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Development of a Resilience Framework for Storm Hardening and Recovery

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SUMMARY

Resilience improvement is a strategic objective within the critical infrastructure sectors, including electric power. Continuous improvement of power system resilience requires a well-thought-out strategic vision, well-executed action plans, and an effective mechanism for prioritization of resilience investment options under financial constraints. In this paper, we study the requirements and the steps that need to be taken to develop a resilience optimization framework. This framework requires a set of inputs, models, and outputs to facilitate a systematic, risk-informed, data-driven, resilience-focused decision-making process. The resilience optimization framework should enable electric utilities to strategically plan for and efficiently respond to an increase in high-consequence disruptive events.

KEYWORDS

Resilience, Metrics, Hazards, Severe Storms, Optimization Framework

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1. INTRODUCTION

A keystone of modern society is a resilient power grid that ensures an uninterrupted supply of electricity to citizens and interdependent lifeline systems even during disruptive events. As the power grid evolves, grid operators are faced with an evolving risk landscape. Changing power demand, increased reliance on renewable and distributed energy resources (DERs), and increasing penetration of smart technologies introduce additional layers of complexity to grid operations. In addition, the increasing frequency of natural disasters [1], climate change [2], physical attacks (e.g., 2014 attack on a Pacific Gas & Electric substation) [3], and cyber-attacks (e.g., malware BlackEnergy) pose significant risk and challenges to the uninterrupted operation of the power grid.

Commonly used reliability metrics—such as Customer Average Interruption Duration Index (CAIDI), System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Frequency Index (CAIFI), among others—measure the reliability of the system and ensuring grid preparedness for disruptions and expected outages that occur under relatively normal conditions. However, due to the changing risk landscape, there is a broad consensus across the board that these metrics do not adequately capture the impacts of many of the emerging risk exposures in the power grid [4]. This is because reliability metrics exclude outage information when high consequence events that have historically been considered low-probability occur. The current dynamically evolving risk landscape, requires a new set of metrics and processes are to assess the *resilience* requirements of the power grid.

Resilience as a concept has emerged as a strategic objective within the critical infrastructure community. According to [5], the term *resilience* is defined as “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.” Grid resilience is the power grid’s capability to ensure continuity of service to communities during high-consequence disruptive events. While it may not be feasible to guarantee the continuity of the operations at nominal or pre-disruption levels, but ensuring even a reduced service level can minimize the negative impacts of these events on communities.

Enhancing and maintaining power grid resilience requires not only a well-thought-out strategic vision and well-executed action plans, but it also requires an effective allocation of capital and resilience investment prioritization under budget constraints to ensure the desired return on investment and achieving the resilience goals. Therefore, in this paper, we provide a blueprint for a resilience optimization framework to facilitate a systematic decision-making structure on steps that need to be taken by the utility in its journey to reach its resilience objectives. Section 2 describes the framework requirements, including resilience goals, resilience metrics, system models, disruption levels, and resilience impacts of various investment alternatives, are described. In Section 3, the framework development process, including overall framework design, models, and methodologies, are introduced. In Section 4, a set of recommendations on resilience optimization framework requirements and developments are made.

2. FRAMEWORK REQUIREMENTS

The resilience optimization framework requires a set of inputs, models, and outputs to facilitate a systematic, risk-informed, data-driven, resilience-focused decision-making process by electric utilities. This framework should enable the utility to strategically plan for and efficiently respond to a wide range of high-consequence and increasingly probable disruptive events caused by natural disasters and climate shocks—that are not generally addressed by the utility’s ongoing reliability measures. In addition, it should provide a holistic, consistent, and adequately accurate means for the utility and its shareholders, communities, and regulators to effectively communicate about resilience issues. To specify the requirements of the resilience optimization framework, we adopted the conceptual models and frameworks from [6,7] along with resilience metric analysis by U.S. Department of Energy in [8]. To achieve the aforementioned objectives, the resilience goals, resilience metrics, system models, disruption levels, resilience impacts of various alternatives, and approaches to analyze and synthesize the outputs are described as follows.

2.1. Resilience Goals

Specifying the resilience goals is the first step in the resilience optimization framework, which lays the foundation for all following steps in the process. To set the resilience goals, the utility should form a cross-functional team of experts from key stakeholders to determine the acceptable level of impacts from a given adverse event under a range of circumstances. Discussion during this phase is required to decide whether setting the resilience goals should be made based on (a) historical performance, or (b) aspirational resilience goals. It is important to quantify the resilience goals in terms of acceptable duration, amount of lost load, and recovery cost for each load for each specific outage event. The quantification should be as specific as possible, including detailed information on the geographical typology (e.g., urban, rural), load type (residential, business, industrial, or critical loads such as hospitals and police stations), hazard type (e.g., tornado, wildfire), hazard intensity (e.g., a category F-5 tornado, and the time period after an event strike (e.g., the first hour, first week).

2.2. Resilience Metrics

Once the resilience goals are defined, the definition of the consequence categories that serve as the basis for resilience metrics is the second step in the process. The consequence categories should be reflective of the resilience goals. In some instances, the consequence estimates and resilience metrics may focus on the impacts directly realized by the utility, such as power not delivered, loss of revenue, cost of recovery, etc. However, in some instances, direct impacts are only part of the resilience assessment. Resilience analyses that aim to include a broader longitudinal community perspective may convert power disruption estimates into community consequence estimates (e.g., number of emergency service assets affected, business interruption costs, impact on the gross regional product, etc.). Broad consequence categories that we propose are

1. Utility Impact: Metrics collection such as total customer outage (residential, business, industrial), value of load not served during the hazard window time ,and speed of recovery, cost of recovery and other such important factors.
2. Community Impact: Value of critical load (e.g., hospitals, fire stations, police stations) not served during the storm window; direct and indirect economic impact of load not served.
3. Environmental Impacts: Total expected cost of disaster risk reduction to avoid environmental damage (e.g., total cost of preemptive de-energization to avoid wildfires).
4. National Security Impacts : Total number of outage occurrences in critical facilities (e.g., key production or military facilities).

All the consequence categories are measured for the defined system specifications and, therefore, may be measured across spatial (geographical) and temporal (duration) dimensions. Data availability may also affect the selection of consequence categories. Resilience analyses are not restricted to a single consequence category to develop metrics. Rather, the use of multiple consequence categories can be beneficial for representing various stakeholder perspectives.

2.3. Hazard Risk Identification

Identification of hazard risk involves the specification of hazards of concern based on stakeholders' prioritized list of concerns. The prioritization of hazards should be made based on a) the likelihood of the hazard occurrence; b) the likelihood and impact of severe consequences should a hazard be realized; c) strategic priorities; and d) availability of resources and budget constraints. Hazard risk identification also includes the development of hazard scenarios and associated uncertainties. Development of hazard scenarios includes detailing the specific hazard conditions. The hazard scenario should include the expected location, time, and duration of the event, and other conditions required to adequately characterize the hazard and its impacts on the power system.

Commonwealth Edision (ComEd) is the largest utility in the northern Illinios serving over 4 Million customers. ComEd has identified the risks posed to infrastructure byvarious hazards. The Illinois Natural Hazard Mitigation Plan (INHMP) [9] identifies seven key natural hazards in the State of Illinois, including severe storms, tornadoes, floods, severe winter storms, drought, extreme heat, and earthquakes. In addition, a recent study [10] identifies the Upper Midwest region to be exposed to a significant level of extreme space weather risk, particularly geomagnetic storms (a.k.a. solar storms).

Given the critical role of ComEd's infrastructure in its service territory and its significant exposures to the eight categories of natural hazards, accurate identification and measurement of such risks are needed to effectively manage their potential impact on and resilience of its infrastructure.

2.4. Disruption Level

Determining the level of disruption requires a specific assessment of the expected level of damage to or stress on exposed assets under various hazard scenarios. That involves an assessment of the vulnerability, i.e., the expected consequences to exposed assets when a destructive event occurs. Specification of the disruption level should not only indicate which assets are damaged or degraded, but it should also specify how severely the asset is impaired, what the consequences of the impairment are, and what steps are required to restore the overall system functionality to its pre-disaster conditions. For example, expected physical damage to grid assets and loss of power due to a heatwave event might include burnout of high-voltage transformer B, experiencing X kWh of load interruption due to loss of transformer B, and reduction of transmission capacity in line L, requiring H hours to bring the system back to its pre-disaster conditions, with $Y in repair expenses and loss of revenue to the utility. Societal costs (e.g., disruptions to critical load, economic impacts) incurred due to loss of load should also be considered.

2.5. System Models

Once the three elements of disaster risk management, i.e., the probability of an identified hazard, power system exposure, and power system vulnerability, are identified, a set of system models are required to collect the data and estimate the expected consequences [11]. To assess the grid resilience, data collection from historical events that characterize the intensity and duration of the disruption to the power system and the community is required. A utility can maintain and improve the quality of data in its Outage Management System (OMS) to be used as a crucial set of input data for a forward-looking resilience analysis process. System-level computer models capable of computing necessary power disruption estimates should be developed and regularly updated. These models should use risk data from previous steps (risk identification, risk exposure, and system vulnerability) as inputs to predict how the power system will be disrupted under various scenarios. For instance, expected physical damage incorporating uncertainty to the grid from a winter storm event could be used as input to a system model that links outages to load not served within the system over time. A set of system models may be required to capture various aspects of the system disruption, including power outage estimation models, restoration models, cost estimation models, and physical damage estimation models, among others. In addition, the interdependencies between models should be considered. For example, consider a restoration model that can determine the optimal restoration schedule of the power grid after a given storm scenario. The schedule determined by such a model can inform systems models to assess system performance during the restoration and the required recovery time. The system models should be used to calculate the consequence estimates (e.g., number and criticality of storm-induced outages) and level of attainment or drop in resilience metrics defined in previous steps.

3. PROPOSED FRAMEWORK

Figure 1 illustrates the process flow of the proposed resilience optimization framework based on the discussions in the previous sections. This framework evaluates the consequences of various resilience enhancement alternatives with a focus on system resilience enhancement against storms by facilitating the decision-making process while considering utility's resilience goals, budget constraints, and uncertainty associated with the outcome of various alternatives. This framework will help the utility plan and differentiate between resilience improvement options and select the most resilient investment.

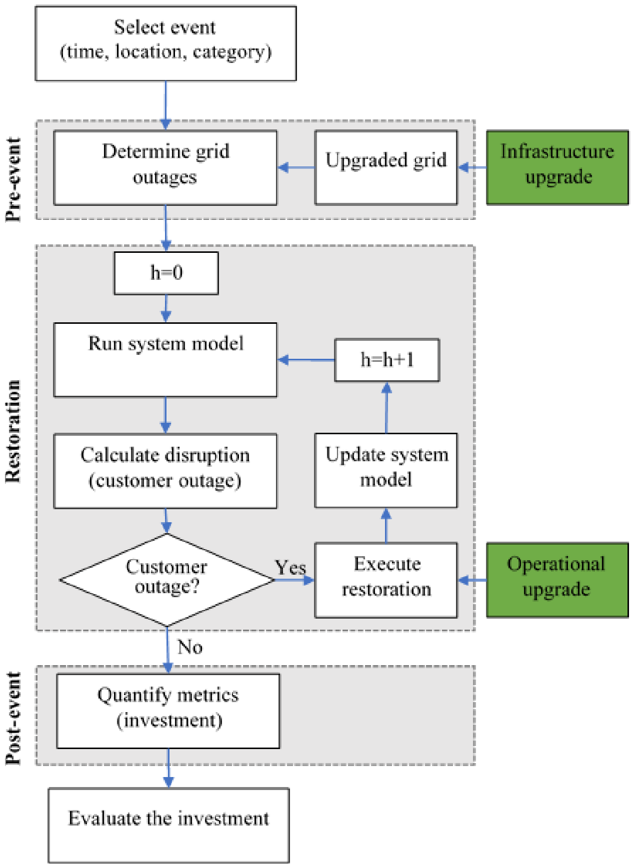

Figure 1. Process flow of evaluating the consequences of resilience enhancement alternatives

This framework includes the following features:

a) *Alternatives*, i.e., a choice to make between at least two different resilience enhancement options. Alternatives include infrastructure upgrades (investments) and operational upgrades (investments);

b) *Differing Consequences (Outcomes)*, which indicates that the results of any two alternatives are different (if they are the same, then the decision problem does not warrant much analysis); and

c) *Uncertainty*, which characterizes different consequences resulting from each alternative.

4. RECOMMENDATIONS

The development of the resilience optimization framework is an important step toward managing the risk at the enterprise level and empowering the communities that a utility serves. Development of this framework, however, will not be a one-time endeavor but rather a new process that should be in place requiring continuous improvement on an ongoing basis. Based on our findings in this study, we make two sets of recommendations on requirements and development of this framework, as follows.

4.1. Recommendations on Framework Requirements

Recommendation #1: We recommend engaging with various stakeholders, including utility's shareholders, representatives of communities, businesses, and industries it serves in, to involve them in the process of developing the resilience goals.

Recommendation #2: We recommend setting realistic resilience targets considering utility's budget constraints, operational limitations, minimum resilience requirement, and expected return on investment on resilience improvement options.

Recommendation #3: We recommend adopting a risk-based approach on utility's resilience framework requirement, considering the risk-reward propositions as the basis of the resilience optimization process.

4.2. Recommendations on Framework Development

Recommendation #1: We recommend considering a combination of in-house and off-the-shelf software packages in the development of the required systems models for the resilience optimization framework.

Recommendation #2: We recommend the utility adopt a model-based approach for analysis needed to plan and differentiate between various planning options to inform the most resilient investment alternatives.

Recommendation #3: We recommend the utility seek consultations from experts outside of the organization and from various interest groups on a regular basis to ensure the adequacy of the desired properties for resilience enhancement alternatives pool.

Recommendation #4: We recommend the utility to develop its capital investment prioritization tool based on Multi-attribute Utility Theory (MAUT) due to its practicality and well-established mathematical modeling foundation.

BIBLIOGRAPHY

[1] Swiss Re, Natural catastrophes and manmade disasters in 2015: Asia suffers substantial losses, 2016, accessed September 30, 2016 at http://media.swissre.com/documents/sigma1_2016_en.pdf

[2] U.S. Department of Energy, U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather, 2013, accessed September 30, 2016, at , http://energy.gov/sites/prod/files/2013/07/f2/20130716-Energy%20Sector%20Vulnerabilities%20Report.pdf

[3] R. Smith, Assault on California Power Station Raises Alarm on Potential for Terrorism, 2014, accessed September 30, 2016, at http://www.wsj.com/articles/SB10001424052702304851104579359141941621778

[4] NARUC (National Association of Regulatory Utility Commissioners), Resilience in Regulated Utilities, accessed September 30, 2016, at https://pubs.naruc.org/pub/536F07E4-2354-D714-5153-7A80198A436D

[5] Obama B., Presidential Policy Directive 21: Critical Infrastructure Security and Resilience, Washington, DC: 2013.

[6] Eric Vugrin, Anya Castillo, Cesar Silva-Monroy, "Resilience Metrics for the Electric Power System: A Performance-Based Approach," Sandia National Laboratories, Albuquerque, NM, 2017.

[7] Jean-Paul Watson et al., "Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States," Sandia National Laboratories, Albuquerque, NM, 2015.

[8] Frederic Petit et al. "Grid Modernization: Metrics Analysis (GMLC1.1) – Resilience," Grid Modernization Laboratory Consortium, U.S. Department of Energy, Washington, DC, 2020.

[9] Bruce Rauner, "2018 Illinois Natural Hazard Mitigation Plan" Springfield, Illinois, 2018.

[10] G. M. Lucas, J.J. Love, A. Kelbert1, P.A. Bedrosian, and E.J. Rigler, "A 100-year Geoelectric Hazard Analysis for the U.S. High-Voltage Power Grid," Space Weather, 2020.

[11] Bill Chiu et al. "Resilience Framework, Methods, and Metrics for the Electricity Sector", Technical Report IEEE PES, 2020