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Data Requirements for Application of Risk-Based Dynamic Contingency Analysis to Evaluate Hurricane Impact to Electrical Infrastructure in Puerto Rico

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SUMMARY

This paper presents a risk-based dynamic contingency analysis framework that was used to evaluate the hurricane impact to electrical infrastructure in Puerto Rico. PNNL developed a scalable risk-based framework for identifying high-voltage transmission resilience improvements by classifying and prioritizing high-risk power grid contingencies (system failures) under hurricane impact. The risk-based framework is founded on grid outage definitions with their associated probabilities of occurrence from hurricane events, in combination with an impact assessment derived from detailed dynamic cascading failure analysis. This paper focuses on a discussion around data requirements for transmission resilience planning for hurricane events, derived from the development of the risk-based framework and its application to Puerto Rico. This paper launches an important first step in encouraging the engineering community and power system industry to move towards establishing resilience planning as a routine practice. Since actual results for Puerto Rico contain sensitive information, sample simulation results will be used to illustrate the data requirements and risk-based dynamic cascading framework on the Puerto Rico power grid, as well as demonstrate the potential for such a simulation framework. The paper includes a discussion on the lessons learned, importance and need for improved datasets that are not usually considered in traditional power system planning. The paper will also elaborate on how the scalable simulation framework and datasets might be expanded to larger footprints and leveraged for modelling other types of natural disasters.

KEYWORDS

Power System Modeling
Power System Stability
Power System Reliability
Power System Planning
Power System Protection
Geographic Information Systems
Geospatial Analysis
Meteorology

I. Introduction

In 2017, the US experienced a significant and prolonged blackout when Hurricane Maria devastated Puerto Rico. Maria made landfall as a Category 5 storm and caused wide-spread devastation to Puerto Rico's electrical infrastructure, which was battered only two weeks prior when Hurricane Irma, another Category 5 hurricane, skirted the north-eastern side of the island. With some estimates reaching $90 billion in damages, it took 11 months to restore power to all the residents on the island[1].

The complexity of the electric power grid coupled with its criticality make advanced analytical tools, capable of forecasting system vulnerabilities and impacts, necessary for comprehensive risk assessment and mitigation. At the Pacific Northwest National Laboratory (PNNL), a research prototype built in-house, along with industry software tools, were leveraged to explore and develop resilience-enhancement options for the power grid of the Commonwealth of Puerto-Rico. With funding from the U.S Department of Energy (DOE), the PNNL team, with decades of experience making complex power systems more resilient, reliable, secure, flexible, affordable and sustainable, developed a risk-based dynamic contingency analysis ("Framework") approach to evaluate the impact of hurricane scenarios on the grid.

PNNL developed this scalable Framework for identifying potential high-voltage transmission resilience improvements by classifying and prioritizing high-risk power grid contingencies (system failures). The risk-based framework is founded on grid outage definitions with their associated probabilities of occurrence from hurricane events, in combination with an impact assessment derived from detailed dynamic cascading failure analysis. The framework makes use of three tools developed by DOE national laboratories:

- **PNNL's Dynamic Contingency Analysis Tool (DCAT):** Analyzes power system dynamic behavior and cascading sequences, including protection and estimation of operator actions, resulting from generator and transmission related outages using the PSS®E commercial tool as a solution engine [1]
- **PNNL's Electrical Grid Resilience and Assessment System (EGRASS) Tool:** A web-based geospatial application integrated with transmission system GIS information and historical hurricane data to model the impact on grid assets, sequentially, over time [2]
- **Argonne National Laboratory's Hurricane Electrical Assessment Damage Outage Tool (HEADOUT):** Provides probability of failure of each electricity asset for a given hurricane event, derived from assets' fragility characteristics, based on 6-hour National Hurricane Center (NHC) advisories [3]

The simulation framework PNNL developed can be utilized to better understand which specific grid element failure sequences are at a higher probability and most detrimental. It can help guide transmission and resource planning expansion decisions by helping prioritize and evaluate system reinforcements that yield the highest positive impact. Additionally, it holds the potential to assist near-term and real-time system operational planning functions to identify likely or worst-case cascading failures to better prepare grid mitigation strategies in advance of hurricane impact.

Other researchers have proposed similar risk-based frameworks such as the Monte Carlo based methodology in [4], containing steps for hazard analysis, fragility analysis, damage analysis, and loss analysis. However, the method in [4] considered quasi-steady state power flow analysis to model the grid. Another recent risk-based method has been proposed in [5] but applied to distribution test systems. The Framework of this paper incorporates a detailed bulk power system model, including steady-state sequences, dynamics, system protection, remedial action schemes, and corrective actions, while building on industry-grade datasets and solution engines to use and improve on the most accurate power system models available. The Framework of this work provides higher-fidelity results, and it also requires larger and diverse datasets.

The Framework requires datasets beyond those required for traditional power system planning. Power grid infrastructure fragility information is needed as well as meteorological information that describes the strength of hurricanes for both historical and expected events. For the power system domain, the framework requires a detailed static and dynamic power system model that includes a combination of detailed control models, system

[1] https://www.fema.gov/hurricane-maria

protection data, as well as system operator corrective action practices to be integrated into DCAT. And most notably, this framework requires geographic location information related to all of these datasets. Accurate and high-quality geographic location information for grid infrastructure and a mapping to elements modelled in traditional system planning and operational tools are major gaps in current industry data collection practices.

II. Risk-Based Dynamic Contingency Analysis Framework

Figure 1 illustrates the Framework PNNL developed and how different tools (DCAT, EGRASS, HEADOUT) interact. Using power system topology information and hurricane model data, HEADOUT is run to obtain the probability of failure for each power system facility. Leveraging the same hurricane data, the EGRASS tool then provides a probable sequence of power system facility failures based on the speed, trajectory, and intensity of the hurricane. Monte Carlo analysis has been adopted to generate a set of probabilistic failure scenarios. These are then used to create dynamic contingencies and fed into DCAT, which models the impact of these failures on the power grid. DCAT Analytics [6][7] is then used to aggregate, summarize, and compare the simulation results of all the Monte Carlo hurricane failure scenarios. A significant amount of GIS mapping was required to accomplish this workflow and enhancements were made to existing tools to develop the risk-based framework presented.

Data requirements to perform this simulation framework are called out in black boxes in Figure 1. They can be grouped into five categories; 1) Field Asset Fragility Information, 2) Meteorological Information, 3) Infrastructure Geographic Locational Information, 4) GIS Dataset Mapping, and 5) Power System Models and Operational Information.

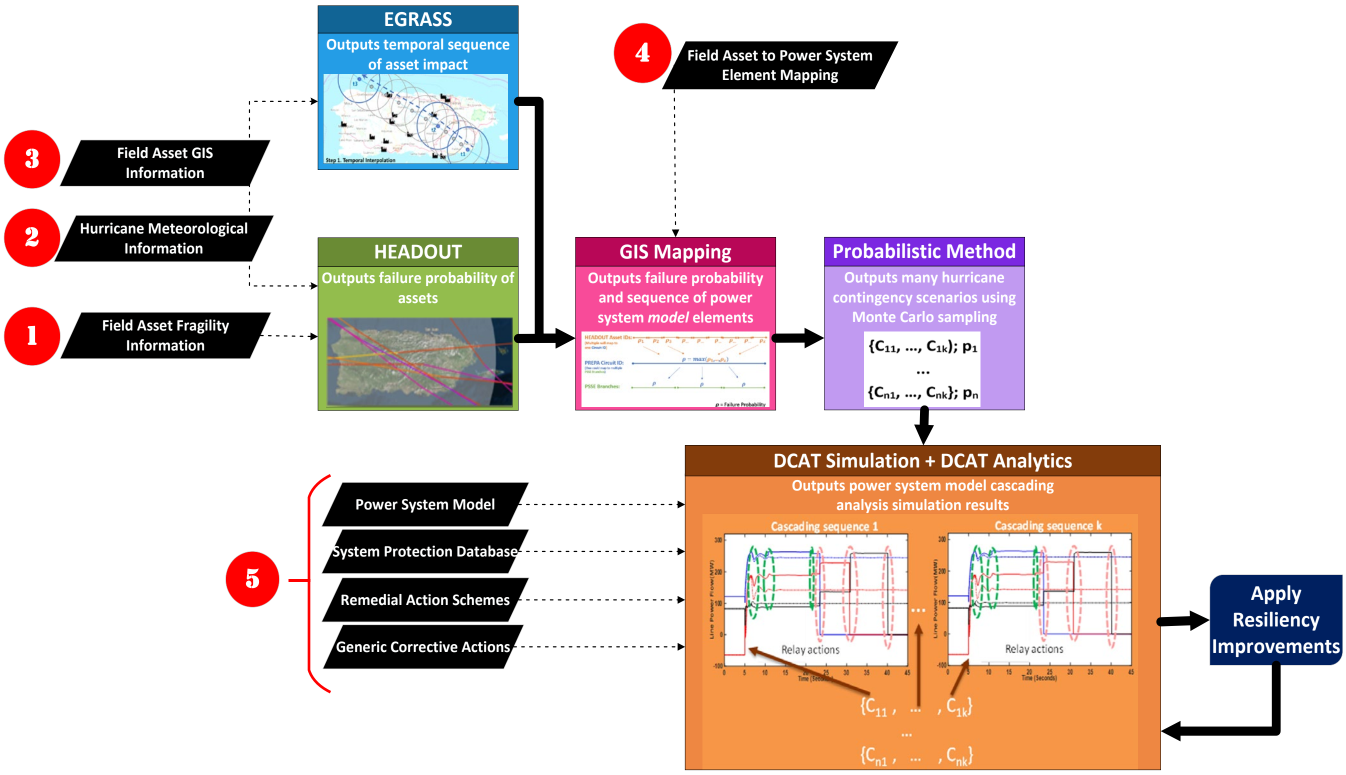


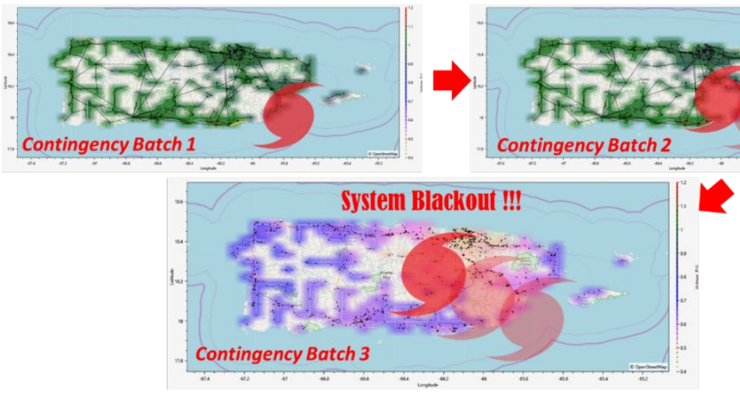
Figure 1. Risk-Based Dynamic Contingency Analysis Framework with data requirements highlighted in black

a. Sample Simulation Results

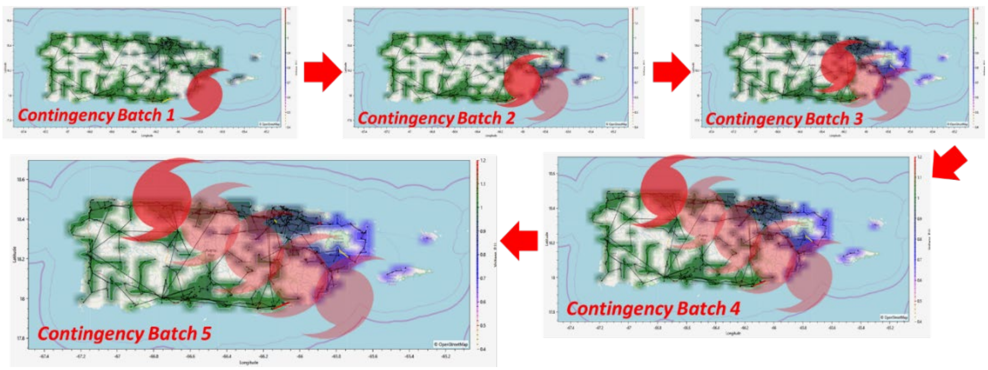
The illustrations in Figure 2 represent the Framework's results of the impact of a generic hurricane, following a similar path as Hurricane Maria, on the island of Puerto Rico. The generic hurricane is less severe than Maria, and it is used here for illustration purposes. Each set of images represents a batch of hurricane contingency scenarios produced by the probabilistic method shown in Figure 1 and shows the transmission infrastructure impact as the hurricane travels over the island. A total of 30 transmission lines fail during the simulated hurricane, which are represented by five contingency batches each containing five to seven transmission system component failures.

The circles in the images below represent the approximate path of the hurricane and, as consequence, the area of transmission infrastructure impacts. The green shading represents healthy system voltage, within acceptable operating range (0.95 to 1.05 per-unit). Blue and purple shading represent unhealthy low voltage conditions, outside acceptable operating range. When system voltage depresses, the grid becomes more vulnerable to cascading failure and stability conditions that can lead to system blackout.

Figure 2 (a) shows how the Puerto Rico system performs under the simulated hurricane, without any system reinforcements. After the third batch of contingencies simulated in DCAT, the system goes into blackout. Figure 2 (b) and (c) show how the Puerto Rico system performs under the simulated hurricane when mitigative actions were modelled; the system upgrades include hardening key transmission facilities and enabling operational corrective actions. As a result, the system was able to survive in all simulated contingency batches when the Hurricane moved over the island.



(a)



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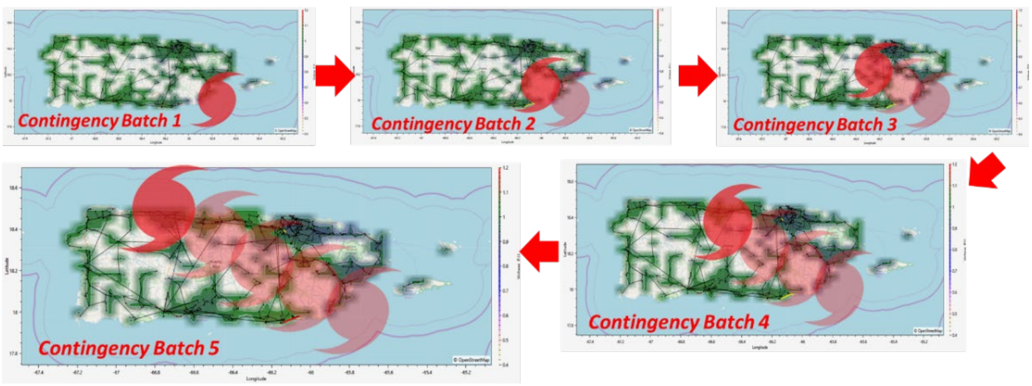

(c)

Figure 2. Illustrative example of simulated hurricane event impact on Puerto Rico's electrical grid system voltage over time: (a) System performance without any system upgrades or operational corrective actions, (b) System performance with system upgrades only and (c) System Performance with system upgrades and operational corrective actions

In addition to this sample result, the PNNL team ran five hurricane event variations based on the historical paths and wind speeds of Hurricane Irma and Maria, on 15 power system configurations. This additional analysis can be found in [8].

III. Data Requirements

The simulation Framework discussed in this paper requires power system models representing system conditions of study interest, electrical infrastructure field asset fragility information, meteorological information of historical, real-time, or forecasted hurricane paths and wind speeds, and most notably, geographic information system (GIS) data and GIS dataset mapping.

a. Power System Models

In a simulation of the Framework presented in this paper, a single power system planning model is a required input. Specifically, power system models (or "cases") used in the analysis are built in the Siemens PTI PSS®E Software, which is a commonly used industry transmission planning tool. As mentioned before, PSS®E is used as the solution engine in DCAT to simulate detailed dynamic cascading processes. The steady-state transmission system information representing the system conditions of simulation interest (generator dispatch, loading, topology, etc.) are used to simulate hurricane contingencies defined by the Framework's probabilistic methodology. For the simulations performed in the Puerto Rico use-case, the hurricane simulation framework was tested on heavy loading, light loading, high solar penetration, and long-term planning cases. The power system model used can be configured to the users' interest and system of choice, whether representing realistic utility infrastructure, or study systems used in universities and academia. Potentially it could also be leveraged in operational horizon analyses with real-time system models.

A dynamic model database associated with the power system model, containing validated generator dynamic models, is also required for DCAT to perform accurate dynamic contingency analysis. It is highly encouraged to also incorporate dynamic models for positive-sequence protective relays on the transmission system and at generation facilities. However, this can pose a challenge if relay settings documented in relay databases cannot be easily translated or mapped to power system planning models, which has historically been an industry gap [9][10]. As an initial step, generic relay settings for commonly used transmission and generation protection schemes can be dynamically modelled and auto-populated into power system planning models if protective relay database mapping to planning models is not readily available [11].

DCAT also contains the capability to model post-contingency Remedial Action Schemes (RAS) and automatic manual corrective actions that can be configured to approximate regional practices. This is additional information that can be gathered and supplied into this simulation Framework for improved accuracy of simulated system behavior.

b. Field Asset Fragility Information

Fragility curves for each electrical infrastructure asset of interest, including transmission line segments, transmission towers, substations, and power plant substations are required for the simulation Framework. Fragility information is related to the type of equipment stress (such as high wind and flooding) from events of interest (such as a hurricane) and the probabilities of failure unique to each asset in the field.

Fragility models have been used to assess probable failure of critical infrastructure for decades and are particularly well-established for seismic events [12]. Fragility curves can be generically classified into four categories: judgmental, empirical, analytical and hybrid [13]. Judgmental approaches rely on the discretion of experts and have the advantage of requiring the least data inputs. However, they are subject to bias and are difficult to validate. Empirical approaches leverage historical observations and use statistical models. Analytical fragility curves rely on structural models to establish the appropriate damage distribution. Lastly, hybrid fragility curves are developed using two or more of the above approaches. One approach with relatively modest data requirements is to directly leverage local construction codes and standards for power system assets [14]. While this approach neglects specific geo-location information and important asset-specific indicators, such as age, it still provides an initial approximation in cases where better data is not available. Reference [14] also compares the simple method with two others, including the methodology used in ANL's HEADOUT which was leveraged as the input for the Framework of this paper. In [15] the authors utilize a fault database to create fragility models for overhead distribution lines relative to wind hazards and evaluate three methods for developing the fragility curves, each with different data requirements. The work in [15] assessed the value of data precision and found that precise geo-spatial information greatly improved the accuracy of the developed fragility curves, which was consistent with the findings of PNNL's work [8] and further underscores this critical data gap in industry.

In the Puerto Rico use-case, fragility probabilities for transmission line segments, transmission towers, power plant interconnection facilities, and transmission substations were modeled in ANL's HEADOUT tool. The resulting asset failure probabilities were translated into sets of power system contingencies for a specific hurricane using the GIS mapping and probabilistic methodology shown in Figure 1. In the future, additional scenarios could be created by varying the fragility curves that are used in the HEADOUT model, allowing the tool to model assets of different ages and with varying levels of reliability.

Collecting asset fragility information is essential and necessary to implement the Framework. The amount of effort to collect this data and the desired level of detail must be weighed against the cost of acquiring high fidelity information versus the added value. The following selections can be controlled to adjust the scope of work required to acquire and integrate asset fragility information:

- **Asset Type Selection:** Fragility information at a higher level of asset detail could be incorporated, beyond what was examined in the Puerto Rico use-case. Additional assets could include circuit breakers, transformers, capacitor banks, series capacitors, switches, and insulators; essentially, any type of asset whose failure potentially causes a transmission system outage. However, the more asset types incorporated, the more effort will be required to attain and maintain databases. Furthermore, additional mapping efforts may be required to associate and translate the specific asset type failure to a power system model contingency.
- **Voltage Threshold Selection:** By setting a voltage threshold, the number of transmission assets to consider within the simulation framework can be reduced. In the Puerto Rico use-case, a threshold of >100kV was selected. Simulation accuracy will improve when the voltage-based asset selection threshold is set lower. However, this will increase the computational complexity. On the other hand, for utilities with larger footprints, the voltage threshold may need to be set even higher to reduce complexity.
- **Simulation Footprint Selection:** In the Puerto Rico use-case, the full utility footprint and full interconnected system was used. For a larger interconnection, only a portion of the electrical interconnection might be of interest, depending on the hurricane threat that may extend one or more utilities. Significant challenges may be associated with acquiring and incorporating interregional asset fragility information from neighboring utilities; the data can be unavailable or labelled and maintained differently.
- **Fragility Curve Source Selection:** Attaining and maintaining accurate fragility curves for each transmission asset of interest may be a challenge due to lack of available information. Generic or approximated fragility curves can be leveraged as an initial step. However, to improve accuracy, asset-specific information should be collected to validate and improve the initial generic curves. Information could include assets age, failure rate, maintenance history, quality, and nearby environmental hazards. Realistic fragility curves could improve accuracy of simulation results, as failure probabilities would better reflect actual risk.

c. Meteorological Information

Meteorological information containing wind speed data is vital to deriving the probability of asset failure and the sequence of failure under hurricane threat. For the dynamic cascading analysis in the electric power system model, it is important to understand when assets are affected by a hurricane on the minute-level scale to realistically model power system contingencies. As a result, PNNL's EGRASS tool was extended, at a prototype level, and incorporated into the risk-based framework to model the temporal sequence of asset failures.

The tool uses NHC 'best-track' GIS data[2], containing the central location of the hurricane and the edges of the 34, 50, and 64 knot wind fields at 6-hour intervals, and maximum wind speeds from the HURDAT2 database[3]to

[2] https://www.nhc.noaa.gov/data/tcr/
[3] https://www.nhc.noaa.gov/data/hurdat/hurdat2-1851-2018-051019.txt

determine failure sequencing. In the future, NOAA wind speed data could be incorporated to improve the spatial resolution of the model.

Using these input datasets, the NHC wind field and best-track data is linearly interpolated from 6-hours to a user-defined temporal resolution. Next, the wind speed at each asset location is determined by linearly interpolating the maximum wind speed from the central hurricane location to each of the wind field edges. The resulting wind field is then used to calculate the wind speed at each electric infrastructure asset at each timestamp.

To determine which assets are affected at each timestamp, a user-defined wind speed threshold is used. Any asset which has a wind speed at its location higher than the threshold is considered affected by the hurricane, and therefore included in the subset for the probabilistic model. Future work might explore enabling a tighter integration between the fragility curves, failure sequencing and probabilistic scenario generation where the sequence of failure would be based on the fragility curves rather than a discrete, user-defined input.

Figure 3 provides an illustration of the visualization offered in EGRASS for Hurricane Maria as it moves across the island of Puerto Rico. Each circle in the leftmost image represents the 64-knot wind field at every hour.

Figure 3. Depiction of the new EGRASS capability to obtain a time sequence of hurricane related outages on electric infrastructure

d. Infrastructure Geographic Locational Information & Mapping

GIS information of electrical system infrastructure of transmission and generation facilities is essential to the simulation Framework. This includes GIS data on individual electrical infrastructure field assets (line segments, towers, generators, substations) as well as GIS data on power system model elements (buses and branches).

High quality and accurate geographic location information for grid infrastructure and a mapping to elements modelled in traditional system planning and operational tools are currently major gaps in industry data collection practice. Often, these two datasets are incomplete. For example, a power system planning model may have GIS for substation buses but may not collect Right of Way GIS information for modeled transmission branches. Additionally, GIS databases for field assets and power system planning model elements may be maintained by siloed departments within a utility, making data collection and maintenance practices unique to one itself.

When attempting to map asset infrastructure, such as those used in PNNL's Framework (transmission line segments, transmission towers, substation footprints, and power plant footprints), to power system modelling assets (bus nodes and transmission line branches) a major challenge arises. Mapping between these datasets may represent a combination of one-to-one, one-to-many, many-to-one, or many-to-many correlations.

Through the Puerto Rico use-case, gaps in GIS mapping to grid planning engineering tools required a significant amount of manual effort. These challenges would likely also be expected when such a framework is applied to other footprints, or inter-regional service territories, where asset naming nomenclature varies, and GIS asset mapping philosophies differ. There is currently no standard industry practice or standard asset naming convention protocols that make this mapping effort an easy task. The simulation Framework presented in this paper requires this mapping to be established so that it can translate individual asset failures to power system bus or branch faults.

Significant improvements to GIS mapping practices of electrical infrastructure that correlate with power system planning models is needed. Specifically, mapping GIS assets to transmission planning tools needs to be improved in order to perform advanced and valuable extreme contingency analyses caused by natural disasters, or other types of regional threats. In addition, power system models and planning tools could include additional model-specific information in their GIS databases. For example, detailed right of way information and asset level data (locations of breakers, towers, switches, etc.) for each branch documented by transmission planners could be incorporated into electrical infrastructure GIS and maintenance databases.

IV. A Scalable Framework

The Framework presented in this paper can be scaled and expanded to larger footprints and leveraged for modelling other types of natural disasters. The Puerto Rico use-case demonstrated in this paper spanned a single utility footprint, but this type of analysis could be expanded to larger footprints, such as the mainland US with the appropriate datasets that aggregate many-utility footprint assets and power system models. It could also be re-framed to simulate power grid vulnerability to other types of natural disasters or threats, such as windstorms, wildfire, heatwaves, freezing weather, etc. Expanding functionality to address different types of threat models may require different input datasets and fragility curves. For instance, the HEADOUT and EGRASS components illustrated in Figure 1 would need to be replaced or enhanced with separate modules that predict failure probabilities of each field asset of interest for the threat of choice.

Working with larger datasets and footprints will require increased computational capabilities, as the number of assets and components that can potentially fail during a given event will be significantly greater. Asset filtering mechanisms may need to be leveraged to reduce the number of considered field asset infrastructure components to fit computational constraints. If implemented on the mainland US footprint to perform wide-area screening, reducing assets to include only those >200kV and above may be required.

Even with the inclusion of only high-voltage assets, there would be a major challenge in aggregating, synchronizing, and re-parameterizing input datasets to seamlessly map between field asset GIS data and power system model elements if the Framework is applied to multi-utility footprints. Lack of industry standards to make such mapping consistent from utility to utility and region to region is an industry gap that creates an expensive and time-consuming obstacle to use advanced analytical tools, such as this Framework.

V. A Call for New Data Guidelines

As presented in the previous section, the Framework requires infrastructure information that is not commonly available or regularly integrated together in power system modelling and planning tools. Implementing such a framework on a single utility footprint, let alone a multi-regional footprint, would be challenging and time consuming if appropriate mapping between datasets is not available. The industry could greatly benefit from standardizing data collection, curation, and maintenance of these datasets so that a seamless integration of field asset infrastructure databases, GIS information, and power system models can be achieved. Specifically, the industry should consider implementing guidelines for consistent data formats that address the following issues:

- Improved integration and curation of GIS information of electric infrastructure field assets with planning and operational models; including standardized asset naming convention protocols between tools and regions (most essential)
- Improved integration and mapping of historical outages of individual infrastructure elements, linked with planning and operational models, as well as with Geographic Information System (GIS) data
- Standardized naming conventions and curation of protection devices in relay databases such that mapping relay functionality to power system planning bus-branch and node-breaker models is improved

If the industry can move towards standardizing these practices, opportunities for integrating advanced analytical tools for scalable footprints, such as this Framework, as well as machine learning and artificial intelligence, can be realized.

VI. Conclusion

Analyzing the impact of extreme events on electric power systems in order to understand and mitigate risk is increasingly critical as natural disasters repeatedly devastate heavily populated communities and vital infrastructure around the world. As described in this paper, existing commercial software tools, coupled with National Laboratory-developed research prototype were used to create a Framework to identify resilience-enhancement options for the island of Puerto Rico. This Framework identified high-voltage transmission resilience improvements by classifying and prioritizing high-risk system failures. It used disparate data sources, such as electrical infrastructure asset fragility, hurricane meteorological information, GIS data, and power system models. During this exercise, a lack of standardized industry data collection practices, asset naming nomenclature, and data curation to map between these datasets was identified as a major barrier to implementing the Framework seamlessly. Therefore, to move towards establishing resilience planning as a routine practice, new industry guidelines to improve and synchronize industry asset mapping and modelling, as well as breaking down the organizational siloes in which these datasets are maintained, are essential to leveraging advanced analytical tools being sought for the future modern and resilient power grid.

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