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Public Utility Commissions to Foster Resilience Investment in Power Grid Infrastructure

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Abstract

In the United States, power system works at 99.9 percent reliability but it does not imply that it is safe and reliable against all types of hazards whether natural, technological or man-made. Especially the high impact low probability (HILP) events also called "black-swan events" offer a complex risk environment for power grid infrastructure. On the other hand, the utility companies have to work in a very competitive and regulated environment maintaining a balance between their investments on infrastructure, rate of returns, serviceability and cost to the customers. Hence, it is not economically feasible and justifiable to harden the entire infrastructure owing to budget constraint and regulatory issues. In such a scenario, enhancing resilience selectively within the power grid infrastructure would serve the purpose of achieving optimum security against any type of hazards, including HILP events. Resilience is the property that incorporates robustness and rapid recovery of infrastructure in face of any type of unprecedented havoc hazards. Enhancing resilience is cost intensive and future return on such investments are also risky and uncertain. Again, "resilience investments" i.e. investments needed to enhance resilience of power grid need approval from Public Utility Commissions (PUC) for cost recovery from public consumers and also must involve other investment agencies to invest in the power infrastructure by offering them good rates of return on investment (ROI). This paper will discuss the various key issues that hinder adequate investments in resilience enhancement of power grid infrastructure. Some of the key issues identified are (i) lack of knowledge about the Black Swan Events and their impact on the power grid infrastructure; (ii) strict regulatory restrictions imposed by PUC within the purview of which the utilities work; (iii) lack of strong value proposition for resilience investment business cases as presented by the utilities to the PUC, and (iv) lack of adequate incentives for the investors to invest in the power infrastructure. A conceptual strategic decision making framework for the PUC is also proposed that would help in approving or incentivizing adequate resilience investments for power grid infrastructure.

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Keywords: Power grid infrastructure; Decision support system; Resilience investment; Black-swan events; Economic impact

1. Introduction

Power Grid Infrastructure (PGI) is the cornerstone of our society. It is one of the most important of the lifeline infrastructures that is expected to provide services even if the other infrastructures fail [1], [2] . The continuity in electricity services is an absolute necessity because without electricity, all the essential services of the society such as continuous business and government operations, public health and safety, and national and economic safety will be disrupted leading to extensive economic loss. In the United States, although the power system works at 99.9 percent reliability, it does not imply that the power infrastructure is safe against all types of hazards whether natural, technological or man-made. Especially the *high impact, low probability (HILP)* events offers a very complex risk environment for the infrastructure [3].

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The HILP events which are also known as *"Black Swan Events"* are considered to be the instigating events that could cause cascading failure of the power infrastructure and consequent disruption in the electric services to such an extent that the restoration of services back to ex-ante disaster condition might take weeks, months or sometimes even years [4]. Co-ordinated physical or cyber-attacks and geomagnetic disturbances are a few examples of such HILP events when the PGI is considered.

In addition to these external threats, there is a growing internal weakness within the PGI systems caused by several factors that further renders vulnerability to the entire system when exposed to such external threats. Examples of some of these factors include aging of the PGI and the increased interdependency of all the other critical infrastructure sectors on the power sector. The increased interdependency introduces fragility to the network structure of PGI [5]. In addition, owing to the climate change, there is an increased frequency of natural disasters which disrupt the power generation and delivery in many instances and thus weaken the power delivery service. For example, increased droughts reduces power generation from the steam power plants leading to scarcity of power; the storms, hurricanes and tornadoes, on the other hand, physically disrupts the power transmission and distribution systems.

Under such circumstances, it is extremely important to protect the national grid and enhance its security in face of the Black Swan Events. Fortunately, electricity service providers understand the importance of reliability of the power system and its need for proper functioning of the society and economy and they take every initiative to maintain/improve reliability of the grid. The North American Electric Reliability Corporation (NERC) defines operating reliability as "*the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components*" and it defines adequate reliability as "*the ability of the electric system to supply the aggregate electric power and energy requirements of the electricity consumers at all times, taking into account scheduled and reasonably expected unscheduled outages of system components*" [6]. It is noteworthy here, that the "reliability" property of the electric system is not capable of assessing the unscheduled and extraordinary unexpected outage risks and thus this property alone is not able to enhance the security of the grid against the Black Swan Events. The reason being these types of events create extra-ordinary hazardous risk scenarios that would cause extensive infrastructure damage and service disruptions — the estimated extent of damage and disruption being much higher than the combined effect of the most severe recent disasters, Superstorm Sandy and Hurricane Katrina in the US [7].

In this context, the "resilience" of infrastructure seems to play an immense important role. Resilience is the property that enhances security of any infrastructure and incorporates robustness and and helps in rapid recovery of infrastructure in the face of any type of unprecedented havoc hazards. However, enhancing resilience is cost intensive and the future return on such investments are also risky and uncertain. Again, "resilience investments" i.e. investments needed to enhance resilience of power grid need approval from Public Utility Commissions (PUCs) for cost recovery from the electricity consumers and also need good rates of return on their investment (ROI). This paper will discuss the various key issues that hinder adequate investments in resilience enhancement of PGI and will establish the need that the PUCs must foster the resilience investments as proposed by the utilities. Finally this paper presents a framework which will help in the decision making process of the PUCs in approving or incentivizing adequate resilience investments for PGI.

Nomenclature

PGI Power Grid Infrastructure
PUC Public Utility Commission

2. Issues related to resilience investments

Enhancing resilience of the critical infrastructure is an absolute necessity to enhance the security of the nation. President Barack Obama signed a Presidential Policy Directive (PPD)-21 on February 12, 2013 and called for national unity to enhance the resilience of critical infrastructures in order to strengthen and maintain proper functioning and security of the critical infrastructures for maintaining nation's security, economic prosperity and well-being of the public [8]. However, there are several issues related to the resilience enhancement of the PGI mostly because such enhancement strategies are costly and need extensive investment for their implementation. In this paper, resilience investment is referred to as the investments needed to implement the resilience enhancement strategies that are needed to improve the security of the grid. The various issues associated with the resilience investments are —

- Lack of knowledge about the Black Swan Events and their impact on the PGI
- Strict regulatory restrictions within the purview of which the utilities need to work
- Lack of strong value propositions for resilience investments to the PUCs by the utilities
- Lack of adequate incentives for the resilience incentives

2.1. Lack of knowledge about the Black Swan Events and their impact on PGI

The world has witnessed various types of disaster risks all the time but recently it seems that the frequency of the occurrence of such disasters is increasing. The Nepal earthquake in 2015, Hurricane Sandy in the United States in 2012, the North American Derecho storm in 2012, the East African Drought in 2011 and Haiti Earthquake in 2010 are a few of the examples. However, common public and the government are not fully aware of the extent of *Black Swan Event* risks that we are facing everyday nowadays [3]. The major reason behind the lack of knowledge and ignorance about the Black Swan Events is the extremely low probability of the events to occur. Lee et al. (2012) describes the Black Swan Events as the "*events which are beyond the realm of normal expectations in history, science, finance and technology and therefore impossible or extremely difficult to predict*" [3]. The preparedness for such events should be generic and on a systemic basis because specific planning is almost impossible in these cases. Moreover, with the increased dependency of the society on electricity in the recent times, the impacts of a significant disruption within the power grid owing to a Black Swan Event will no longer be localized but will flow through the infrastructure network instead leading to a cascading failure of all the other interdependent critical infrastructures. Such a catastrophic failure can propagate across the jurisdictional and transnational boundaries. Thus it is almost impossible to predict how a Black Swan Event will impact the PGI and what consequences will it unfold.

2.2. Strict regulatory restrictions by the Public Utility Commissions (PUC)

The utility companies that own the PGI have to work in a very competitive and regulated environment maintaining a balance between their investments on infrastructure, rate of returns, serviceability to the customers and also cost to the customers. Utilities are natural monopolies and in that way they are empowered to restrict the output and set prices for the customers at higher levels than economically justified in order to earn higher profits. Now, based on the economic principles, it is necessary to have a monopoly structure of the utility to satisfy the overall demand at a lower cost compared to a number of smaller utilities co-existing in a competitive market [9]. However, on the other hand, since utility provides public service it is also important that these utilities are overseen and regulated by the government to protect the public interest in receiving a reliable service at an affordable price [9]. The government approves the investments to be made by the utilities but presently, the procedure that is being followed is biased towards the resilience enhancement investments [10]. Approval of investments is extremely important because it is associated with the approval of the cost recovery process for the investments which includes charging the customer at a higher rate for the enhanced reliability of the electric service that they are enjoying.

2.3. *Lack of strong value propositions for resilience investments to the PUCs by the utilities*

One of the major issues behind the approval of resilience investments is the lack of strong value proposition for investments in building new infrastructure, upgrading the existing infrastructure, or implementing innovative technologies that would help to resist or recover rapidly after being impacted by a disaster. The several issues behind lack of strong value proposition of a resilience investment are as follows.

- First, there is a common misconception among the utility providers and regulatory commissions about the terms "reliability" and "resilience" in context of a power grid. As discussed before, reliability can be defined as the ability of the power system to withstand sudden disturbances and continue supplying adequate power to the consumers at all times taking into account *expected and reasonably expected unscheduled* outages of the system components [6]; on the other hand, resilience of PGI is the ability of the power system to reduce the magnitude and/or duration of *any* disruptive event and restore the power system to its ex-ante reliability state [4]. Thus, in this context, it can be easily understood that although the power grid works with 99.9 percent reliability, it is a common misconception that the grid is also resilient. But, the instances of power outages in the U.S. such as North Eastern power outage in 2003, power outage in New York City due to Superstorm Sandy in 2012, power outage from North American Derecho in 2012 and others confirm that incorporating resilience in the power infrastructure has become extremely important and reliability does not necessarily confirm that the power grid is also resilient.

- Second, most of the resilience building options are cost intensive and when these are combined with the uncertainty and low probability of occurrence of such disasters, often times such investments seems to be unnecessary. The regulatory commissions are reluctant to approve such investments and recover the costs from public by increasing their monthly utility rates as the effects from such projects are not to be experienced by the customers immediately. However, when the HILP events unfold, the impact is catastrophic and disruption spreads in the infrastructure network as a contagious disease causing extensive economic and social loss. Thus the expected loss increases in such cases if the infrastructure is not rendered to be resilient and this would increase the benefits for the resilience investments.

- The utilities however do not consider such extensive impacts and economic loss at present. The existing benefit-cost analysis of the investments protocol consider the value of the lost load for the customers at a flat rate i.e., it considers the value of electricity loss to the customers to be constant (electricity loss is less than 8 hours) which is not applicable in case of HILP events [10]. The Interruption Cost Estimate (ICE) calculator used by the utilities and regulators to estimate the cost and benefit of a power interruption while assessing the need for reliability investments does not consider the compounding value of the lost kilowatt-hours over time [7]. Under instances of longer period (greater than 8 hours) of power outage, the value of the lost power to both the residential and non-residential customers are increasing and thus often times the economic damage for prolonged power outages are undervalued in the current estimation system [10]. Moreover, the compounding value of the economic loss due to business disruption as a result of the power loss is also not considered.

Thus, the present investment analysis framework often times undervalues the resilience investment and fails to establish a strong business case to present in front of the public utility commissioners.

2.4. *Lack of adequate incentives for resilience investments*

The resilience investments would add value in the long term and under circumstances of HILP events. However, the regulatory commissions are reluctant to approve the cost recovery for such investments. Thus, it is an extremely risky affair for the utility companies and investors to perform such types of investments and most of the times they are not willing to venture such resilience enhancement projects without public support and a confirmation from the regulatory commission to recover the cost of such investments. Thus, regulatory commissions should offer some sort of incentives such as offering higher rates of return for such investments, approval of the cost recovery process, etc. such that it would be a win-win situation for both the utility companies and the public.

3. Research Needs

There is a need for a paradigm shift in the strategic decision-making process of the utility companies to account for the enhancement of PGI security that would aid in developing the business case for resilience investments to present in front of the PUC. On the other hand, such a decision support system would also assist the PUCs to prioritize, approve and incentivize the business cases related to resilience investments presented by different utilities in the state. The proposed risk-based decision support system (RDSS) for analyzing the needs of resilience investment projects would be able to address the following gaps of the current investment assessment procedure:

- consider the risks of the power grid in face of the black swan events
- consider increased loss due to compounding value of lost load over time for the customers in case of a prolonged electricity failure, and
- consider the economic loss due to cascading failure of the interdependent critical infrastructure sectors owing to the loss of electricity.

4. Development of the Integrated Risk-based Decision Support System (IRDSS) Framework

The proposed IRDSS framework for evaluation of resilience investments will consider a transformative approach that would help the utilities to prioritize the resilience investment decisions and would help them to develop a strong business case for approval of the investments by the regulatory bodies.

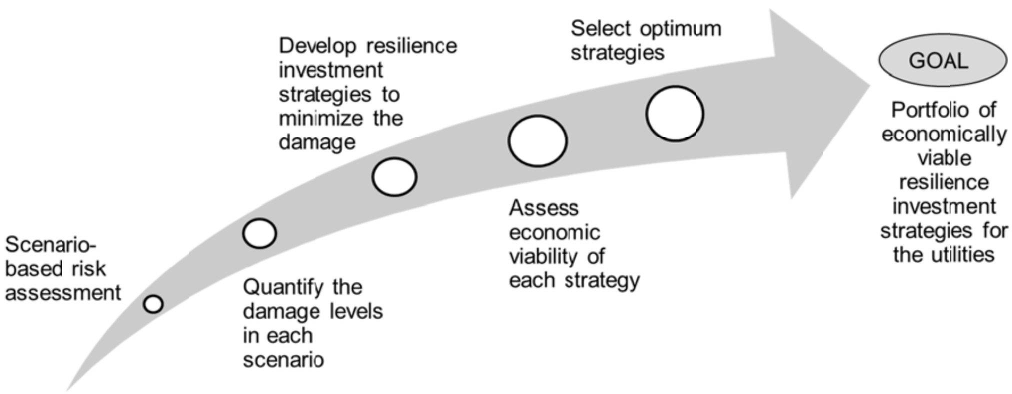

Fig 1. Research Development Flow Chart

The decision support system will be built on the foundation of the common risk management principles. It will be followed by development of a portfolio of different strategies that would be relevant to enhance the resilience of the PGI. The optimum strategies will be selected using a multi-objective optimization process and consequently a cost sharing mechanism for the best investment strategies will be proposed. This will eventually help in the policy analysis for resilience investments.

The research methodology can be divided into three phases: (i) assessment of the HILP risks to the power grid, (ii) development of a portfolio of different strategies to enhance the grid resilience in face of such HILP events and (iii) assessment of economic viability of the strategies and selection of the optimum strategies for resilience investment. The flowchart of the proposed Integrated Risk-based Decision Support System (IRDSS) is shown in Fig. 1.

4.1. Assessment of HILP risks to power grid: Phase I

Kaplan and Garrick (1981) first proposed the quantitative definition of risk that includes answering of the three questions called "triplets" — (i) "what can go wrong?" / "what can happen?" (ii) "how likely is that it can happen?"; and (iii) "if it happens, then what are the consequences?" [11]. This definition augmented the earlier definition of risk proposed by Lowrance in 1976 (risk was defined as a measure of probability and `severity of adverse effects) by introducing the concept of scenarios ("what can go wrong") [12]. The risk triplet is represented by —

$$R = \{< S_i, P_i, X_i >\} \quad (1)$$

where, S_i is an identified scenario (refers to categories of scenarios), P_i is the probability of the scenario to occur and X_i is the consequence / damage measure of a scenario. Kaplan modified the definition of risk as —

$$R = \{< S_i, P_i, X_i >\}_c \quad (2),$$

where the subscript "c" indicated the "complete set" of scenarios including the "As-Planned Scenario (S_0)" [13]. The scenario based risk analysis is appropriate for this research as it takes into account the high damage low probability scenarios compared to the conventional definition of risk that measures risk as probability times consequence (severity of the adverse events) and thus cannot differentiate the high damage low probability scenario with low damage high probability scenario [11].

The scenario based risk analysis phase will lead to identification of the different sources of risks owing to the Black Swan Events and isolate the critical ones that might lead to cascading failures, develop "what-if-scenarios" pertinent to the risk sources and estimate the consequences of the failures in terms of damage levels such as duration of power outage.

4.2. Development of a portfolio of different strategies to minimize the economic damage: Phase II

Subject matter experts (SME) and operating personnel from the utility industries will be interviewed to develop a list of all the possible strategies that could be used to reduce the impact of the different risks represented by risk scenarios. The strategies will be focused on different alternatives

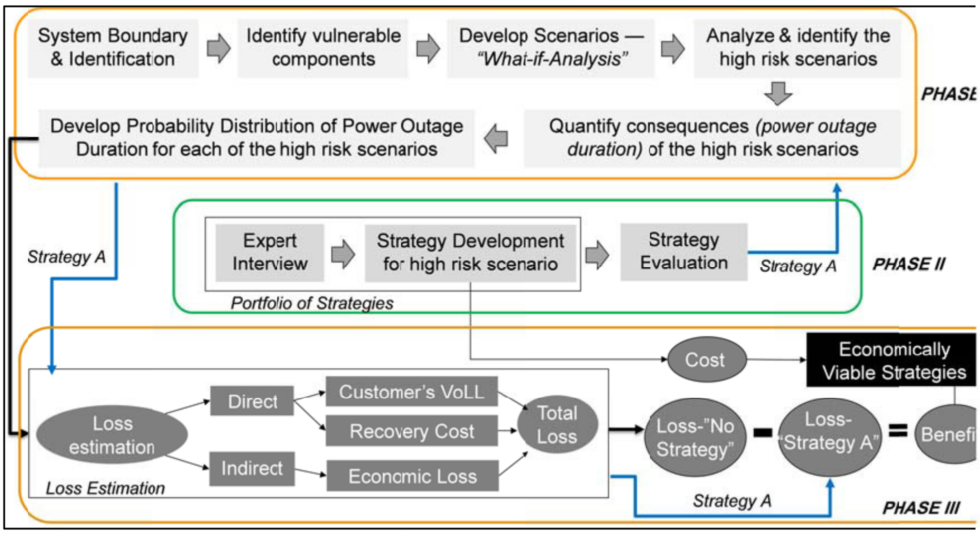

Fig 2. Research Framework

that would be used to enhance the resilience of the power grid. Now, the word "resilience" is being widely used in different industries including civil infrastructures, economic systems, sociology, physiology and others. However, the meaning of resilience is not same in all the cases. NERC has defined the resilience of bulk power system in terms of *"adequacy"* — ability of the power system to supply power to the customers all the time taking into the account the "reasonably expected scheduled and unscheduled outages" and "security" — ability to withstand sudden damages [6]. Since this definition only focus on the bulk power system, the National Association Regulatory Utility Commissioners (NARUC) defined resilience of the utility as the "*robustness and recovery characteristics of utility infrastructure and operations, which would avoid or minimize interruptions of service during an extraordinary and hazardous event*" [10]. In this research, NARUC's definition of utility resilience will be adopted and strategy development phase will only focus on the strategies that would increase the resilience of the grid by incorporating robustness and redundancy in the system or hardening the critical equipment or help in rapid recovery of the system in case the HILP event affects the system.

4.3. Assessment of economic viability of the strategies: Phase III

Preliminary screening of the strategies need to be conducted after Phase II to select the set of economically viable strategies. Economically viable strategies refer to the strategies whose life-cycle cost will be less than the benefits that it will offer over time. The life-cycle cost of the strategies/ alternatives will also be obtained from the experts and utility database. The benefits of such strategies will be measured in terms of the reduced losses owing to the implementation of the strategies. The economic benefits of each strategy can be computed in two steps. The loss estimation which includes both the direct and indirect losses are calculated first for the no-strategy scenario and then the same is calculated for the scenario considering the implementation of the particular strategy (say *Strategy A*). The difference in the losses will yield the benefit for Strategy A. Finally, those strategies for which the economic benefits will be higher than the overall life-cycle cost will be considered as the economically viable strategies and thus this will help the decision makers to select the best strategies that would enhance the security of the grid.

5. Expected Outcomes

The expected outcome of the proposed research is to develop an ***Integrated Risk-based Decision Support System (IRDSS)*** for the utilities to help them in strategic decision making in prioritizing the resilience investments needed to enhance the security of the grid in face of HILP events. This would also support them to develop business case for the resilience investments to get it approved by the state utility regulators. Such an outcome will also help the PUCs to make better policy decisions regarding approving / incentivizing such resilience investments. The specific outcomes from this research are as follows:

- Development of various risk scenarios and corresponding damage levels on the power infrastructure due to the impact of a HILP event on the PGI
- Development of a portfolio of optimized strategies to minimize the impact of HILP events on the grid
- Assessment of benefits of the strategies computed in terms of reduced losses will include —
    - evaluation of the increasing value of lost electricity services over time from customer's perspective
    - assessment of the compounding economic loss caused due to business interruption of the interdependent critical infrastructures
- Estimation of the cost of investment needed to implement the strategies
- Prioritization of the optimum strategies based on their costs and benefits

In order to achieve the expected outcomes, some of the assumptions that will be considered in this research are as follows:

- The research will focus on a single state investor owned utilities
- Portfolio of strategies will include those strategies that will enhance the resilience of the grid
- The model will only consider risks of the natural HILP events and not the intentional manmade / terrorist attacks.

6. Conclusion

The resilience enhancement of power grid is of utmost importance to secure the grid in face of the HILP events. Resilience enhancement strategies are cost intensive and thus they do not receive much attention either from the Public Utility Commissioners (PUCs) or the utilities. Most of the times, these types of investments are undervalued at present as they do not consider the compounding value of load lost to the customers or the indirect business loss in the other electricty dependent economic sectors due to prolonged outages. Moreover, the significant low probability of occurrence of the HILP events have further reduced the importance of such resilience investments. The Integrated Risk-based Decision Support System (IRDSS) will be able to consider the HILP event risks and analyze the different high risk scenarios considering their impact on the PGI and also the economy. Such a system will integrate the scenario based risk analysis and the compounding economic loss owing to the PGI damage to evaluate the different resilience enhancement strategies. Thus, instead of undervaluing it most of the times using the current investment evaluation system, the proposed IRDSS platform will help to adequately value the resilience investments and help in the decision making process of the PUCs to foster such investments.

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