of tabulating the damage to the transmission lines, visualizing the damage in the power network is more vivid and straightforward. Moreover, the damage to the transmission towers and lines at each time step will be formatted and stored as output files for further analysis. The loss in the power system is determined by operation cost, unserved load, and over-generation [16]. Those indicators can be calculated based on the calculated failure probability of the lines. The detailed algorithms to evaluate the loss can be found in [16].

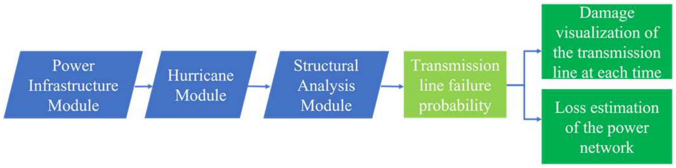

Fig. 1. The workflow of the power network reliability analysis

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III. CASE STUDY: TEXAS MEDIUM-SCALE POWER NETWORK TESTBED

We validate the efficiency of the proposed data generation engine and the logic of the workflow by estimating the failures of the transmission line in Texas during Hurricane Harvey. The input and output files of the novel data generation engine in the testbed case are explained in detail. The processing time and file size are monitored to ensure the usability of the workflow.

Application of the Novel Data Generation Engine

The synthetic power grid adopted in this testbed is the 2000-bus Texas power system test case [10]. The 2000-bus Texas power grid is represented by the buses, links connecting two buses, and generators. In this power grid, each transmission line links two substations, with the geographic coordinates of these substations available. Hence, adopting the assumptions in the power infrastructure module, the end coordinate of the transmission line, the number of towers in each line can be calculated, and the associated geographic coordinate of the towers can be obtained. Fig. 2 shows the mapping between the synthetic power grid and to Texas region. After the processing, there are 1713 transmission lines and 136913 transmission towers.

The hurricane model used is the Hurricane Harvey numerical model, which utilized the data from the NCEP GFS FNL (National Centers for Environmental Prediction Global Forecast System final analysis) and the MODIS (Moderate Resolution Imaging Spectroradiometer). The numerical model simulates the landfall of Hurricane Harvey from August 25th to August 27th with a one-hour time interval. Fig. 3 depicts an instance of Hurricane Harvey in the Texas Region. The mean wind speed can be directly calculated from the wind profile. However, the wind angle calculated is the angle relative to the horizontal direction. To evaluate the failure probability of the line, one needs a relative angle between the transmission line and the wind profile. In Fig. 2, it is clear that the direction of the line is not aligned with the horizontal direction. After the mean wind speed and the relative wind angle have been calculated, the next step is implementing the nearest neighbor search algorithm to assign the wind speed and wind angle to each tower at each time interval. The usability requirement section will illustrate the efficiency of the nearest neighbor search algorithm.

In the structural analysis module, the failure probability of the towers and lines will be calculated. For the rapid analysis, the fragility curves of the transmission tower will be generated using the tower finite element model offline. The transmission tower fragility curve expresses the failure probability as a function of the mean wind speed and relative wind angle at 10m height. The towers in the synthetic power grid are assumed to be identical. Therefore, a homogenous fragility curve can be used for all the towers in the testbed. The detailed transmission tower inventory can be found in [17]. Fig. 4 shows the fragility curves that are used in the case study. In the implementation, the wind speed is discretized from 0-70 m/s with 5 m/s intervals, and the wind angle is discretized to 0^0 , 30^0, 45^0, 60^0, and 90^0.

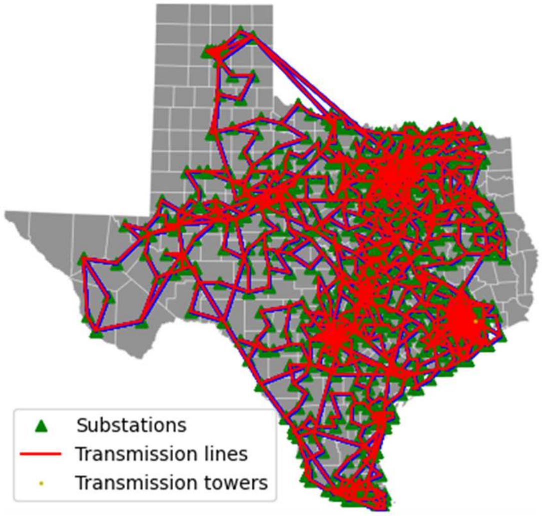

Fig. 2 The distribution of the power network components processed by the power infrastructure module

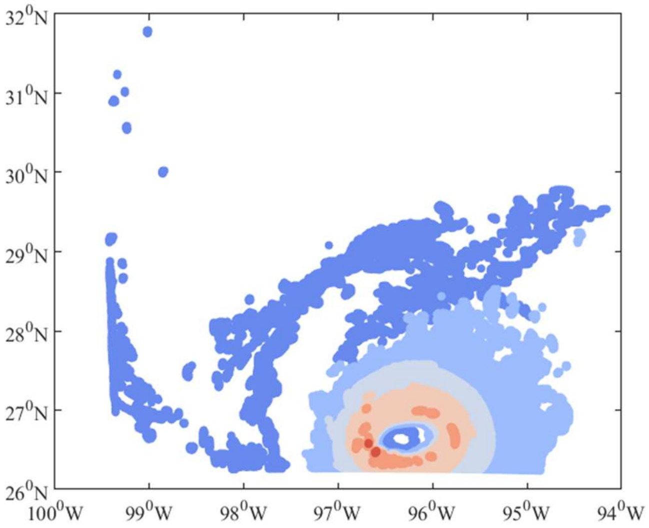

Fig. 3 Wind velocity distribution in the Texas region during Hurricane Harvey.

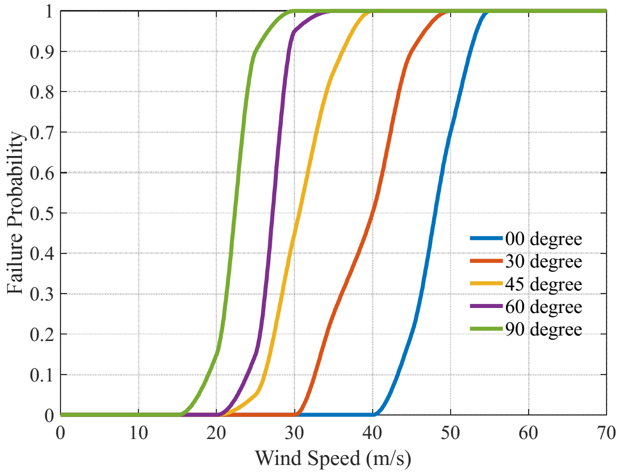

Fig. 4 Transmission tower fragility curves

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Power Network Damage Visualization

As described in Eq (2), the failure probability of the transmission line is time-dependent. Therefore, the damage to the transmission line aggregates with time. Fig. 5 to Fig. 8 shows the failure progression of the transmission line during Hurricane Harvey from August 25th to August 27th. From the observation, as Hurricane Harvey developed, the failure of the transmission line gradually increased. In the synthetic power grid, the transmission line failure probability greater than 90% after the hurricane faded away took up 1.59%, similar to the observed damage ratio reported by the North American Electric Reliability Cooperation (NERC).

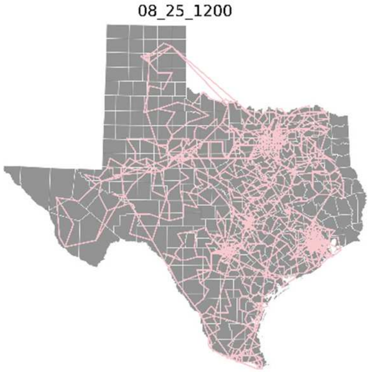

Fig. 5 The failure of the transmission line in the 2000-bus Texas power grid at 12:00 am August 25th

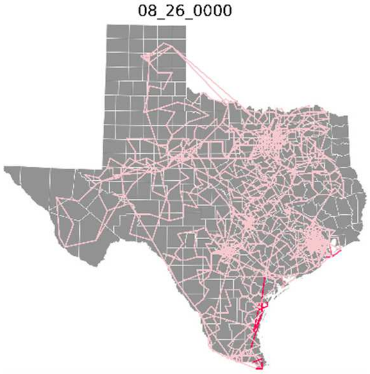

Fig. 6 The failure of the transmission line in the 2000-bus Texas power grid at 00:00 am August 26th

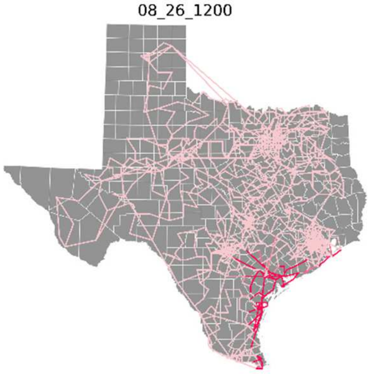

Fig. 7 The failure of the transmission line in the 2000-bus Texas power grid at 12:00 am August 26th

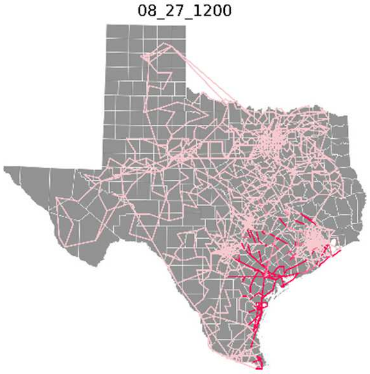

Fig. 8 The failure of the transmission line in the 2000-bus Texas power grid at 12:00 am August 27th

Assessment of the Usability Requirement

In developing the data generation modules and the scientific workflow, the usability requires that the input and output file size and the processing time are acceptable. In the developed data generation module, three obstacles limit the usability: (i) the reduction of the file size of the hurricane model; (ii) the transmission tower structural analysis; and (iii) the assignment of the wind profiles to each tower.

For obstacles (i) and (ii), the reduction of the numerical hurricane model is associated with the methodologies applied to perform tower structure analysis. For the implemented testbed, the structural analysis is performed using fragility curves, in which the mean wind speed and wind angle are the input parameters. The raw Hurricane Harvey numerical model contains 66 million wind profiles along the height from 0m to 100m. However, since only the data at 10m in each wind profile are useful for the transmission tower fragility analysis, the size of the numerical model can be reduced significantly. Therefore, with the structural analysis method, the 100 Gb Hurricane Harvey numerical model was reduced to a 7.5Gb file containing the mean wind speed and wind angles.

Moreover, for obstacle (iii), with the nearest neighbor search algorithm, assigning the wind profile to each tower at each timestamp only takes 35mins. However, assigning the wind profile to each tower by comparing the distance between the tower and the wind profile, the processing time is several hours, which is much longer and unacceptable. With the efficient data generation and processing techniques, the testbed case only takes 50mins to visualize the transmission line progressive failure in the Texas region under Hurricane Harvey.

IV. CONCLUSION

This paper develops a novel data generation engine and scientific workflow for a regional power network under a hurricane. The design philosophy of the data generation engine is based on the structure components, the power grid; the loading model, the numerical hurricane model; and the structural analysis model. Then a workflow is proposed to efficiently transfer the data from different modules to perform a regional power grid reliability analysis. We utilize transmission-line fragility models to satisfy rapid failure probability evaluation of the transmission tower under a hurricane. With the input loading requirements for evaluating the tower fragility curve, the raw

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hurricane numerical model is processed to extract only needed information so that the files transferred in the workflow are significantly smaller. The smaller intermediate hurricane loading file size greatly improved the computational efficiency. Another heavy computational part is assigning the tower with the associated wind profile in the hurricane in each time step. The nearest neighbor search algorithm is utilized where the computational cost is reduced. The synthetic 2000-bus Texas power grid under Hurricane Harvey is studied to verify the logistic rationality and feasibility. The results show that:

- With the transmission tower fragility models, the hurricane module can extract the most efficient information from the numerical hurricane model, reducing the loading file size from 100Gb to 7.5Gb.
- The transmission towers are assigned with wind profiles utilizing the nearest neighbor search algorithm, where the processing time is compressed from several hours to half an hour.
- The calculated transmission line damage ratio is comparable with the actual observations. Hence, the logistic of the workflow is reasonable.

In conclusion, the proposed data generation engine and workflow satisfy the current requirement for power network reliability analysis in accuracy and efficiency.

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