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Evaluating the Effect of Resource Constraints on Resilience of Bulk Power System with an Electric Power Restoration Model

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Abstract

Although reliability standards for electric power systems are well accepted, methods and metrics are not established for evaluating the effects of large-scale disruptions that exceed N-1 criteria for bulk power systems. This paper introduces a model for simulating restoration of bulk power systems following such disruptions. The model allows analysts to simulate disruption of a bulk power system by designating system components as damaged or nonfunctional. The analyst further defines recovery resource availability and restoration priorities. The model then compares resource requirements to constraints to calculate the timeline of repair completion and the dynamic restoration of power across the network. Resilience metrics quantify the impacts and costs of the disruption to the utility. These quantities enable the analyst to evaluate how proposed system improvements affect restoration and resilience of the bulk power system. The paper concludes with an illustrative case study on a simplified seven-bus system.

Keywords: resilience; reliability; bulk power systems; restoration model

1 Introduction

Critical infrastructure, such as the energy, transportation, and communications sectors, provides essential goods and services and has been described as the "backbone of [a] nation's economy, security, and health" (U.S. Department of Homeland Security 2014). Disruptions to any critical infrastructure, permanent or temporary, can have significant, negative impacts on individuals, communities, economies, and even nations. Consequently, critical infrastructure protection is a vital component of national security activities in countries across the globe.

Historically, critical infrastructure protection activities focused on prevention of disruptive events through implementation of physical protection strategies. Over the past decade, infrastructure security communities realized the impossibility of protecting all infrastructure assets against all threats all of the time, so critical infrastructure owners and operators developed complementary strategies for responding to disruptive events such as hurricanes, earthquakes, and intentional, malicious acts. Consequently, resilience emerged as a complementary objective to prevention goals.

Infrastructure resilience activities have some fundamental differences from physical protection and prevention activities. Whereas physical protection schemes are generally asset-focused schemes aiming to stop a disruption before it occurs, resilience is an inherently systems-level concept focusing on consequence management and recovery actions that occur after a disruption has occurred. Strategies for enhancing infrastructure resilience are often designed to leverage infrastructure connections and dependencies to overcome the effects of disruptions. For example, rerouting in transportation and communication and information systems is possible because of high degrees of system connectivity and redundancy. Network dependencies can also have negative impacts on infrastructure resilience (e.g., cascading blackouts that affect water, manufacturing, and other infrastructure systems that require power), so resilience activities must be designed to account for impacts, as well. Consequently, systems of systems modeling, analysis, and engineering are commonly applied practices for understanding and enhancing critical infrastructure resilience.

The increased emphasis on resilience is seen in policy documents from across the globe. The Homeland Security Advisory Council's (HSAC) Critical Infrastructure Task Force's (CITF) 2006 recommendation that critical infrastructure resilience be a top-level strategic objective for the U.S. Department of Homeland Security kicked off many resilience initiatives and policies in the United States (HSAC, 2006). The recent Presidential Policy Directive 21 (PPD-21) formalized current U.S. policy on infrastructure resilience, establishing resilience to be equally important as infrastructure security (Obama, 2013). In the United Kingdom, the Civil Contingencies Secretariat created a Natural Hazards Team "to establish a cross-sector resilience programme between the government, regulators and industry" and a Critical Infrastructure Resilience Programme (CIRP) to facilitate interactions between those entities (U.K Parliamentary Office of Science and Technology, 2010). In the 2008 National Security Statement to the Parliament, the Australian Prime Minister stated that "a cohesive and resilient society and strong economy" was one of the country's top five security objectives; Australia subsequently developed a Critical Infrastructure Resilience Strategy to define the country's infrastructure resilience policy formally (McClelland, 2010). Canada, Germany, Singapore, and Israel all have similar resilience programs, with Crisis and Risk Network (2011) providing a good summary of resilience programs in these countries.

Although each critical infrastructure sector provides unique and important services, the energy sector is often identified as being "uniquely critical" because all infrastructure sectors strongly rely upon electric power and/or fuels. In particular, disruptions to electric power can have immediate, and sometimes, severe, consequences for the affected population. Power outages can disrupt both business operations and government functions. In the most severe cases, often involving extreme weather events like 2012's Hurricane Sandy and the 2013 blizzard in the northeastern United States, power losses can be detrimental to people's health and safety, resulting in deaths in some cases, as well as damages in the billions of dollars. Hence, electric power sector resilience is often a top concern within the critical infrastructure community.

Electric power utilities have long assessed performance of the electric power grid with reliability metrics. These well-established metrics are used in planning and regulatory activities. Many models and tools are accepted and available for analyzing reliability of power systems. The same is not true for resilience of electrical power systems because resilience is a relatively new concept for infrastructure systems. Reliability metrics and tools are not immediately useful for resilience analyses because reliability metrics and requirements are generally applicable to a limited set of higher probability events. This more limited application may not be appropriate for or currently capable of resilience analysis that includes large regional, lower probability events. Hence, despite the need for electric power resilience analysis methods and tools, few, if any, are available. To date, no resilience analysis method or tool has gained common acceptance by the power industry.

This paper introduces a new model for simulating and analyzing resilience of bulk power systems. The Electric Power Restoration Model (EPRM) is a simulation framework that quantifies the resilience of bulk power systems for various disruptions, recovery sequences, and sets of resource constraints. The EPRM measures resilience by estimating the duration and magnitude of power outages and the cost associated with restoration and recovery activities. These quantities are combined into sets of resilience metrics.

Section 2 of this paper reviews the use of reliability metrics by power utilities. Section 3 describes previous work in the development of infrastructure resilience analysis methods. Section 4 introduces the EPRM and details its resilience metrics, mathematical formulation, and numerical implementation.

Section 5 contains an application of the EPRM to a simple power model, and Section 6 concludes the paper and outlines future research opportunities.

2 Reliability

Bulk power systems (BPSs), defined in this paper as an interconnected electrical power system including generation, transmission, and control components, provide needed power the vast majority of the time. Nevertheless, power disruptions periodically occur. Disruptions may be small or large. The North American Electric Reliability Council (NERC) classifies loss of a generation station without a loss of load to be a Category 1 disruption (NERC, 2012). A Category 5 disruption, the most severe classification, involves loss of generation or load of 10,000 megawatts (MW) or more, a likely occurrence in a major blackout.

Power outages have many causes. Large power disruptions are most frequently caused by weather events (29%), equipment failures (28%), human errors (11%), or some combination of these events (NERC, 2012a, Figure 5). Disruptions may have multiple causes and involve both physical and cyber components. For example, the 2003 blackout in the northeastern United States resulted from both physical equipment failures (overloaded lines sagging into trees, generators tripping due to excess demand) and cyber component failures (failures of the emergency monitoring system to adequately notice conditions and control responses) (U.S.- Canada Power System Outage Task Force, 2004).

Given the many potential events that could cause a power disruption, the major challenge for power providers is the delivery of power in as reliable, safe, and cost-effective manner as possible. Numerous standards and guidelines apply and extend mandatory U.S. Department of Labor Occupation Safety & Health Administration (OSHA) standards to ensure operation and maintenance of electric power equipment is performed safely.[1] Incentives to deliver power as cheaply as possible include both market mechanisms and regulation of utility prices by state public commissions in rate case evaluations. Reliability is considered through the use of systematic operating and planning standards developed by NERC and its ten Regional Reliability Councils (RRCs) that operate in the BPSs. One of the key principles in maintaining reliability is the N-1 criterion. This criterion is embedded in NERC Operating Policy 2.A—Transmission Operations: "All CONTROL AREAS shall operate so that instability, uncontrolled separation, or cascading outages will not occur as a result of the most severe single contingency" (U.S.-Canada Power System Outage Task Force, 2004). Essentially, this requirement means that BPSs must be operated at all times to ensure that the system remains in a stable condition (remains intact) following the loss of the most important generator or transmission facility (worst anticipated contingency) during the most stressed system conditions anticipated (such as winter and summer peak load conditions).

Reliability metrics were developed and are widely accepted for measuring reliability of power systems. For example, the *System Average Interruption Frequency Index* (SAIFI) is a measure of total customer interruptions per customers served, and *System Average Interruption Duration Index* (SAIDI) is a measure of total duration of customer interruptions per customers served (Transmission and Distribution Committee of the IEEE Power Engineering Society, 2004). These and other indices provide independent objective methods for evaluating and comparing the reliability of different power providers, which can inform economic and regulatory decisions.

Power providers have several tools for analyzing the reliability of their systems. They can use offline system studies, such as power flow and transient stability studies, to anticipate and plan for systems to

[1] See the OSHA website (www.osha.gov/SLTC/electrical/) for details on Federal and State electric standards.

withstand worst-case scenarios and still maintain reliable power service by determining response actions necessary if such events occur (Dorf, 1997). These techniques are typically used for planning purposes. Online techniques, such as power system state estimation, gather current power system data in real time and then assess how stressed the system is and whether the system is nearing a condition that will result in an outage (Tinney et al., 1970; Schweppe and Rom, 1970). The combination of reliability standards, metrics, and offline and online power system studies greatly enhances power system reliability.

Power providers generally focus reliability analyses and efforts on N-1 contingencies. The rationale for this focus is three-fold. First, N-1 reliability is an operational requirement that power providers must demonstrate to regulatory entities. Second, by focusing on N-1 contingencies, power providers are planning for the most likely events because the probability that an N-1 contingency will occur is higher than the probability that an N-k contingency, k>1, will occur. Finally, the set of N-k contingencies is prohibitively large, and planning for every possible contingency would exhaust resources and significantly increase operating costs. Consequently, utilities and power providers have less understanding of potential impacts of large-scale disruptions and best practices for addressing these disruptions.

Still, additional mechanisms and policies have been have been put in place to address N-k contingencies. These policies come under the heading of power system restoration. NERC tasks its RRCs with developing power system restoration guidelines and policies with which each provider serving within an RRC region must comply. For example, the Western Electricity Coordinating Council (WECC) RRC uses a document entitled WECC Power System Restoration (WECC, 2009) to provide overall guidelines for power providers under its jurisdiction to develop specific restoration plans for their specific power systems. The guidelines specify the responsibilities involved with power restoration, specific considerations involved in restoration, and coordination of restoration with RCCs and other utilities, as well as identifying conditions requiring restoration without proscribing how a particular restoration plan should be developed. Restoration plans often make use of detailed information on equipment constraints to avoid damaging equipment or initiating further delays due to improper operations during the restoration process (Adibi, 2008). In general, restoration is planned to occur in stages, with care being taken to ensure the power system is not further damaged or disrupted during the restoration process (Adibi and Martins, 2008).

A large body of technical literature is devoted to many different aspects of power restoration. A collection of relevant papers discuss defining the power restoration problem, restoration techniques, training, case studies, and specific system equipment restoration issues (such as generators, transmission lines, transformers, etc.), as well as current and novel tools and techniques to address power restoration (Adibi, 2000). Adibi and Martins (2008) provide an excellent overview of major power restoration issues.

3. A New Emphasis on Resilience

Although the concept of resilience is relatively new to the critical infrastructure community, it has been studied and researched for several decades in other contexts. Material scientists defined resilience as a thermodynamic property of solid materials more than 100 years ago (Trautwine, 1907; Park et al., 2013). Holling is widely credited with introducing the concept into complex systems studies in 1973, when he wrote about resilience for ecological systems. Over the following four decades, resilience research has spread far beyond these initial areas of study, with infrastructure security becoming one of the current major areas of application.

Although consensus has not been reached on a precise definition of infrastructure resilience, there is general agreement that infrastructure resilience is related to the infrastructure's ability to absorb, adapt, and/or recover quickly and efficiently from disruptive events so that it can continue to provide goods and services. Methods and metrics were developed for analyzing and measuring resilience. Madni and Jackson's (2009), Park et al.'s, and Vugrin and Camphouse's (2011) works are generally applicable to complex systems. Many techniques were developed for specific systems of application. Rose (2007) led much of the resilience research for economic applications. The Multidisciplinary Center for Earthquake Engineering Research (MCEER) focused on the development of technologies to make communities more resilient to earthquake events (Bruneau et al., 2003). Fiksel (2006) developed a systems-based approach for examining the resilience and sustainability of industrial, social, and ecological systems, and with the increasing concerns about cyber security, cyber resilience has become an area of active research (Bodeau and Graubart, 2011; Goldman, 2010).

Recent efforts sought to characterize and promote resilience of the electric power grid. These efforts considered different techniques for improving grid resilience. For example, the Electric Power Research Institute (EPRI) states that resilience of distribution systems is composed of three elements: prevention, recovery, and survivability (McGranaghan et al., 2013). EPRI suggests a number of current practices (e.g., vegetation management) and new technologies (e.g., unmanned aerial vehicles to conduct airborne damage assessments) for use to improve resilience of electric power distribution systems. The Trustworthy Cyber Infrastructure for the Power Grid (TCIPG) Center's resilience efforts primarily focused on improving resilience of cyber components of the grid (Sanders, 2010; Sanders, 2013). Many researchers focused on how smart grid technologies could beneficially as well as negatively affect resilience (e.g., Dagle, 2013; Ouyang and Dueñas-Osorio, 2011; Al Majali et al., 2012; Sridhar et al., 2012; and Intergraph, 2010).

Vugrin et al. (2010, 2011) showed that resource constraints and prioritization of recovery activities can affect recovery and resilience of transportation networks. This conclusion is also true for electrical power systems. Regional disruptions caused by hurricanes, earthquakes, and other events that overwhelm contingencies designed for N-1 events can easily damage dozens of grid components. Utilities will likely be resource-constrained, requiring effective prioritization of recovery activities. Due to the magnitude of these events, reliability models are not entirely sufficient for performing power restoration, prioritization, and resilience analyses. The following section introduces a new model to identify how resource constraints and recovery activity prioritization affect resilience of BPSs.

4. A Model for Resilience Analysis of Bulk Power Systems

This section describes a new model to evaluate how prioritization of recovery tasks and recovery resource constraints affect resilience of BPSs and their restoration following a disruption. The section first describes the general scenario that the EPRM simulates and concludes with a description of the conceptual model and its software implementation.

4.1 Scenario Description

The scenario under consideration is a disruptive event that exceeds the N-1 scenario definition; e.g., a hurricane, earthquake, or another event occurs that physically compromises the functionality of several components of a BPS. These components could be generators, transmission lines, substations, transformers, or other equipment contributing to the overall performance of the BPS. Multiple components are assumed compromised, as is true in major power disruptions.

The initial physical insult can lead to cascading failures that affect the functionality. Tripped circuits and line failures are examples of cascading failures. This equipment damage is indirectly caused by the initiating event. Complete restoration of the bulk power system cannot occur until these failures are repaired.

Upon recognition of the disruption, the utility may take actions to limit the cascading failures. Grid separation, or islanding, is an example of a proactive measure that a utility might take. Load shedding − i.e., purposefully reducing power delivery to certain loads − is another example. Other mitigation responses may be automated. The result of these actions is that the system is stabilized and further system damage is prevented.

Given that multiple BPS components are compromised and resources are likely limited, the utility must prioritize repair activities. Repair crews are dispatched to assess damage and to initiate repairs. Equipment must be repaired and then re-energized to restore functionality. Prior to the disruption, utilities generally identify priority loads or load centers. Restoration sequences for loads are typically determined by these priorities and by resource constraints.

Once physical damage to a component is repaired, the component will be energized only if it can be done safely and can be stably inserted into the BPS without affecting other components. If additional damage will occur, the utility will wait until additional repairs are completed or the component can be inserted into the BPS without introducing stability issues.

4.2 Model Description

The EPRM is a rule-based simulation framework that enables an analyst to simulate disruption to a specified BPS network and then investigate how priorities and resource availability affect power restoration. The EPRM is composed of the following submodels (Figure 1):

- **Network configuration:** The first step in the simulation process is defining the BPS and characterizing its subcomponents.

- **Damage specification:** In the next step, the analyst identifies which BPS components have been damaged and the degree of damage sustained.

- **Resource configuration:** The analyst can specify resource availability and the costs associated with resource usage (e.g., cost of labor and replacement parts).

- **Load prioritization:** In the event that the BPS is not able to provide enough power to satisfy all load demand, the analyst can specify load priorities that determine which loads will not receive their demand requirements until higher priority loads are met.

- **Recovery task scheduling:** The model compares recovery task resource requirements with resource availability and recovery priorities to determine the sequence for repairs.

- **Dynamic power flow restoration:** After each component is repaired, EPRM uses the PowerWorld™ Simulator to solve power flow equations that describe flow of power across the BPS network, as well as allowing only stable transitions during repair stages.

- **Resilience metric calculations:** The EPRM uses Vugrin et al.'s (2011) systemic impact and total recovery effort metrics to quantify resilience of the BPS under the specified recovery task priority and resource configuration.

The EPRM consists of a Java graphical user interface that runs in conjunction with the PowerWorld™ Simulator. The developers selected the PowerWorld™ Simulator because of its widespread use and acceptance by utilities, its relative ease of application, and the developers' familiarity with the simulator. The conceptual model, as described below, can be applied to a different power flow simulation program to create a similar but different capability.

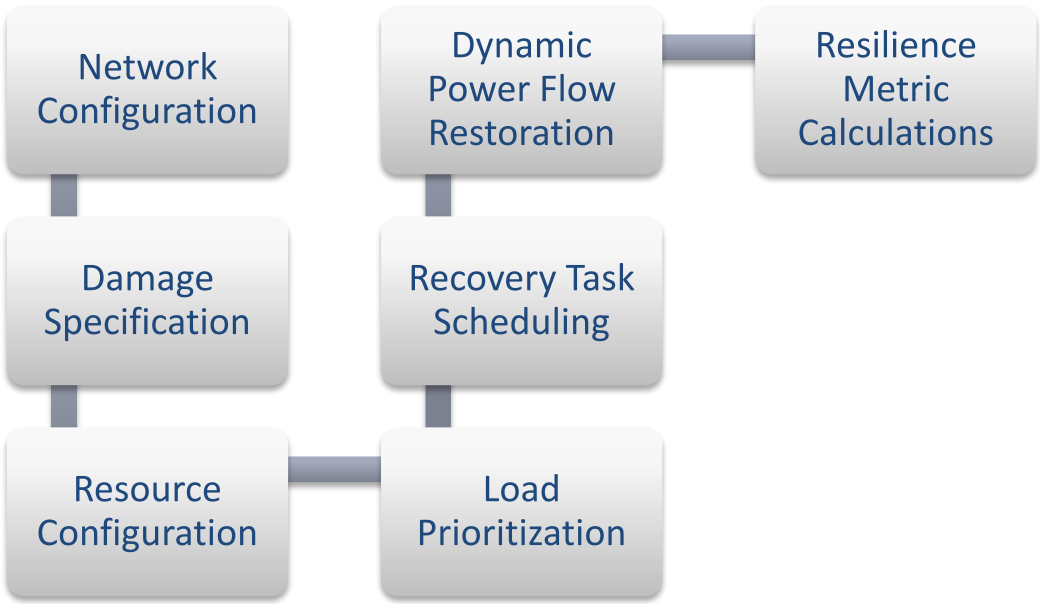

Figure 1: Electric Power Restoration Model Diagram

4.2.1 Network Configuration

The first step in the EPRM model is the identification of the BPS system and the system specifications. BPS components may include generators, buses, transmission lines (branches in the PowerWorld™ nomenclature), and loads. The EPRM initializes the BPS specifications by reading from a PowerWorld™ Simulator case file. The case file further indicates component connections, component capacities, and other information required to characterize the BPS. The sample test case and subsequent evaluation by the EPRM illustrates how these components are integrated by the EPRM.

4.2.2 Damage Specification

Once the BPS network configuration is described, an analyst can define a disruption to the system by specifying damaged components and the degrees of damage (heavy, moderate, or light). Specifying a component as damaged renders the component nonfunctional in the simulation until the component is repaired. Each component-damage level combination determines a repair sequence: i.e., a set of tasks that must be completed to restore the component to a functional state. For example, the default tasking for a branch that suffers light damage includes:

1. Damage assessment that requires a two-person line repair crew, no additional equipment, and three hours for completion.

2. Pole repair that requires a four-person line repair crew, one pole, and eight hours for completion.

3. Line repair that requires a four-person line repair crew, line, and eight hours for completion.

4. Insulator repair that requires a ten-person line repair crew, four insulators, and four hours for completion.

The default repair sequence for a branch that suffers moderate/heavy damage has the same tasks and set of personnel requirements, but equipment and time requirements are double or triple the light damage requirements. Repair sequences for different component and damage-level combinations may vary by the number and type of personnel requirements, number and type of equipment requirements, and time requirements. Appendix 1 lists the personnel, equipment, and time requirements for all default component and damage-level combination requirements. The EPRM contains default values for all possible repair sequences, but the model also allows the analyst to customize the sequences by adding and/or changing repair tasks and their associated personnel, equipment, and time requirements.

The damage specification module also allows the analyst to specify component restoration priorities. Damaged components are ranked 1, 2, … with a lower rank indicating a higher priority for repair. This ranking is a key input for recovery task scheduling.

4.2.3 Resource Configuration

In the resource configuration module, the analyst specifies resource availabilities and costs. Two types of resources are considered in the model: personnel and parts. The personnel resource represents different work groups (e.g., bucket truck teams, generator teams, etc.) available to repair a component. The parts resource represents the parts of a component needed to repair that component (e.g., poles, lines, capacitors, transformers, etc.). Available quantities, time required to order and receive additional parts, and costs are configurable for each simulation.

Default personnel categories include generator, bus, branch, and load repair personnel. The analyst specifies the number of personnel available in each category and the hourly labor rate for each personnel category. Similarly, the resource configuration module lists total number of equipment parts required to complete all repair tasks, the quantity of replacement parts that are immediately available for use, the length of time required to receive additional parts that must be ordered, and the cost of each part. Appendix 1 lists the default categories of equipment parts included in the EPRM. If the analyst adds additional repair tasks requiring different personnel types or equipment part types in the damage specification module, these custom categories are automatically added in the resource configuration module. The analyst has the flexibility to use default values for availability, costs, and shipping time for personnel and parts.

These default values are used to demonstrate how the EPRM works and are not intended to represent actual repair stages, damages, resource requirements, and costs. Actual values would be supplied by the utility based upon its system, resources, and background data.

4.2.4 Load Prioritization

In the event that the utility cannot meet power demand, the analyst specifies load priorities to determine load shedding. The lowest priority load will be shed first when there is a loss of generation, the second lowest priority load will be next to be shed, and so on until the power delivered is equal to the demand from the remaining loads. If the analyst chooses, multiple loads can be assigned the same priority ranking, and these loads will have the same reduction in power (measured in megawatts) in the model.

Additionally, this module allows the specification of the excess generation parameter. This parameter determines the generator capacity utilization rate: i.e., the amount of excess generation in the system at the time of the disruption. This parameter enables modeling of BPSs at or near peak load demand conditions.

4.2.5 Recovery Task Scheduling

The previously described EPRM modules establish system and scenario parameters for the analysis. The remaining modules perform a series of calculations to describe the dynamics of the power restoration process and the resilience of the BPS.

Figure 2 illustrates the recovery task scheduling module. This module creates resource pools and resource managers for each personnel and part resource category defined by the user. The number of personnel in each personnel resource category is fixed, and the personnel resource manager dispatches personnel to sequenced recovery activities. Part resources are managed by a resource manager that evaluates inventory levels, places orders for parts, and updates the resource pools when the orders arrive.

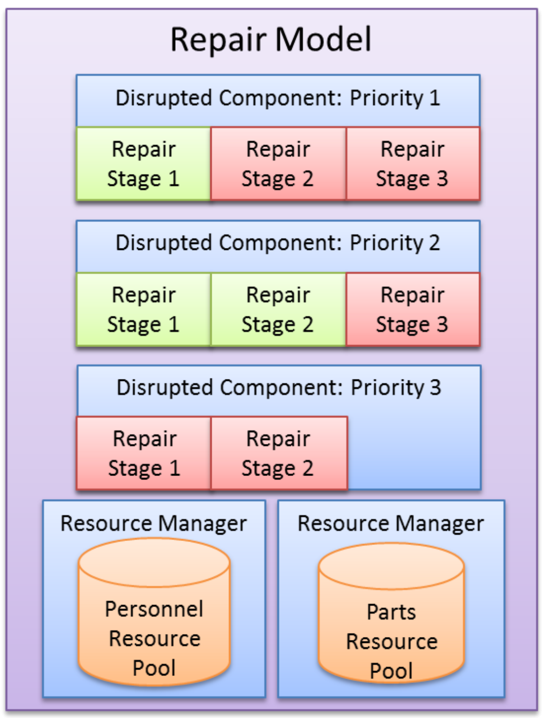

Figure 2: Diagram of EPRM's Repair Model

The recovery task scheduling module is a time-stepped model that evaluates resource-pool levels and repair statuses of components at each time-step. Disrupted components are assigned a priority level in the damage specification module and contain one or more repair stages. The repair model loops over all the disrupted components starting with the highest priority component. If that component currently is not being repaired , the module queries the pool of available resources to determine whether enough resources (personnel and parts) are available to proceed with the next repair stage for the component. If enough resources are available, work can start on that repair stage for the component and the resource managers are notified that the personnel will be unavailable for the duration of the repair stage and the parts used will be subtracted from inventory levels. If parts resources are not available, the resource pool is replenished representing a parts resource manager ordering additional parts, if they have not already been ordered. The recovery task scheduling module loops over each disrupted component until there are no more resources available. This process is repeated at each time-step for each component (that is not currently being repaired) until the module has identified the repair start and end times time for all disrupted components. Key outputs from this step include:

- Times at which repairs are completed for each disrupted component.
- Number of parts used in repair activities.
- Labor hours worked by personnel for repair activities.

4.2.6 Dynamic Power Flow Restoration

The dynamic power flow restoration model uses the repair completion times from the recovery task scheduling module to calculate power flow during each load restoration stage of the recovery process. The completion of a component repair establishes a different damage state for the BPS because a disrupted component will be nonfunctional prior to its repair completion and functional following the completion. Changes in damage states can potentially change power flows across the BPS.

The EPRM uses the PowerWorld™ Simulator to estimate power flow across a BPS for a specified network configuration. PowerWorld™ Simulator (www.powerworld.com) is a commercial power flow software package that simulates high-voltage BPS operation. In the simulator, the user builds a model of the BPS and specifies the underlying electrical parameters associated with each system component (generators, transmission lines, transformers, loads, etc.) connected according to the system topology with specified initial generator output values and load values. The EPRM interfaces with the PowerWorld™ Simulator by reading PowerWorld™ Simulator case files that describe a BPS and using the PowerWorld™ Simulator's Optimal Power Flow Analysis Tool to determine power flow during each stage of the restoration process. PowerWorld™ Simulator primarily operates as a standard power flow model to balance power flows between generators and loads by considering the parameters of the system, such as generator and transmission line ratings and their limits as well as the initial conditions of the system.

With this understanding, the power flow calculations proceed in the following manner:

1. Assume N components are damaged in the disruption scenario.

2. Let times t0, t1, …, tN define the times (restoration stages) at which repairs to the damaged components are completed. These times are determined in the recovery task scheduling module. (Time t0 indicates the time that the disruption occurs and none of the damaged components are functional.)

3. Execute the PowerWorld™ Simulator for the damage state at time t0 to determine power flows across the network in this damage state configuration. The simulator performs the following steps to make the determination:

    a. Assume power flows are constant across the network for times $t0 \leq t < t1$.

    b. At time t1, assume the first component repair (as determined by the recovery task scheduling module) is completed. The PowerWorld™ Simulator then determines whether energizing the repaired component will destabilize the BPS and lead to additional failures.

c. If destabilization will not occur, the PowerWorld™ Simulator calculates power flows under the assumption the first component is repaired and energized. Assume these power flows are constant for times $t1 \le t < t2$.

d. If destabilization will occur, assume the component is repaired but not energized. Furthermore, assume power flows for time t0 continue until t2.

4. Repeat steps 2 and 3 until all repairs have been completed (through time tN). When checking for destabilization, assume all components that have been repaired in the previous and current time steps are energized.

Completion of these steps produces estimates of power provided to each load customer.

4.2.7 Metrics

In addition to estimating power flows across the BPS during the recovery period, the EPRM calculates a set of network metrics that can be used to assess the resilience of the BPS to the specified disruption scenario. The EPRM adapts the general infrastructure resilience metrics originally proposed by Vugrin et al. (2011) and customizes them for BPSs. These metrics include Systemic Impact (*SI*), Total Recovery Effort (*TRE*), and the Recovery Dependent Resilience (*RDR*) index.

For general infrastructure systems, Vugrin et al. (2011) define *SI* as the cumulative consequences resulting from a system's decreased performance following a disruption. The EPRM uses peak load delivery as the primary performance metric. The *SI* quantity ultimately converts load not delivered into monetary terms that represent the utility's lost revenue.

Vugrin et al. (2011) further define *TRE* to be the cumulative resources expended during the recovery process that follows a disruption. Resources can include labor, equipment, and other cost categories. Additionally, *TRE* can include the cost of adaptations that the infrastructure may make to continue to deliver services and goods during the recovery period. EPRM calculates a *TRE* quantity that includes the cost of labor, the cost of replacement parts, and the additional power generation costs that may occur from operating the BPS in a degraded state. Generally, BPSs are run in a manner that minimizes the cost of power generation. If a disruption damages one or more generators or segregates a portion of the system from one or multiple generators, the BPS may need to adapt by generating power in a manner that is more costly (compared to the status quo) in order to provide power to all of its customers. The EPRM's *TRE* quantity term sums the additional generation costs with the costs of labor and replacement parts.

Vugrin et al. (2011) combine the *SI* and *TRE* terms into the *RDR* index. The EPRM performs that same calculation, so the *RDR* term represents the total consequences of the disruption to the utility. Consequently, lower *RDR* values indicate higher levels of resilience and vice versa. The EPRM calculates the *SI*, *TRE*, and *RDR* quantities in the following manner:

$$SI = \sum_t \sum_j c_j \left(PL_j^U - PL_{j,t}^D \right) \Delta t$$

$$TRE = \sum_t \left\{ \left(\sum_i LC_i \times pers_{i,t} \right) + \left(\sum_k EC_k \times part_{k,t} \right) + \left(\sum_m \left[OC_{m,t} - OC_{m,U} \right] \times pow_{m,t} \Delta t \right) \right\}$$

$$RDR = \frac{SI + \alpha \times TRE}{\sum_{t} \sum_{j} c_j \left(PL_j^U \right) \Delta t}$$

where

- PL_j^U is the peak load under undisrupted conditions for the j^{th} load.
- $PL_{j,t}^D$ is the peak load after the t^{th} recovery step is completed for the j^{th} load.
- Δt is the duration of the t^{th} step: i.e, time t minus time $t-1$.
- c_j is a weighting factor for the j^{th} load that establishes priority loads. A load that is higher priority will have a larger weighting factor than a load with lower priority.
- LC_i is the hourly labor cost for personnel in category i.
- $pers_{i,t}$ is the number of labor hours worked by personnel in category i during the t^{th} repair time step.
- EC_k is the unit cost of a replacement part in category k.
- $part_{k,t}$ is the quantity of replacement parts in category k used in the t^{th} repair time step.
- $OC_{m,U}$ is the hourly operating cost for generator m under undisturbed conditions.
- $OC_{m,t}$ is the hourly operating cost for generator m during the t^{th} time step.
- $pow_{m,t}$ is the power generated per hour (kw/hr) by generator m during the t^{th} time step.
- The RDR denominator is a normalization term that scales the RDR index by the size of the BPS. Additionally, α is a weighting factor that the analyst specifies to indicate the relative importance of continuing to deliver power versus conserving recovery resources. If load delivery is more important, α should be less than 1. If conserving resources is more important, α should be greater than 1. Setting α to 1 indicates both factors have equal importance.

Because RDR values are unitless, they are most informative in a comparative sense. That is, *RDR* values can be used to determine if one BPS is more resilient to a disruption than another relatively comparable BPS, if a BPS is more resilient to one category or type of disruption than another, or if one set of restoration priorities results in a faster, cheaper recovery and therefore more resilient BPS.

5 Illustrative Restoration Example

5.1 Scenario Definition

This section demonstrates application of the EPRM model to a simple 7-bus system, shown in Figure 3.[2] This system represents a simplified power system with buses located in three areas (top, left, and right) with different amounts of generation and loads at the various buses distributing power between each through interconnecting transmission lines. In the PowerWorld™ Simulator, an area represents a region in which different utilities can trade generation using automatic generation controls. The 7-bus case file is configured to use the PowerWorld™ Simulator optimal power flow algorithm to dispatch power optimally from the generators with the lowest cost that also will meet load and transmission requirements. By utilizing different areas, the test case can model power interchanges and associated costs between

[2] The PowerWorld™ case file for this system comes with the PowerWorld™ Simulator and is designated as the 7BusOPF case.

regions to model other factors in power systems, such as power purchases between utilities. The generator outputs will vary as costs change and as loads at various buses change.

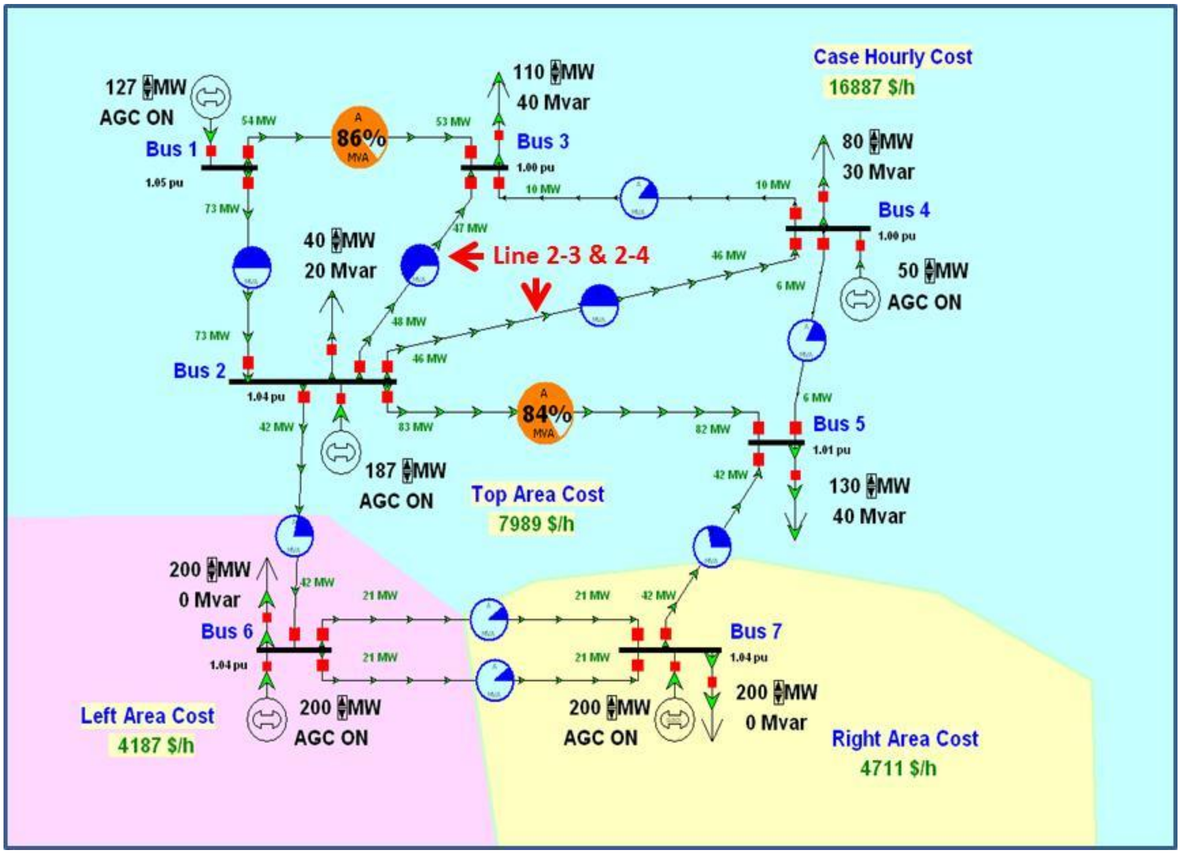

Figure 3: PowerWorld™ Simulator 7-Bus System

The following assumptions are made to represent the disruption scenario:

- Power lines between Bus 2 and Bus 3 (Line 2-3) and between Bus 2 and Bus 4 (Line 2-4) are simultaneously disrupted (see Figure 3, red arrows), along with the generator (Generator 4) feeding Bus 4, and designated as nonfunctional. This scenario represents two lines becoming damaged due to a weather event or any combination of the power outage causes described previously (Section 1). The scenario further assumes significant damage to downstream equipment connected to Bus 3 and 4 (Load 3 and Load 4) due to a combination of high current and voltage and frequency perturbations acting on these loads.

- Any additional lines that would subsequently exceed 150% of rated power flow[3] as a result of damage to aforementioned lines and loads are assumed to be disrupted and nonfunctional, as well.

[3] Power lines usually have a withstand limit that permits them to be temporarily loaded above their rated limits for short periods (e.g., <150% line rating for ~0.5 - 2 hours), according to criteria developed by the utility/regulatory body to allow power lines to be temporarily overloaded. As long as these temporary limits do not exceed physical limits, such as thermal ratings of lines, or cause stability issues on the system, they are allowed. Withstand limits allow utilities to extend the operation of their systems without incurring additional outages during stressed situations during peak system load conditions or after the loss of adjacent lines or equipment. The temporary

Lines 1-3, 2-5, and 4-5 are assumed to be nonfunctional because they exceed the 150% threshold. In total, five lines, two buses, and one generator are assumed to be damaged and nonfunctional (Figure 4). In effect part of the system has been islanded and incurred a blackout. Power flow between Bus 2 and Bus 6 (Line 2-6) is stressed (105%) but able to sustain loads according to the overload criteria used. This example illustrates that the loss of two or more major pieces of equipment (beyond N-1 conditions) can lead to a cascade with further system degradation and loss of equipment until the new system conditions can stabilize.

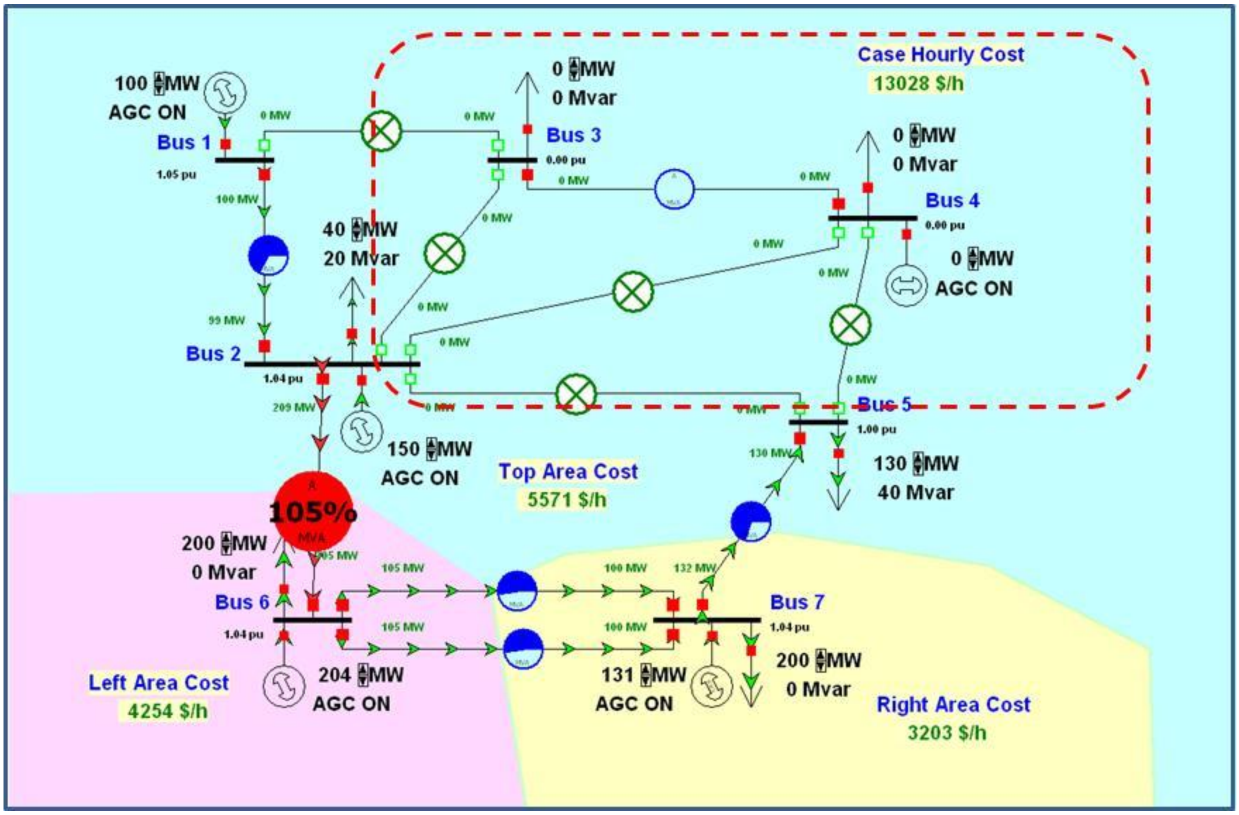

Figure 4: Seven-bus System in the Fully Disrupted State

In addition to the line criteria (i.e., lines may not exceed 150% of their load rating), analysts imposed the following restoration requirements:

- Generator megawatt (MW) and megavolt amperes reactive (MVAR) output ratings cannot be exceeded.
- Voltages at buses must be maintained within a certain range (e.g., between 0.95 and 1.05 per unit).
- Frequency oscillations must be minimized to prevent over/under frequency trips of generators and lines.

excess allows more time for control measures to be taken to relieve the stress. For this test case, analysts allowed lines to be temporarily overloaded provided they don't exceed 150% of rating.

- Special considerations occur during the restoration process. These considerations include overvoltages, which can occur when power lines are energized from unloaded (or severely underloaded) buses; load rejection, in which load inrush increases proportional to the time of an outage (for example, due to coincident startup of air conditioning units on a hot day); and many other particular considerations to ensure that voltage and frequency oscillations do not occur during the restoration process.

None of these criteria may be violated during the restoration process. These criteria are evaluated in the dynamic load restoration calculations described in Subsection 4.2.6 to assess whether a component should be energized or not.

Table 1 shows the components that are assumed to be damaged in this scenario, their damage level, and their priority for restoration as they are input into the EPRM for this scenario. The branches initially affected (2-3 and 2-4) are assumed to have sustained heavy damage levels and the subsequently affected branches (1-3 and 4-5) are assumed to have light damage. Tables A-2 and A-3 in Appendix A lists availability and requirements for personnel and equipment. Additional model parameters are also listed in Appendix 1.

Table 1: Scenario Damage Specifications

Priority	Component	Damage Level
1	Load 3	Heavy
2	Load 4	Heavy
3	Gen 4	Light
4	Branch 1-3	Light
5	Branch 2-3	Heavy
6	Branch 2-4	Heavy
7	Branch 2-5	Light
8	Branch 4-5	Light

5.2 Results

Table 2 lists the times at which repairs are completed. The generator (Gen 4) is the first component to be repaired (after 22 hours), followed shortly after by repairs of branches 1-3 and 3-4. These components are only the third, fourth, and seventh priorities, but they are completed first because the parts are immediately available and personnel are available to start their repairs immediately according to the model. Repairs begin immediately for Load 3, the top priority, but the load is not completely repaired until thirty-three hours, because repair of the heavy damage takes more time than the repairs for the generator and lightly damaged branches. Aggregate power is fully restored when Load 4 is repaired, after 134 hours, but repairs are not fully completed until 596 hours. Repair of the branches is delayed because the repairs require more insulators, towers/poles, and overhead line than the utility has on hand in this model. Hence, repairs cannot be completed until these additional parts are ordered and received.

Table 2: Repair Completion Sequence and Times

Priority	Component	Completion Time (hours after disruption)
3	Gen 4	22
4	Branch 1-3	24
7	Branch 3-4	28
1	Load 3	33
2	Load 4	134
8	Branch 4-5	144
5	Branch 2-3	356
6	Branch 2-4	596

Figure 5 displays total power delivered following the disruption. Immediately following the disruption, the BPS can provide only 520 MW, compared to the nominal load of 760 MW for the entire system. Repair of the generator after 22 hours increases the power provided to 570 MW, and it is further increased to 680 MW at 33 hours after two branches and Load 3 are repaired. Personnel constraints prevent starting repairs to Load 4 until repairs to Load 3 are finished. Hence, power is fully restored only after 134 hours when Load 4 is completely repaired. Parts and personnel constraints cause the delays for repairing all of the branches.

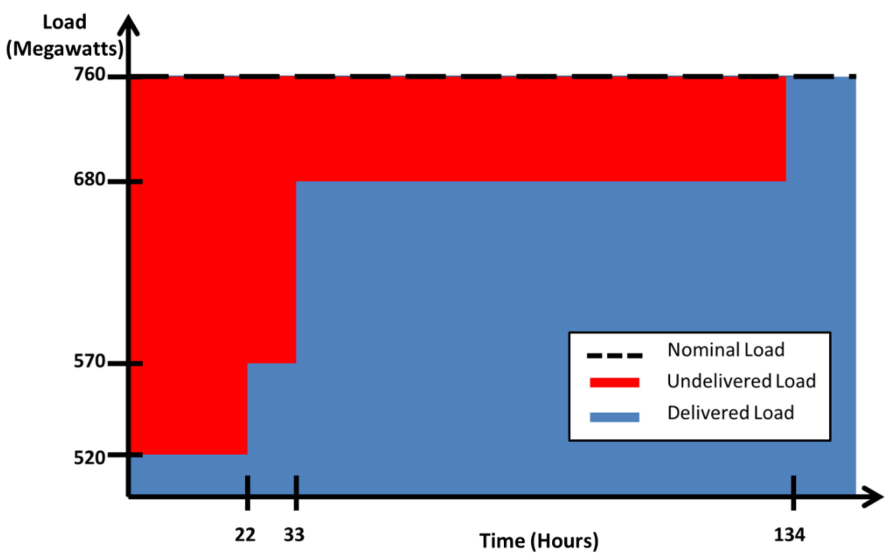

Figure 5: Restoration of Aggregate Load

Disruption costs are summarized in Table 3. Labor costs exceed $300k, and replacement parts cost almost $150k. The additional generation costs are almost $100k. Hence, TRE, the cost of repairing and adapting to the disruption, is approximately $550k. SI, revenue lost as a result of the disruption, is calculated to be approximately $410k, so the cumulative impact of the disruption to the utility is estimated to be approximately $970k.

Table 3: Disruption Costs: Summary Statistics

Time Until System Restoration (Hours)	596
Cost for personnel	$310,000
Cost for parts	$150,000
Additional Generation Costs	$100,000
TRE	$560,000
SI	$410,000
Total Costs	$970,000

The EPRM can be used to estimate how changes to the BPS can reduce the impact of a disruption and the overall costs to the utility. For example, in the disruption scenario, the quantity of insulators, towers/poles, and overhead line the utility keeps on hand is a limiting constraint. Consequently, repairs to the branches are delayed because the utility must wait to complete the repairs while additional quantities are ordered and delivered. To analyze the effect that the equipment shortage has on the BPS, the disruption scenario can be rerun with increased inventory levels for insulators, towers/poles, and overhead line.

Figure 6 shows total load restoration for the revised scenario. Load is fully restored after eighty-two hours, more than two days faster than in the initial scenario (Table 4). Repairs are completed in ninety hours, more than twenty days faster than estimates for the resource-constrained scenario. Having additional parts in inventory also significantly reduces costs to the utility. *SI* is reduced from $410k to $370k. Labor and parts costs are the same, but the additional generating costs decrease from $100k to $40k. Overall, costs to the utility decrease by approximately $100k, more than a 10% reduction.

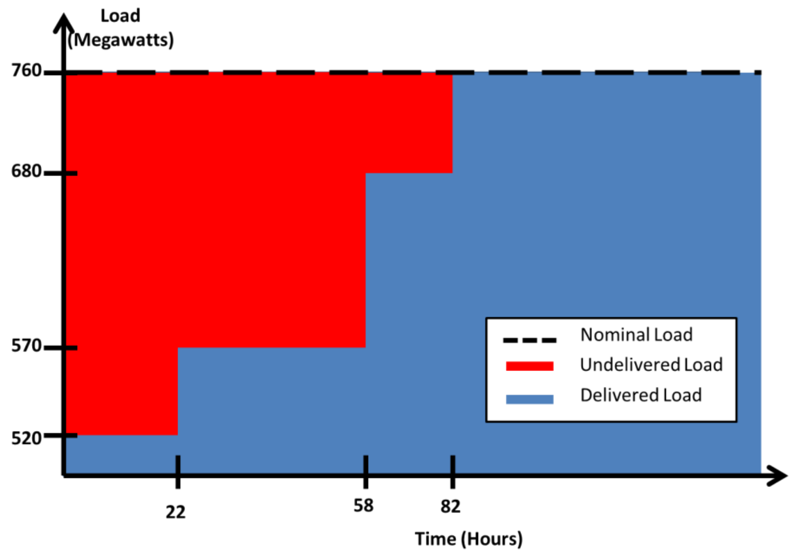

Figure 6: Restoration of Aggregate Load with Increased Availability of Replacement Parts

Table 4: Disruption Costs: Summary Statistics

Time Until System Restoration (Hours)	90
Cost for personnel	$308,000
Cost for parts	$146,000
Additional Generation Costs	$36,000
TRE	$490,000
SI	$370,000
Total Costs	$860,000

6 Summary and Opportunities

This paper introduces the EPRM, a new simulation tool that can be used in the context of recovery planning for BPSs experiencing disruptions that exceed N-1 criteria. The EPRM enables an analyst to describe the configuration of the BPS of concern, simulate a disruption to that BPS, establish restoration priorities, configure recovery resource availability, and evaluate how priorities and resource availability affect recovery duration, recovery costs, and ultimately, the resilience of the BPS. This capability is intended to complement well-established metrics associated with power reliability. Designing and managing power systems that maintain N-1 criteria reliability is, and will continue to be, a critical issue for the foreseeable future. The EPRM provides a complementary capability to analyze scenarios that exceed N-1 criteria.

For illustrative purposes, the paper presents a simplified scenario with a 7-bus system to demonstrate application of the EPRM. The EPRM can be used with a larger system model and more detailed repair stages to assess the potential impact of disruption scenarios in larger systems, as well as the impacts when different priorities are assigned to the system components, to estimate the impact of particular disruptions in terms of time to restore loads, costs, and the systemic impact of the disruption.

The EPRM shows promise for use as a planning tool, to evaluate the overall resilience of the system, and to guide improvements in system resilience. A generic set of steps to perform these tasks includes:

- Perform a set of case studies to evaluate resilience of the system to various disruptions.
- Collate studies to evaluate the overall resilience of the system.
- Propose and evaluate how system improvements can increase the resilience of the system in terms of benefits and cost. Proposals can include both improvements, which make a system less likely to undergo a disruption (e.g. system infrastructure improvements), or more efficient responses to disruptions, which limit the outage times and costs associated with disruptions.

Application of these steps to a BPS could provide a utility with a better overall understanding of the resilience of the BPS and how to improve upon it.

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Appendix 1 – Default EPRM Parameters

Table A-1: Default Repair Stages

Damage Level	Stage	Number of Personnel	Part	Quantity	Time (hours)
Generator					
Light	1	3	None	0	2
	2	3	None	0	20
Moderate	1	6	None	0	4
	2	6	None	0	40
Heavy	1	9	None	0	6
	2	9	None	0	60
Bus					
Light	1	5	None	0	1
	2	3	Relay	2	10
	3	3	Capacitor	2	10
Moderate	1	10	None	0	2
	2	6	Relay	4	20
	3	6	Capacitor	4	20
Heavy	1	15	None	0	3
	2	9	Relay	6	30
	3	9	Capacitor	6	30
Load					
Light	1	2	None	0	1
	2	2	Overhead Line	1	10
Moderate	1	4	None	0	2
	2	4	Overhead Line	2	20
Heavy	1	4	None	0	2
	2	4	Overhead Line	2	20
Branch					

Damage Level	Stage	Number of Personnel	Part	Quantity	Time (hours)
Light	1	2	None	0	3
	2	4	Tower/Pole	1	8
	3	4	Line	1	9
	4	10	Insulator	4	4
Moderate	1	4	None	0	8
	2	8	Tower/Pole	2	16
	3	8	Line	2	18
	4	20	Insulator	8	8
Heavy	1	6	None	0	9
	2	12	Tower/Pole	3	24
	3	12	Line	3	27
	4	30	Insulator	12	12

Table A-2: Default values for personnel resources

Type	Available Personnel	Cost per hour
Generator	12	$340
Bus	10	$275
Branch	12	$210
Load	10	$190

Table A-3: Default values for parts resources

Component Type	Part	Number Available	Reorder Time (Hours)	Cost
Bus	Relay	5	40	$1,500
Bus	Cb	3	100	$10,000
Bus	Capacitor	2	150	$25,000
Bus	Transformer	1	10000	$100,000
Bus	Pt/Ct	1	1200	$40,000
Bus	Microwave/Communications	1	1200	$40,000
Branch	Line	4	60	$7,000
Branch	Tower/Pole	2	120	$5,000
Branch	Insulator	10	50	$400

Component Type	Part	Number Available	Reorder Time (Hours)	Cost
Load	Transformer	2	500	$5,000
Load	Underground Line	4	100	$5,000
Load	Overhead Line	5	100	$4,000
Load	Cb/Re-Closure/Switch	2	350	$1,200