

Integrating Engineering, Economic, and Social Modeling in Risks of Cascading Failures Across Interdependent Complex Networks

Lamine Mili, Frederick Krimgold, Jeffery Alwang, and John E. Bigger

Abstract – Planning for electric power reliability and recovery from catastrophic failures requires knowledge of the interdependencies between electrical systems and the economic and social systems that they serve. To date, however, such planning has been conducted in an atomistic fashion, with little recognition that system interdependencies have major effects on benefits and costs of catastrophic failures. This paper stresses the need to integrate social, economic and engineering modeling in the risk assessment and management of cascading failures leading to blackouts. Evaluation of cascading economic and social impacts of major power losses will be based on contingent and subjective valuation methods built into a computable general equilibrium model. This model is being validated using surveys in the Washington DC Metropolitan region. The assessed risks and costs are integrated in the power system planning phase.

Keywords- Risk assessment, cascading failures, partitioned multiobjective risk, direct and indirect economic losses.

I. INTRODUCTION

Many crucial social and economic services depend on the normal operation of the electric power system. This reliance makes it difficult to determine total costs associated with power outages since costs cascade through social and economic systems and extend far beyond damage to the service-providing facility in both time and geographic area. However, there is virtually no unified theory to guide risk management based on realistic estimates of both the direct and indirect costs of power system outages. Better understanding of the complex interdependencies between electric power systems and social and economic networks will assist in the design of means to maintain the risk of blackouts at an acceptable level and minimize losses afterwards.

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The first stage of the risk-weighted comprehensive cost-benefit analyses entails the assessment of the conditional risks of cascading failures in the electric power systems together with the evaluation of the direct and indirect costs created through linked economic and social networks. During catastrophic events, subjective valuation of costs and benefits may diverge from those values under more normal conditions. These values will be captured using contingent valuation techniques and the cascading economic and social impacts of major power losses will be estimated using a computable general equilibrium model.

This model is being validated using surveys carried out in the Washington DC Metropolitan region. Finally, the assessed risks and costs are integrated in the decision process of the planning phase. Composite power system expansion will make use of the partitioned multiobjective risk method to achieve tradeoffs between conflicting objectives of resiliency to catastrophic failures and efficiency for normal operating conditions of these infrastructures.

The paper is organized as follows. Section II outlines the structural design of interdependent power, social and economical networks. Section III deals with the risk assessment of cascading failures in power transmission systems. The economical and social consequences of power systems failures are highlighted in Section IV. The indirect losses related to specific chains of dependency of critical infrastructure failures in the Washington Metropolitan Area are described in Section V. Conclusions and future work are provided in Section VI.

II. STRUCTURAL DESIGN OF INTERDEPENDENT NETWORKED SYSTEMS

We assume that the failure rates of power system components (including the probabilities of failures that are exposed only during a fault, termed Hidden Failures) are known since they can be estimated from historical data. Component failure rates are routinely estimated by the power utilities for reliability assessment purposes. However, frequency estimation of some man-made hazards (e.g., terrorist attacks, intentional sabotage, non-intentional human error) cannot be extrapolated into the future because the nature and magnitude of these hazards depend heavily on the unique political, social, economic and organizational environment in which they occur. It is then reasonable to assume that the probabilities of man-made hazards are unknown. Consequently, decision analysis is carried out in a situation where nature-generated failures have known

probabilities, while some of the man-made failures have unknown probabilities.

To explore the question of how decision rules can be set up in this context, we can consider a two-person game where a terrorist (or nature) is playing against a critical infrastructure decision-maker. From a game theoretic viewpoint (Von Neuman and Morgenstern [1], Keeney and Raiffa [2]), this sets up a zero-sum game situation between two antagonistic players since no cooperation between them can take place either before or during the terrorist attack. One terrorist's goal might be to inflict with sufficiently high probability a great deal of physical damage to the critical infrastructure at a small cost for him, while the objective of the decision maker is to make the cost of inflicting such damage prohibitively high for the terrorist at the minimum possible cost to himself. Another terrorist's goal might be to inflict monetary rather than physical damage by sending false information about a planned attack, prompting the decision maker to expand resources in infrastructure protection. Consequently, the decision maker wishes to keep these expenditures from becoming prohibitively high while providing the infrastructure with some degree of robustness. He may achieve this goal by minimizing the risk of catastrophic failure of the infrastructure subject to an upper bound on the design cost rather than seeking a least-cost design subject an upper bound on the risk function as it is commonly carried out.

Because the services provided by critical infrastructures are vital to the economy and health of a nation, and their interruptions may have adverse, large-scale social impacts, it is reasonable to assume that the decision-maker is risk averse and will adopt a minimax strategy aimed at preventing the worst-case scenario. The goal of this strategy is to minimize the maximum conditional risk of a catastrophic failure over all possible actions that the decision-maker might take subject to limits on the costs of the design. The conditional risk is here defined as the product of the conditional probability of a cascading failure by its severity. Formally, we have

$$\begin{aligned} & \min_i (\max_j u_{ij}), \\ & \text{subject to} \quad c_i \leq b \quad \text{for } i=1, \dots, I, \end{aligned} \quad (1)$$

where u_{ij} is the conditional risk of the j^{th} catastrophic failure under the i^{th} action, which has a cost c_i , and where I is the total number of actions.

While we may define a catastrophic failure as a failure whose severity is larger than a given threshold, fixed a priori by the decision-maker, it is not clear how to measure the severity of a failure. This calculation presents a research challenge because, unlike the direct impacts of a failure, such as damage to equipment and fatalities, the indirect impacts are not easily quantifiable, especially if they include impacts such as business interruptions and human suffering due to psychological stress or adverse health impacts. Some of these costs are not borne nor even considered by the decision maker. In addition, the minimax criterion is aimed only at providing security against extreme events. As a result, it does not guarantee good performance of the design under events

with moderate severity or under normal operating conditions of the system. Therefore, an appropriate trade-off between conflicting objectives of resiliency and efficiency must be determined. We propose to use the partitioned multiobjective risk method to address this issue.

The frequencies of most natural hazards can be reasonably estimated from historical data and extrapolated, at least in the short-term. These hazards include normal equipment failures and short-circuits in power substations or on lines. While they may, under the right conditions, result in cascading failures, the minimax criterion should not be used for these routine events since it produces an overly-conservative system design. In fact, as proposed by Haimes [3], a better criterion would be to minimize the conditional expected-value risk functions, f_i , $i = 1 \dots n$, where n is the number of the partitioned regions of the damage severity. As depicted in Fig. 1, we typically consider for the design d_j , three ranges of severity: low, moderate, and high ranges, which are denoted by S_{1j} , S_{2j} , S_{3j} , respectively. Assuming that the severity is a random variable X with a cumulative probability distribution function $P(x; d_j)$ and a probability density function $p(x; d_j)$, the partition of the severity maps a similar partition of the exceedance probability defined as $1 - P(x; d_j)$. Consequently, the conditional risk functions are written as

$$\begin{aligned} f_i(d_j) &= E[X | p(x; d_j), x \in S_{ij}], \\ & \text{for } i = 1, 2, 3; j = 1, \dots, m. \end{aligned} \quad (2)$$

We can define the unconditional expected-value risk function $f_4(d_j)$ for the design d_j as the weighted sum of the conditional risk functions, $f_1(d_j)$, $f_2(d_j)$, $f_3(d_j)$, with positive weights w_1 , w_2 , and w_3 , respectively. Hence, we have

$$f_4(d_j) = w_1 f_1(d_j) + w_2 f_2(d_j) + w_3 f_3(d_j),$$

subject to $w_1 + w_2 + w_3 = 1$. (3)

By letting $f_5(d_j)$ denote the cost of the design d_j , the optimal design is then defined as the solution to a multiobjective optimization problem expressed as

$$\min [f_1, f_5]^T, i = 1, \dots, 4. \quad (4)$$

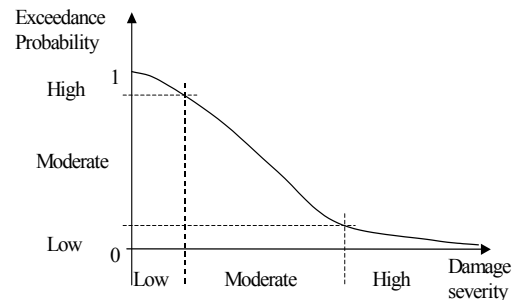


Figure 1: Exceedance probability versus the damage severity.

As indicated by Haimes, the advantage of the optimization given by (4) over other alternatives is that it allows the decision maker to perform through the weights w_1 , w_2 , and w_3 , tradeoffs between the marginal costs associated

with unit increments of the risks functions. Due to the high sensitivity of the expected catastrophic risk to the chosen partitioning of the damage severity, the final decision cannot be reached without carrying out a sensitivity analysis. The latter requires the modeling of the tails of the probability distributions, which can be achieved by making use of the statistics of extremes [4, 5, 6]. Note that the tails of these distributions are much longer than those of the Gaussian distribution as shown for example by a study carried out by Doyle of California Institute of Technology [7] based on the analysis of the major disturbances in electric power systems published by the North American Electric Reliability Council [8]. In this research, we will extend this approach to account for catastrophic cascading failures in networked systems by making use of algorithms based on event trees as explained below.

III. RISK ASSESSMENT OF CASCADING FAILURES IN ELECTRIC POWER SYSTEMS

In this section, we propose methodologies together with algorithms that assess the risk of catastrophic failure - defined as one that results in the outage of a sizable amount of load (commonly 10% of peak) - in electric power networks. To this end, we will employ risk-based security analyses using Monte Carlo methods that build on the pioneering work of Thorp, Phadke, Horowitz, and Tamronglak [9].

In previous research funded by EPRI [10], Mili et al. [11] developed an algorithm that calculates the probabilities of cascading failures in an electric power system for a given production and load configuration. The developed approach is based on an event tree [12, 13] consisting of a collection of events that occur in sequence as follows. First, the triggering event may be a permanent or a temporary fault with a probability P_{Fi} and $P_{Fi}(1 - P_{Pi})$, respectively, where P_{Fi} is the probability of a fault and P_{Pi} is the conditional probability that the fault is permanent. Once the fault occurs, the circuit breakers of the faulty line should open to clear the fault. However, they may remain stuck in a closed position with a conditional probability P_{Bi} . In the event of a temporary fault, the breakers should reclose after a programmed delay, an event that may fail to occur with a conditional probability P_{Ri} . In addition to the relays of the faulty line, other relays may also sense the fault current. Unlike the former relays, the latter should block their tripping mechanisms and not open the lines under their control. However, one or several of them may each suffer from a hidden failure (HF) with a small probability P_{Hi} and thereby, trip the associated non-faulty line.

This sequence of line trips may result in either a system failure or line overloads. In the latter case, another sequence of line trips due to relay hidden failures may lead to system failure or to line overloads and so forth. Consequently, the conditional probability of a system failure is written as

$$P_{Si} = P_{Fi}(1 - P_{Bi}) \{P_{Pi}(P_{HPi} + P_{LPi}) + (1 - P_{Pi}) [P_{Ri}(P_{HTNi} + P_{LTNi}) + (1 - P_{Ri})(P_{HTRi} + P_{LTRi})]\}, \quad (5)$$

where P_{HTNi} and P_{HTRi} denote the conditional probabilities of a system failure due to relay hidden failures, given the

occurrence of a temporary fault and the non-reclosing or the reclosing of the faulty line, respectively. Similarly, P_{LTNi} and P_{LTRi} denote the conditional probabilities of a system failure due to line overloads.

The developed algorithms are able to identify weak links in power systems for a wide variability of the load and generation profiles over time. The risk functions $f_i(d_j)$, $i=1, \dots, 3$, involved in (3) for a design d_j , are defined as the conditional expected loss of load probability (ELOLP) times the severity of the system failure assessed by means of the computable general equilibrium method explained in Section IV.

More specifically, the algorithm proceeds as follows. For a given design scenario of generation and transmission expansion denoted by d_j , the procedure first identifies the outage sequence of lines, generating units, and loads for a given initiating fault, which is typically a short-circuit applied to a line or a node of the network. Then, for this sequence of events, it calculates the total loss of load and the total socio-economic cost associated with it. Finally, it calculates the total risk of the system failure by multiplying its estimated conditional probability by the socio-economic cost. This risk is then classified as low, medium or severe. The algorithm repeats these calculations for all the initiating faults and calculates the unconditional expected-value risk function, $f_4(d_j)$ given by (3) and the dollar value of the design d_j denoted by $f_5(d_j)$. The whole procedure is then repeated for each of the n selected design scenarios of generation and transmission expansion, d_j , $j = 1, \dots, n$. The best design will be the one that minimizes the vector-valued risk-cost function given by (4).

For a large power system, it is a formidable task to evaluate the probability of system failure induced by a fault on every branch of the network. Consequently, a fast screening method must be used to identify beforehand the regions of the network that may include weak links. These regions are those network areas that have the smallest reserve margins in transmission and/or generation. Since the severity of the system failure depends on the load and generation profiles that are considered, a large sample of the system operating conditions have to be investigated. Monte Carlo methods may be used to overcome this problem, especially variance-reduction methods [14]. A general account of these methods is provided by Rubinstein [15].

Thorp et al. [16] advocate the use of importance sampling to identify the weak links of a power transmission network. Marnay and Strauss [17] compare antithetic and stratified sampling when estimating chronological production hourly marginal cost. They recommend the use of a procedure that combines antithetic sampling and proportional stratification; the latter method is being investigated and may be adapted in this effort.

IV. ECONOMIC AND SOCIAL CONSEQUENCES OF POWER SYSTEMS FAILURES

Ultimately the concern for power system functionality stems from the economic and social benefits of service delivery and the desire to avoid losses due to interruption of

service. The value of power system resiliency (or robustness) must be evaluated in terms of both the benefits of services delivered and of the value of losses avoided. Direct losses from power failure can be measured in a straightforward manner and generally accrue to the affected infrastructure. These losses may be private in nature, but sometimes they affect the public sector (as in the case of transportation infrastructure). Indirect losses include disruption of production, losses to firms and households dependent on service, health-related problems and other losses that accrue over time due to disruption of flows of goods and services. Indirect losses tend to be external to the decision structure of the affected utility, with the result that the private decision calculus may largely ignore social costs and benefits. These latter costs must be identified and measured if they are to be internalized by infrastructure providers or incorporated into the disaster planning and management decision process.

Power failure consequence management and recovery time management can significantly reduce indirect losses. Measures to limit the propagation of failure through a power system and the social and economic networks that are linked to it can contribute to the reduction of both direct and indirect losses. Similarly, risk-informed mitigation planning can reduce both the likelihood of loss and the magnitude of any loss that occurs, but it can be made more comprehensive – and therefore more effective – by having better measures of indirect costs of catastrophic failures.

Direct losses can be measured by observation and assessment of damage. Indirect losses require more complex analyses. Indirect losses are increased by a series of economic and social effects that cascade from the loss of infrastructure services. Interruption of supply chains and communication links may transfer the economic and social impact of infrastructure failures far beyond the geographic area of direct impact. Also, valuation of losses (and benefits of service restoration) may differ among social groups and will depend on the degree to which social processes (health care delivery, education, etc.) depend on the service. Thus, valuation of costs from disrupted services must include the effects of a disaster on subjective values of services and the social impacts of their interruption.

Differences in valuation of losses together with the divergence between private and social costs associated with catastrophic infrastructure losses contribute to post-catastrophe recovery plans that differ from recovery following typical loss of services. For example, a typical electric utility will restore service to its customers in the following order of: a) life and safety-related (e.g., hospital, police, and fire facilities), b) emergency communications (e.g., 911 facilities), c) other critical facilities (e.g., water and wastewater facilities), d) then major feeders where the largest number of customers can be brought back at once. It may use the value of its service in terms of price-times-quantity-of-sales as one criterion for service restoration. In the case of a catastrophic loss, public cost considerations may far outweigh the private costs. Crocker et al. [18] present evidence that valuation of benefits from losses depend on the institutional and social

context in which an individual resides, suggesting that standard, non-market valuation techniques can be adopted to examine valuation in the context of a high-impact, low-probability event.

The objectives of the economic portion of this study are:

- 1) To devise a conceptual framework for clearly delineating between and then measuring direct and indirect public and private costs associated with catastrophic losses of critical infrastructure.
- 2) To develop measures of service valuation under catastrophic losses that facilitate understanding of how such valuation diverges from valuation under “normal” circumstances.
- 3) To model and measure cascading economic and social effects from a catastrophic infrastructure loss over sector and space, and to determine methods for estimating vulnerability of different social and economic arrangements to such cascading failure.

The assessment of cascading failures in the infrastructure will provide input to the economic analysis. Economic systems represent networks comprised of sectoral and spatial linkages through markets. Cascading failures of critical infrastructures create similar cascading effects in the economy to the extent that the economy is an extension of the infrastructure network. Results from the analysis of cascading network failures will be used to provide input to a regional and sectoral economic modeling effort. A regional computable general equilibrium (CGE) model will be employed to model spatial and sectoral cascading of different infrastructure losses [19]. CGE models are constructed to represent all supply, demand, and transportation linkages and institutions in a regional economy. They build on a base of inter-firm linkages and incorporate firm and household responses to price and income changes. Regional CGE models can be used to examine linkages between firms and households across two regions and how events in one region cascade into others. See Burniaux and Truong [20] for an application to energy modeling.

A major effort involves identifying activities that are typically not captured in these models. For instance, a typical regional CGE model aggregates energy into an activity or industry. This project will separate different forms of energy and, within the electricity sector, build a module to incorporate generation, transmission and distribution functions. Techniques pioneered in Peterson, et al. [21] are being employed.

Optimal risk management must be based on useful characterization of potential loss, including public losses and accounting for the difference in valuation under catastrophic conditions. In order for decision-makers to understand tradeoffs between risks of loss and costs of protective investments, they must comprehend the full potential for loss. This research will provide tools with which to improve that knowledge.

V. INFRASTRUCTURE VULNERABILITY ASSESSMENT SURVEY FOR THE METROPOLITAN WASHINGTON REGION

The ultimate aim of this work is to provide the conceptual framework for consideration of all approaches to investment in infrastructure security, including risk reduction, disaster mitigation and recovery design. It supports the analysis of competing proposals for vulnerability reduction and it will provide the basis for evaluating investments in critical infrastructure protection, emergency response and restoration strategies.

Specifically, this work defines indirect losses related to specific chains of dependency of infrastructure systems. The primary example will be based on failures of the electric power system of the Washington metropolitan area during Hurricane Isabel, a major natural disaster. On September 18-19, 2003, Isabel came ashore and followed a path through a number of states, including Virginia, Maryland, and the District of Columbia. Areas were without electric service for up to 21 days. Both the electric utilities and various government agencies—federal, state, and local—have collected data on a range of impacts of Isabel.

The research will trace the attributable losses through data collected by public and private surveys and studies funded by government agencies and private utilities. Claims data will also be studied and analyzed. Indirect costs will be tracked forward from initial point of failure through field investigation and through damage claims. This forward tracking of indirect loss is carried out for the purpose of developing the conceptual understanding of indirect loss and tracking system interdependencies. As a future work, the epidemiological communicable disease tracing methodology [22] will be adapted for the case of tracking indirect losses. This is a new approach to valuation of service interruption

The empirical investigation and model validation will utilize the network of established contacts developed during previous and ongoing research projects funded by the Metropolitan Washington Council of Governments (MWCOC) and the U.S. Department of Homeland Security (DHS).

The MWCOC project involved interviewing executives and managers of public and private infrastructure organizations serving the region to document the state of their security programs and changes that had been implemented since the events of September 11, 2001. The MWCOC region includes 17 federal, state, county, and city jurisdictions and the District of Columbia. The project also sampled infrastructure protection programs in metropolitan areas across the country.

Questions asked are related to the following: a) security organization within the organization; b) the areas covered in vulnerability assessments; c) interactions with upstream suppliers and downstream customers; d) interdependencies that were identified; and e) priorities for load shedding and restoration of service.

Phase I of the DHS project is a multi-university effort to examine critical infrastructure protection in the National

Capital Region (NCR is almost identical with the MWCOC area). Personal interviews and review of public records were used to document the impact of Hurricane Isabel on the four infrastructure organizations, both public and private. Over sixty key officials from infrastructure service organizations along with federal, state, and local government officials were interviewed.

Hurricane Isabel's widespread and long-term impacts were examined to determine how both physical and security aspects of each infrastructure fared. Interview questions covered: a) preparations for, operations during, and recovery after the hurricane's passage; b) capabilities and limitations of physical, communications, and control systems; c) adequacy of emergency plans, both government and private; and d) effectiveness of public-private institutional interactions.

Phase II of the DHS project will include evaluation of vulnerability assessment methodologies used by the infrastructure organizations. It will also include the identification of "best practices" used in the assessment activities.

Results from the two studies already completed revealed a near void in the area of identifying interdependencies: among similar utilities, between other infrastructures, and between upstream suppliers and downstream customer organizations. The electric power system is essential to the operation of every other infrastructure facility or service in the region. The prolonged disruption of the electric infrastructure throughout the region after Hurricane Isabel led to a domino-like failure of nearly every regional infrastructure system within a matter of hours or days.

VI. CONCLUSIONS

Planning for electric power reliability and recovery from catastrophic failures also requires knowledge of the interdependencies between electrical systems and the economic and social systems that they serve. To date, however, such planning has been conducted in an atomistic fashion, with little recognition that system interdependencies have major effects on benefits and costs of catastrophic failures. This paper stresses the need to integrate social, economic and engineering modeling in the risk assessment.

We begin with an engineering approach to identify cascading risk within electrical supply systems. The partitioned, multiobjective risk method is extended to account for the risks of cascading failures in interdependent networked systems. Monte Carlo-based variance reduction methods are being explored to assess these risks. Furthermore, we are investigating the effects of specific natural phenomena on different electric utilities and regions of the country. In particular, we investigate the substation design and restoration planning of these utilities.

We use the descriptive information from the engineering analysis of cascading failures to derive an accounting framework for private and social costs (and benefits). The accounting framework will be used to structure the analysis of costs and benefits. Contingent valuation methods together

with subjective risk assessments are being developed to determine and quantify the significance of differences in value of services under catastrophic and non-catastrophic loss scenarios.

A regional computable general equilibrium or CGE model is being developed to analyze the economic impacts of scenarios developed in the engineering analysis. The model will be used to generate real measures of welfare change (equivalent variation) and estimates of costs across sectors and space. The model we develop will be validated through results of the survey carried out for the MWCOG. In addition, utility claims data will be studied and indirect costs tracked forward from an initial point.

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