

**Carnegie Mellon University
Information Networking Institute**

THESIS

**SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
Master of Science in Information Networking**

Title: “Survivability of the U.S. Electric Power Industry”

Presented by: IMJU BYON

Accepted by the Information Networking Institute.

Thesis Advisor: _____ **Date:** _____
Dr. David A. Fisher

Thesis Advisor: _____ **Date:** _____
Dr. Howard F. Lipson

INI Dept. Chairman: _____ **Date:** _____
Dr. Richard M. Stern

Carnegie Mellon University

*Survivability of
the U.S. Electric Power Industry*

A Thesis Submitted To the
Information Networking Institute
in Partial Fulfillment of the Requirements

for the degree

**MASTER OF SCIENCE
in
INFORMATION NETWORKING**

by

IMJU BYON

**Pittsburgh, Pennsylvania
May 2000**

Copyright © 2000 by Imju Byon. All rights reserved.

Abstract

Survivability is defined as the ability of a system to fulfill its mission, in a timely manner, in the presence of attacks, accidents, and failures. The mission of the U.S. electric power industry is to reliably and profitably generate and supply electricity wherever and whenever it is needed in North America. However, the U.S. electric power industry is becoming increasingly dependent on information systems, including highly distributed information systems that operate in unbounded networks, such as the Internet. As a result, the vulnerabilities of these information systems can undermine the industry's ability to supply electricity reliably to its customers. In addition, the current restructuring (deregulation) of the electric power industry creates problems that can threaten the ability of the competitive market to provide reliable electricity service to its customers. We will show that traditional computer security is not adequate to protect the mission of the industry and that a survivability approach is required.

In order to study the survivability of the electric power system, simulating the system would be beneficial because we cannot test the real electric power system to evaluate survivability problems and solutions. The Easel simulation language developed at the Software Engineering Institute (SEI) in Carnegie Mellon University (CMU) is appropriate for investigating survivability issues (such as choosing which one of several alternate policy implementations would be the most survivable). In particular, the Easel simulator is based on emergent algorithms, which achieve global effects through local actions and neighbor interactions. Easel is beneficial to simulate the electric power system because the industry has emergent behavior and survivability is a key emergent property that we want the system to have.

A primary goal of this thesis is to study the electric power system's survivability issues and requirements in the environment of deregulation. We also identify abstractions of the electric power system that would be the actors (performing local actions and neighbor interactions) in a simulation. Finally, we identify topics for future study in this critical research area.

Acknowledgement

First of all, this thesis is dedicated to my parents for their constant support and love. I am grateful to my thesis advisors Dr. Howard Lipson and Dr. David Fisher for their advice and guidance. I would like to express special thanks to Sandra Waltons, in the customer center at PJM Interconnection, LLC, for information on the details of control center operation.

Table of contents

Chapter 1.	<u>Introduction</u>	1
1.1.	<u>Motivation</u>	1
1.2.	<u>The goals of this research</u>	2
1.2.1.	<u>The scope of this thesis</u>	2
1.2.2.	<u>Contribution of this thesis</u>	3
1.2.3.	<u>Our focus in the electric power system</u>	4
1.3.	<u>Rest of the paper</u>	4
Chapter 2.	<u>The Concept of Survivability</u>	6
2.1.	<u>Limitations of traditional approaches</u>	6
2.2.	<u>The definition of survivability</u>	7
2.2.1.	<u>The domain of survivability: Unbounded Networks</u>	7
2.2.2.	<u>The definition of mission</u>	8
2.2.3.	<u>Key properties of survivability</u>	8
2.3.	<u>Available approaches for survivability</u>	9
2.3.1.	<u>Control System Architecture</u>	9
2.3.2.	<u>Survivable Network Analysis</u>	10
2.3.3.	<u>Emergent Algorithms</u>	11
2.4.	<u>Easel</u>	13
2.4.1.	<u>Language</u>	13
2.4.2.	<u>Capabilities of Easel simulation for simulating the electric power system</u>	14
Chapter 3.	<u>Survivability Requirements of the Electric Power Industry</u>	15
3.1.	<u>Mission of the electric power industry</u>	15
3.2.	<u>Reliability in the electric power industry</u>	15
3.2.1.	<u>Adequacy</u>	16
3.2.2.	<u>Security</u>	17
3.2.3.	<u>Key considerations for survivability requirements in terms of function</u>	17
3.3.	<u>Business requirements for the mission</u>	19
3.3.1.	<u>The conflicts with reliability requirements in the mission</u>	20
3.4.	<u>Considerations for survivability in deregulation</u>	20

<u>Chapter 4.</u>	<u>Identifying key abstractions of the industry</u>	22
4.1.	<u>Overview of the abstractions</u>	22
4.2.	<u>Physical structure</u>	24
4.2.1.	<u>Electricity</u>	24
4.2.2.	<u>The Public</u>	25
4.2.3.	<u>Generation system</u>	29
4.2.4.	<u>Transmission system</u>	32
4.2.5.	<u>Distribution system</u>	38
4.2.6.	<u>Process abstraction for the physical structure</u>	39
4.3.	<u>Operational structure</u>	40
4.3.1.	<u>Security coordinators</u>	41
4.3.2.	<u>System control center (Control area)</u>	41
4.3.3.	<u>Local control center (Utility)</u>	46
4.3.4.	<u>Operation process abstraction to exchange electricity</u>	47
<u>Chapter 5.</u>	<u>Conclusion</u>	50
5.1.	<u>Survivability requirements of the U.S. electric power industry</u>	50
5.2.	<u>Identifying key abstractions</u>	52
5.2.1.	<u>Identifying the actors for a survivability simulation</u>	52
5.2.2.	<u>Survivability scenarios</u>	52
5.3.	<u>General survivability</u>	53
5.3.1.	<u>Long-term evolution</u>	53
5.3.2.	<u>Measurement of survivability</u>	53
5.4.	<u>Future study</u>	54
	<u>Bibliography</u>	56
	<u>Appendices (A-G)</u>	72

Table of figures

Figure 1.	A diagram to describe relationships of actors included in the abstractions of the electric power system.....	4
Figure 2.	The Survivable Network Analysis Method [ELLM 98].....	10
Figure 3.	Overview of abstraction of the electric power industry	23
Figure 4.	Average Revenue from Electricity Sales to all retail consumers by state, 1996 [DOE J00]..	28
Figure 5.	A simple, hypothetical power network [F 97]	32
Figure 6.	Simplified diagram of the physical structure of the electric power system	39
Figure 7.	Overview of the operational structure in the U.S.	40
Figure 8.	Interconnected Control Area map in US [F 97].....	43
Figure 9.	Diagram to show electricity exchange between control areas A, B, C to implement contract between utility X and Y	47
Figure 10.	Abstractions of the electric power industry including attackers	52

Table of tables

Table 1.	Unit-of-Measure equivalents in electricity.....	24
Table 2.	Retail sales, revenue, average price paid and shares by end-use sector in 1996.....	27
Table 3.	Total number of retail customer from 1990 and 1996.....	28
Table 4.	Gross generation by utilities from 1993 and 1997.....	30
Table 5.	Generating Capability at U.S. Electric Utilities by North American Electric Reliability Council Region and Hawaii, 1993 through 1997 (Megawatts).....	31
Table 6.	Distribution of Transmission lines by Voltage Rating, 1994.....	37
Table 7.	Peak load of some control areas and number of generation units. [PJM m99].....	43
Table 8.	Bulk-power reliability criteria in integrated industry [DOE S98]	45

Chapter 1.

Introduction

1.1. Motivation

The dependency on information systems is growing in the electric power industry. However, as illustrated by the recent denial-of-service attacks on major E-commerce sites [CNN 00], the vulnerabilities of information systems have become a new type of threat that every organization should be aware of. The electric power industry also should recognize these new threats and assure the public that electricity service will be provided reliably in spite of the new threats.

However, the fulfillment of the industry's mission, reliable electricity supply, has been challenged today due to deregulation¹ in the electric power industry. There are some controversies that deregulation to increase efficiency in the industry could adversely affect reliable electricity service [DOE S98, DOE J98, DOE J00, S J00]. Even though the industry performed admirably in maintaining reliability over the past years, careful consideration about the impacts imposed by the competition is also required for reliable electricity supply.

Therefore, we need to address these new issues and implement appropriate policies in order to ensure a reliable supply of electricity to the customers in this changed environment.

The survivability approach is well-suited to addressing this problem because this approach is all about the fulfillment of the mission of a system, which includes fulfilling mission requirements such as reliability in the electric power industry. Survivability is defined as the ability of a system to fulfill its mission, in a timely manner, in the presence of attacks, accidents, and failures [LF 99]. Based on this survivability approach, we are going to

¹ The order EPACT (Energy Policy Act) issued in 1992 encourages competition in the electricity energy market, to improve the efficiency of the industry, by opening transmission access to all electricity market participants. (A transmission line is an electric line used to transmit a large amount of electricity for the purpose of delivering electricity to bulk users. Refer to <http://policyworks.gov/org/main/mt/homepage/mtv/epact.htm> for more information about EPACT.) In

research the mission fulfillment ability of the electric power system.

1.2. The goals of this research

The long-term goal of this research is to improve the survivability of the electric power system. A practical approach to achieve this goal is to build a simulation because we cannot test the real electric power system to evaluate survivability problems and solutions. For this purpose, we are going to use the Easel (the Emergent Algorithm Simulation Environment and Language) simulation language being developed at the Software Engineering Institute in Carnegie Mellon University [F 99]. Easel is appropriate for investigating survivability issues (such as choosing which one of several alternate policy implementations would be the most survivable). In particular, the Easel simulator is based on the concept of emergent algorithms, which achieve global effects through local actions and neighbor interactions. Easel is beneficial to simulate the electric power system because the industry has emergent behavior and survivability is a key emergent property that we want the system to have.

Therefore, two goals of this thesis are to study the electric power system's survivability requirements in the environment of deregulation and to identify abstractions that will be the actors (performing local actions and neighbor interactions among the actors) in a simulation.

1.2.1. The scope of this thesis

What we did

In this thesis, we focused on the following:

- ***Survivability requirements.*** We studied the industry's primary requirements and problems to provide a foundation for survivability research. From the study, we defined the mission of the electric power industry under deregulation. From the defined mission, we described survivability requirements of the industry. This will be discussed in detail in chapter 3.
- ***Identification of abstractions of the electric power system that would be the actors (performing local actions and neighbor interactions) in a simulation.*** We studied the operation and control mechanisms of the industry to identify

addition to that, most states are encouraging customer choice of electricity generation suppliers.

these abstractions. From the study, we defined the local actions and the neighbor interactions to be used in a simulation.

What we didn't do

In this thesis, we could not provide following:

- ***Detailed description of electric power operation.*** During this study, we found that we needed some detailed knowledge of electric power operation to understand the internal workings of the electric power system. However, it is beyond the scope of this thesis, and therefore we did not include a detailed description of electric power operation. Nevertheless, this type of knowledge may be necessary for anyone doing further study in this area. The book, *Power System Operation* [M 88], will help the reader to gain enough knowledge to serve this purpose.

1.2.2. Contribution of this thesis

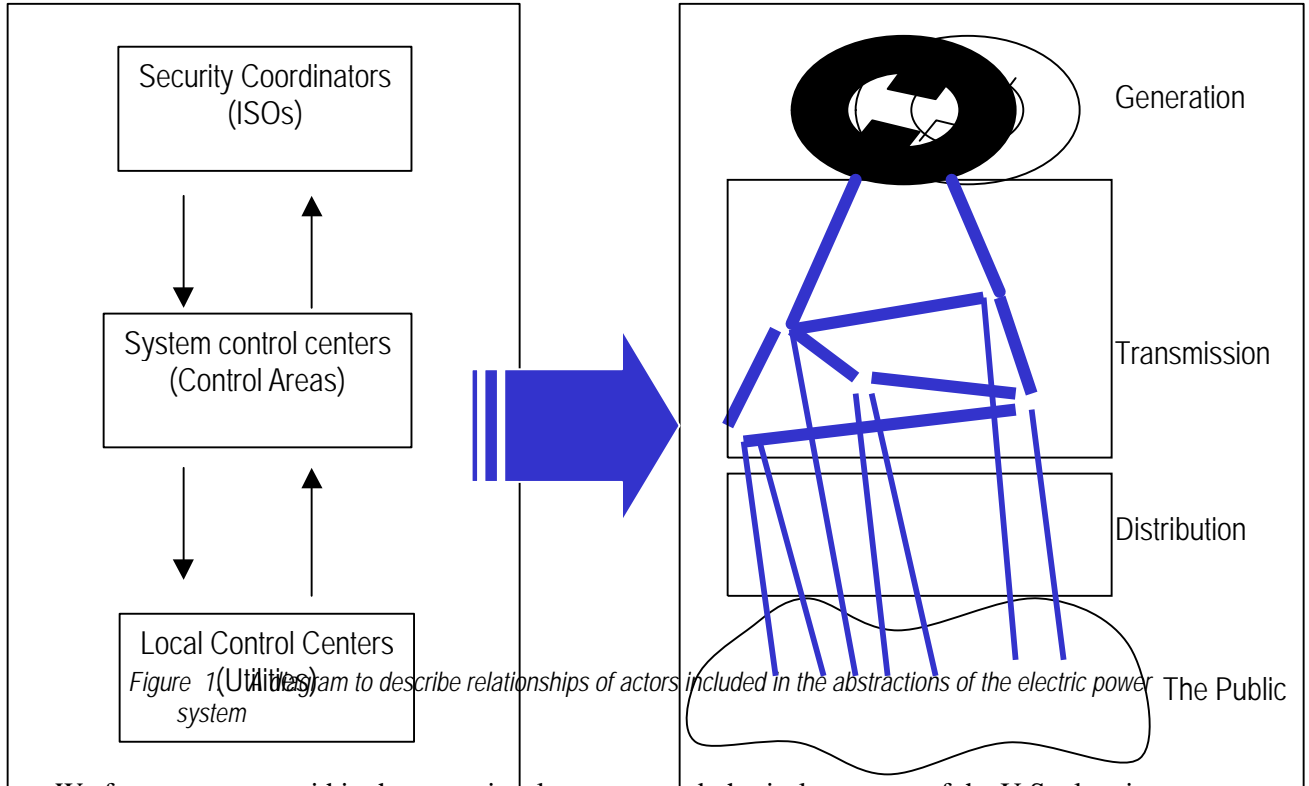
This thesis was written to initiate survivability research about the electric power industry. Not only were we new to this application area, but also survivability research is a relatively new area, so we focused on building a foundation for a computer scientist to start their survivability research about the electric power system and industry. Therefore, this thesis contributes in the following three ways.

- This thesis describes electric power industry concepts using the vocabulary of computer science and survivability/security.
- This thesis describes survivability requirements for the electric power industry from an emergent algorithm perspective.
- This thesis identifies several major questions and problems that should be addressed by future research.

1.2.3. Our focus in the electric power system

Operational structure

Physical structure



We focus on actors within the operational structure and physical structure of the U.S. electric power industry. The operational structure represents how organizations are structured to make critical decisions for daily operations in the electric power system. The physical structure corresponds to the physical system used for supplying power to the public. These two structures represent points of attack in the electric power system, which could cause problems in supplying electricity if they are attacked or they fail. This will be discussed in detail in chapter 4.

1.3. Rest of the paper

This thesis consists of five chapters, a bibliography, and several appendices, including an electricity operation glossary. Chapter 1 introduced the motivation, goals, scope and focus of this research. Chapter 2, the concept of survivability, explains the survivability approach including limitations of traditional approaches, the definition of survivability, available

approaches for survivability, and a brief introduction of the Easel simulation language. Chapter 3, survivability requirements of the electric power industry, contains a definition of the mission of the industry, refined requirements for the mission, and considerations for survivability in deregulation. Chapter 4, identifying key abstractions in the industry, describes actors in terms of their local actions of and neighbor interactions in the electric power system. In addition, it describes some survivability “what if” scenarios. Chapter 5, conclusion, summarizes the work in this thesis and identifies topics for future study in this critical research area. After chapter 5, the bibliography is presented. The appendices of this thesis include the geographic structure of the electric power system, reliability organizations, benchmark of modeling of simulators for energy power system, information system used in the PJM² system control center, ATC (Available Transfer Capability) computation used in PJM, cascade outages, and an electricity operation glossary.

² PJM is one of control centers especially responsible the operation and control of the bulk electric power system throughout major portions of five Mid-Atlantic states and the District of Columbia [PJM m99].

Chapter 2.

The Concept of Survivability

The approach we are using, survivability, is relatively new area. Before investigating the electric power industry, it is important to understand this survivability concept. In this chapter, we are going to introduce the survivability concept to better understand our approach to the electric power system. This chapter describes the limitations of traditional approaches, the definition of survivability, and available approaches for achieving survivability. In addition, the EASEL simulator and language, which is a simulation tool being developed for survivability research purposes, will be introduced later in this chapter.

2.1. Limitations of traditional approaches

So far, we have considered computer security as a protection solution. However, because security is based on a fortress model, the computer security method can harden against attacks but it fails to support continued fulfillment of a system's mission when the system is compromised by any kind of disturbance [SKDG 98, LF 99]. The fortress model indicates a technique to use barriers between the outside and inside of the system to protect it. However, a small hole in the barriers can compromise the entire system. For example, the firewall technique prevents unauthorized access to private or local networks. However, if an adversary steals a user's password and he or she enters the system disguised as the user, then the system is exposed to the adversary and the rest of system can be compromised.

The fortress model is based on a binary relationship that distinguishes insiders from outsiders of the system. This binary relationship is especially ineffective in highly distributed network systems like the Internet. As connections between systems are increasing, a user regarded as an insider in your system could be an outsider of your system also. It is hard to recognize a user precisely in this highly distributed system. Therefore, in a highly distributed system, a system using a fortress model can be compromised by outsiders who are treated like trusted insiders.

The computer security technique does not focus on fulfilling the mission. Therefore, once the technique is compromised then this incident allows adversaries to compromise the whole system. The solutions from traditional approaches do not solve the problem completely.

Therefore, we need an approach that focuses on mission fulfillment of a system in an integrated way and lets us develop and use methods to enable a system to fulfill its mission in a timely manner in any case.

2.2. The definition of survivability

Survivability is the ability of a system to fulfill its mission in a timely manner, in the presence of attacks, failures, or accidents. [EFL 97].

A survivable system should fulfill its mission in a timely manner under any conditions. Therefore, in case of disturbances, some degradation of performance might appear, but the system should continue to fulfill the mission. For instance, suppose there is a mail server system and the server went down for one day. Because the mission of the server is to deliver mail, the mail that users ask it to send should be delivered in any case. As a way to fulfill its mission, a survivable mail server could provide a paper-mailing service for the mail that the system could not deliver electronically. Although the users of the system experience some degradation of performance, having their mail delivered through postal services means that eventually the mail is delivered to the intended recipients and the system does not fail to fulfill its mission (as long as timeliness requirements are not violated).

As shown in this example, what is most important in survivability is to fulfill the mission of the system. Therefore, survivability is closely related to business risk management [LF 99]. However, the current environment that the system should survive in is a complicating factor, because the system usually operates in a large-scale, highly distributed network. In the next section, we are going to explain the characteristics of this environment.

2.2.1. The domain of survivability: Unbounded Networks

The unbounded network symbolizes the current computer-networking trend, the Internet. A bounded system is one in which all of the system's parts are controlled by a central administration, which has global visibility over the system. On the other hand, in an unbounded system, like the Internet, there is no central control over its parts and no entity has global visibility [EFL 97].

We typically have less information about attacks in an unbounded system than we would for a bounded system. Every entity in an unbounded system lacks complete and precise

knowledge about the system. Because of this, it is more difficult to protect a mission in an unbounded system than in a bounded system. The traditional solutions, which can easily defeat attacks in the bounded systems, might not be applicable to unbounded systems. An effective survivability solution should be based on a solid understanding of unbounded systems.

2.2.2. The definition of mission

The mission refers to a set of abstract requirements or goals [EFL 97]. To devise a survivable system requires a precise definition of its mission. The mission is the highest-level system requirement. From the starting point of the mission definition, the mission can be refined into more detailed mission and survivability requirements to support fulfillment of the mission. If a system's designers do not understand its mission, then the system cannot be designed to perform correctly in case of disturbance. Therefore, survivability analysis always begins from defining the mission of a system.

2.2.3. Key properties of survivability

The successful survivable system should have the following properties [EFL 97].

- Resistance: the ability of a system to repel attacks.
- Recognition: the ability to detect attacks as they occur and to understand the state of the system.
- Recovery: the ability to maintain essential services during attack, and to recover full services after attack.
- Adaptation and Evolution: the ability to evolve to improve survivability, based on knowledge learned about attacks and on changes in the environments.

2.3. Available approaches for survivability

To learn how to improve survivability, we chose three existing approaches, and we introduce them in this section. First is a control system architecture method researched at the University of Virginia. Second is a survivable network analysis method and third is an emergent algorithm method. The last two are researched at the Software Engineering Institute in Carnegie Mellon University. In the following sections, we are going to explain each of these approaches.

2.3.1. Control System Architecture

This research suggests a control system applicable to hierarchically distributed information systems. This method places a control system in each node in an information system. The responsibility of the control systems, called a controller in their work, is to administer and protect the information system residing in the node [SKDG 98].

Every controller has multiple control models to administer their nodes. A control model is one of various operating regimes existing in the node that can operate the information system. This diversity enables the system to resist attacks that know only some of control models in its target node. For example, in a case of attack, a control system in an attacked node can detect the attack and switch from a current control model to another control model. If the attacker does not know the newly changed control model, then they cannot attack the system anymore. Therefore, the control system architecture can be considered to be a survivable system because it continuously provides a service even in the presence of attack. This diverse and adaptive technique of the controllers is a core technique of this approach.

Nevertheless, this control system architecture has a serious flaw, in that each controller to provide diversity and adapt becomes a single point of failure³. For instance, if a controller is attacked and loses the ability to control its node, the diversity and adaptive techniques do not work after all and the rest of the system becomes open to the attackers. Although it shows a good regime for information system survivability, it could fail in fulfilling a mission of the system.

³ Single point of failure, here stands for a component whose failure causes the entire system to fail.

2.3.2. Survivable Network Analysis

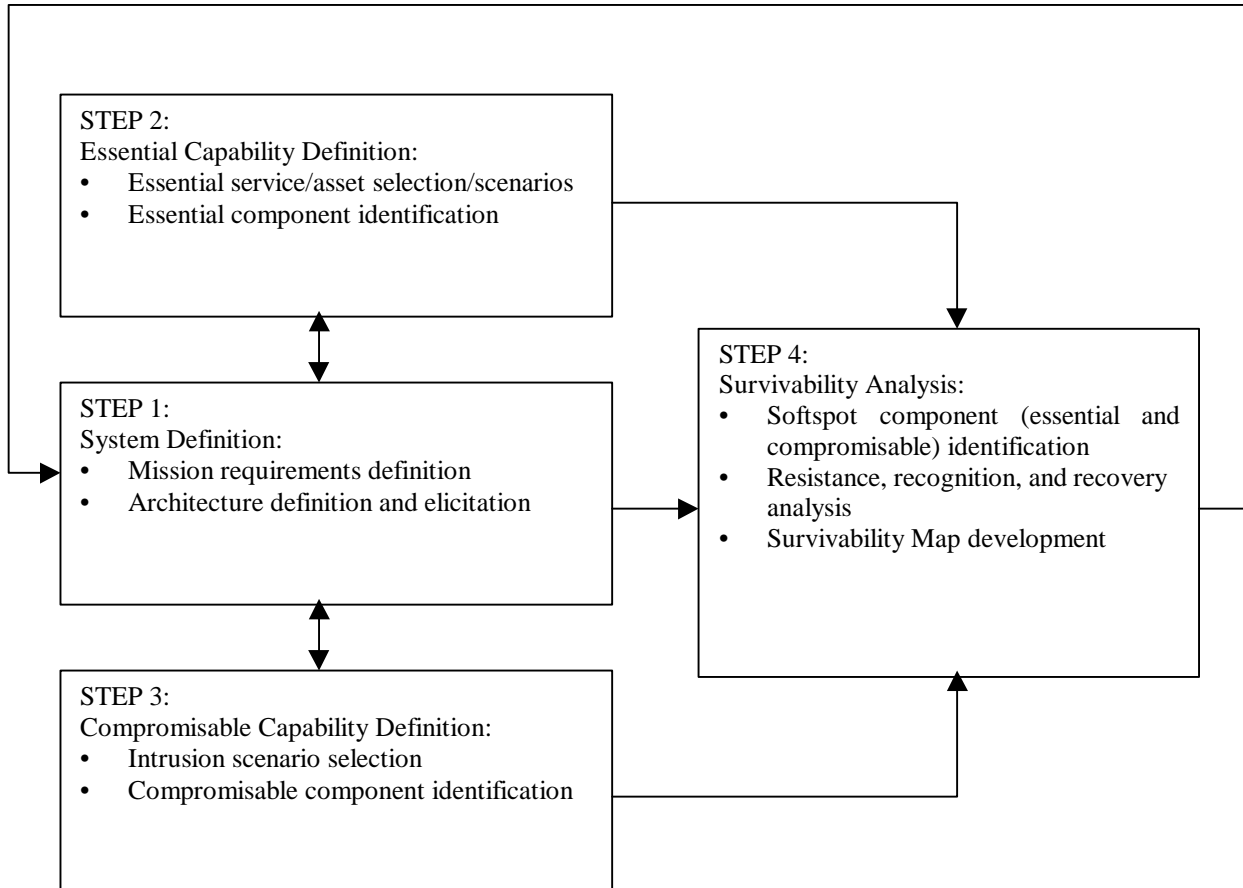


Figure 2. The Survivable Network Analysis Method [ELLM 98]

The Survivable Network Analysis (SNA) approach is a software engineering process to evaluate survivability [ELLM 98, EFL 97, LML 98]. This method is a discipline for developers to evaluate the survivability of their systems at the system architecture level.

This method is composed of four principle steps, as shown in the figure 2. By iterating these four steps, the survivability network analysis ensures that the proposed architecture implements the key properties (recognition, resistance and recovery) of survivability.

SNA is a good methodology to integrate traditional technology. However, as we discussed in

the section 2.2.1, simple integration of traditional techniques might not be effective in some cases, as we have observed from many incidents in the Internet. SNA does not address some phenomena that are likely to occur in unbounded systems.

2.3.3. Emergent Algorithms

Concept of emergent algorithms

Emergent algorithm is a concept borrowed from biology and social behavior, which can be seen in our life in such things as the stock market, the human immune system and an ant colony's self organized behavior [BT 00, O 98]. Emergent algorithms achieve global effects through local actions and neighbor interactions [FL 99].

The markets have emergent algorithms. For example, a merchant who sells TV sets determines the price of his TVs according to communication with customers or neighbor merchants and local information such as cost of selling a TV. He does not have ability to look at all the prices available in TV market. Furthermore, he does not need to know global information. This market does not require a central coordinator to control the market price of TV sets. Only the interactions between merchants and customers enable the supply of TV sets to customers.

As in the example, a global property that prevails for a system as a whole, but does not necessarily exist within individual components of the system, is defined as an emergent property [FL 99]. Neighbor interactions are analogous to a protocol in network applications. In systems using emergent algorithms, the effects of local actions and neighbor interactions (based on neighbor relationships) determine the survivability of the system.

Emergent algorithms as a survivability solution

The concept of emergent algorithms is beneficial to survivability for the following reasons.

- ***It exploits properties of unbounded networks.*** Because it achieves global effects through local actions and neighbor interactions, it is appropriate in unbounded networks where every entity has only local visibility.
- ***Massive failures/compromises of components are required to compromise the whole system.*** Because actors in an emergent algorithm only interact with near neighbors, there is no single or constant number of points of failure to attack. That is, the system can fulfill its mission as long as the number of failures is less

than proportional to the size of the network. As a result, only massive failures or compromises can defeat the whole system.

2.4. Easel

An emergent algorithm simulation environment and language (Easel) is being developed to conduct survivability research by simulating unbounded systems using emergent algorithms. Easel will be used in future research to simulate the electric power system in order to evaluate the survivability of the industry. In this section, we will provide a brief overview of the language concepts (i.e., “actors” and “neighbors”) that we will use to describe the key abstractions of the electric power system. These abstractions can be used in the future to create an Easel simulation. We will describe the key abstractions of the electric power industry in chapter 4.

2.4.1. Language

Easel uses its own language to describe simulation. The language has strong user defined types, boundary checking, and is a structured language with syntax similar to Algol, Ada and Pascal. Because it distinguishes communication entities (i.e. neighbors) from other entities, it is appropriate to simulate emergent algorithms.

Actor

An actor could be any active entity in a simulation. It can be a program, simulation, and processor with multiple threads, a machine, a human being, or any object in the real world that we want to represent. There are some reserved types for special kinds of actors, which include an observer, a facilitator, and a processor. However, user defined actors are the elements which are necessary to implement emergent algorithms in a simulation. Every actor has a local action defined in the algorithm. In addition, the aggregation of the local actions, and neighbor interactions, leads to global properties of the emergent algorithm.

Neighbor relationship

A neighbor relationship represents a protocol of interaction among actors in an unbounded system.

Simulator

The EASEL simulation system is targeted to simulate a loosely coupled concurrent processing model, but is hosted on a uniprocessor platform. The EASEL simulation system and language is implemented in C on a PowerPC Macintosh platform. The implementation of the simulator will be finished in the year 2001.

2.4.2. Capabilities of Easel simulation for simulating the electric power system

- *It is suitable for simulating alternative policy implementations to assess their impact on survivability.* Because the Easel simulation system is based on emergent algorithms and the electric power system has emergent properties, Easel simulations of the electric power system can provide accurate results to assess the survivability impact of various changes in policy. An alternative policy can be represented as changes in local actions and neighbor interactions of actors. Then by running a simulation with the changed policy, we can observe the effect of the new policy.

- *Interdependencies with the other infrastructures can be simulated.* Because the Easel simulation system can be used to describe neighbor interactions in the system, neighbors can be any of the other critical infrastructures, such as the telecommunications and financial infrastructures. From the simulation, we could see how the absence of electricity would affect the other critical infrastructures, and how disruptions in the other critical infrastructures would affect the survivability of the electric power industry.

Chapter 3.

Survivability Requirements of the Electric Power Industry

In this chapter, we explore the survivability requirements of the electric power industry. This chapter consists of a mission definition of the electric power industry, refined mission requirements in terms of reliability, and issues about the electric power industry under deregulation.

3.1. Mission of the electric power industry

To achieve survivability of the electric power industry, we need to define the mission of the electric power system. Here, we define a mission for the electricity infrastructure.

Reliably and profitably generate and supply electricity,
wherever and whenever it is needed in North America.

Many parts of our life are dependent on electricity. The public would like to have reliable electricity service. Therefore, whenever and wherever the public wants it, electricity should be supplied to the public on time. The mission described above represents such dependencies and expectations of the public in North America about electricity service.

However, the deregulation begun in 1992 has changed the industry [DOE J98, DOE J00, F 97, S J00]. The introduction of competition in the generation market of electricity changes the requirements of the industry, because today reliability requirements cannot be achieved without appropriate return on investment. Therefore, the mission of the electric power industry includes providing electricity service reliably and profitably at the same time. Therefore, any survivability solution for the electric power industry should satisfy the reliability goal and profit goal of the mission at the same time.

3.2. Reliability in the electric power industry

Reliability is a fundamental requirement of the electric power industry. In general, the

adjective ‘reliable’ is defined as worthy *of reliance or trust*⁴. This term reliability is defined in the electric power industry as follows.

Reliability – The degree of performance of the elements of the bulk-power system that results in electricity being delivered to customers within accepted standards and in the amount desired. Reliability is measured by the frequency, duration, and magnitude of adverse effects on the electric supply [DOE S98].

Thus, reliability depends upon the ability of the various actors that participate in the electricity service operation. Reliability can be addressed by considering two basic and fundamental aspects of the electric system – adequacy and security. The definition of adequacy and security is as follows [DOE S98].

Adequacy – The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and seasonably expected unscheduled outages of system elements. Adequacy refers to the amount of resources available to supply the aggregate customer electrical demand and energy requirements

Security – The ability of the electric system to withstand sudden disturbances such as short circuits or unanticipated loss of system elements.

3.2.1. Adequacy

Adequacy issues tend to be long term in nature such as the construction of facilities. Security issues (here, this security term is used differently from security in the computer security area) are related to the ability to withstand short-term emergencies in the electric power system. More specifically adequacy can be explained as the following two aspects.

- Sufficient generation capacity to meet peak time demand plus reserves for contingencies
- Broad and sufficient electricity line network to supply power

If utilities expect that there would be more demand in the future, the utilities should build generators with more capacity than exists today. If an area is likely to have more peak demand and current electricity lines are not enough to supply power, the utility should build additional high voltage electricity lines. Simply, adequacy implies that there are sufficient generation and transmission resources installed and available to meet projected needs, plus reserves for contingencies.

In general, the utilities forecast demand⁵ and sales for the next few years and decide on

⁴ Reference from the American Heritage Dictionary of the English Language, third edition.

⁵ [F 97] introduces a simplified equation to predict power demand on page 79. It consists of GNP, Price increase for the last three years and current year.

construction of facilities based on their financial analysis. This procedure is called “Adequacy planning” in the industry⁶.

3.2.2. Security

On the other hand, security implies that the electric power system will remain intact even after outages or other equipment failures occur. More specifically security can be explained as follows.

- Ability to fulfill instant demand and copes with emergency situations.

The security aspect typically addresses immediate operations that occur within an already built system. It often requires activation and operation of automatic protection devices, and generally involves intervention by an operator. For example, a generator should be available anytime to meet demand, a backup generator should be ready for emergencies, and the utilities should ensure electricity is reaching to every customer. This is called “*Security*” or “*Operation control*” in industry terms⁷.

However, these reliability requirements are not easily accomplished in the industry because of some special characteristics that the electric power system has. In the following section, we are going to address those considerations.

3.2.3. Key considerations for survivability requirements in terms of function

The electric power system has fundamental differences from other industries due to the physical characteristic of electricity. For example, cash used in a financial infrastructure does not need to be delivered to the customer instantly from the Mint because it can be stored somewhere for some period. Moreover, your phone call gives you busy signal if your call cannot get through to your receiver. However, this does not apply in an electric power system, because electricity can be stored no longer than a few seconds. Generated electricity should immediately be fed into customers’ outlets. Therefore, the physical characteristics of power flow govern all operating practices in the system and the industry has built a robust

⁶ An extensive explanation of planning can be found in chapter 3 and 8 of the book, “Electric Utility Restructuring: A guide to the competitive era” by Peter Fox-Penner [F 97]. The planning decision is made by each utility every year and is verified by the control area. The adequacy planning procedure can be found in policy 6 in the control area operating manual in NERC [NE 00].

⁷ But a more extensive explanation about current practice can be found in the control area operating manual

system to maintain this.

The U.S. electric power system consists of an interconnected network spread throughout the country. The interconnectivity contributes to survivability because the system still can receive electricity from outside of an area in spite of the failure of a generator system. On the other hand, the interconnectivity contributes to increasing the complexity of operation because activities between entities need to be coordinated.

There are two main features to be considered for an electric power system to keep running. The final report of the task force team on electric system for restructuring, “Maintaining Reliability in a Competitive U.S. Electricity Industry” explains these issues as follows [DOE S98].

Main feature 1.

The need for continuous and near-instantaneous balancing of generation and load, consistent with transmission-network constraints. This requirement stems from the absence of technologies to store electricity easily and involves metering, computing, telecommunications, and control equipment to monitor loads, generation, and the transmission system, and to adjust generation output to match load or reduce load to match available generation. In order to keep this feature, the network should be at the same frequency and maintain voltage because increasing the load causes it to lower frequency and voltage generation should be dispatched to return to normal state.

Main feature 2.

The passive nature of the transmission network, owing to very few “control valves” or “booster pumps” to regulate electrical flows on individual lines. Power flows according to the laws of physics, rather than from ownership, contract rights, or State boundaries. Control actions are limited primarily to adjusting generation output and to opening and closing switches to reconfigure the network.

The two characteristics, lead to the following three reliability considerations that dominate nearly all aspects of power system design and operations [DOE S98].

Consideration 1.

- Every action affects all other activities on the grid. From a reliability point of view, the activities of all players must be coordinated, often across large geographic regions. (This caused from transmission systems’ interconnection.)

in NERC [NE 00] and the PJM operating manual in PJM [PJM 99].

Consideration 2.

- Outages can increase in severity and cascade over large areas. Failure of a single element can, if not managed properly, cause the subsequent rapid failure of many additional elements, disrupting interconnected transmission systems over a broad geographic area.

Consideration 3.

- The need to be ready for possible contingencies, more than current operating conditions, dominates the design and operation of bulk-power systems. It's usually not the present power flow through a line or transformer that limits allowable transfers of power, but rather the power flow that would occur if another element failed.

The considerations stated above provide the rationale about operation practices exercised in the electricity industry. From these considerations, we can conclude that cooperation between the utilities is critical to maintain a stable electricity network. This has resulted in the voluntary forming of control areas among utilities. Forming control areas with several utilities is also beneficial for utilities because they can save operating cost by aggregating demand in the region they have to serve. It contributes to reducing the possibility of large-scale outages because the control areas have better visibility over the electricity network. A more detailed explanation about the control areas is covered in chapter 5.

3.3. Business requirements for the mission

In the past, utilities were the responsible entity for all aspects of reliability requirements. However, under deregulation, profit generation in addition to these reliability requirements became required in the industry. In this section, we are going to discuss briefly the business requirements in the industry.

Although the utilities are responsible for the reliable supply of electric power, if they cannot profit from the operation, they cannot fulfill their mission. Therefore, in the same manner as other business, the electric power system has the following business requirements:

- Efficient utilization of current assets to maximize profit
- Effective investment in construction of facilities to meet future demand

The above business requirements are closely related to the reliability requirements in the above section. For example, to meet the adequacy requirements, utilities should build sufficient facilities, but they have to recover their investment cost.

3.3.1. The conflicts with reliability requirements in the mission

However, the construction cost of generators is especially high in this industry. In the past, this conflict was easily resolved because regional monopolies guaranteed that the utilities would recover the cost. Under deregulation, this becomes more difficult. Furthermore, electricity service is an essential commodity, and is not easily charged at a high price. As a result, there are severe conflicts between reliability and business requirements in deregulation.

3.4. Considerations for survivability in deregulation

William Sweet describes the following considerations that the industry faces in the deregulation situation in the article, “Power & Energy” in the IEEE, Spectrum [S 00].

- Deregulation discourages utilities from investing in the construction of new facilities
- It reduces incentives for the utilities to share information and cooperate
- There is no one to enforce reliability in the industry

After deregulation, the utilities were reluctant to invest in new facilities and that results in a decreasing ability of the industry to fulfill their mission in a timely manner. If the utilities do not build enough generators, they cannot overcome emergencies that might need more power than their capacity, which means the utilities will fail to fulfill their mission. Competition certainly reduces incentives for the utilities to share information and cooperate.

As we discussed in the section 3.2.3, the electric industry needs cooperation to maintain a stable electricity network. Cooperation is specially required in deregulation, because transportation of electricity between regions is increasing and requires more careful operation than ever before [MA 99]. However, it is hard to expect such cooperation among the utilities with different interests.

This is made even worse by service restructuring, which means that now more than one service provider can be involved in providing electricity service to a customer. If some

problems happen during service, responsibility for the problems might not belong to anyone until the dispute is resolved.

Furthermore, in the past, the peer pressures among the utilities naturally forced the utilities to comply with the voluntary reliability rules. Nevertheless, in the current deregulation, the utilities may not comply with the reliability rules if it conflicts with their interests. In fact, more violations of the reliability rules are found in current deregulation [S 00]. However, there is no suitable entity to enforce compliance.

Chapter 4.

Identifying key abstractions of the industry

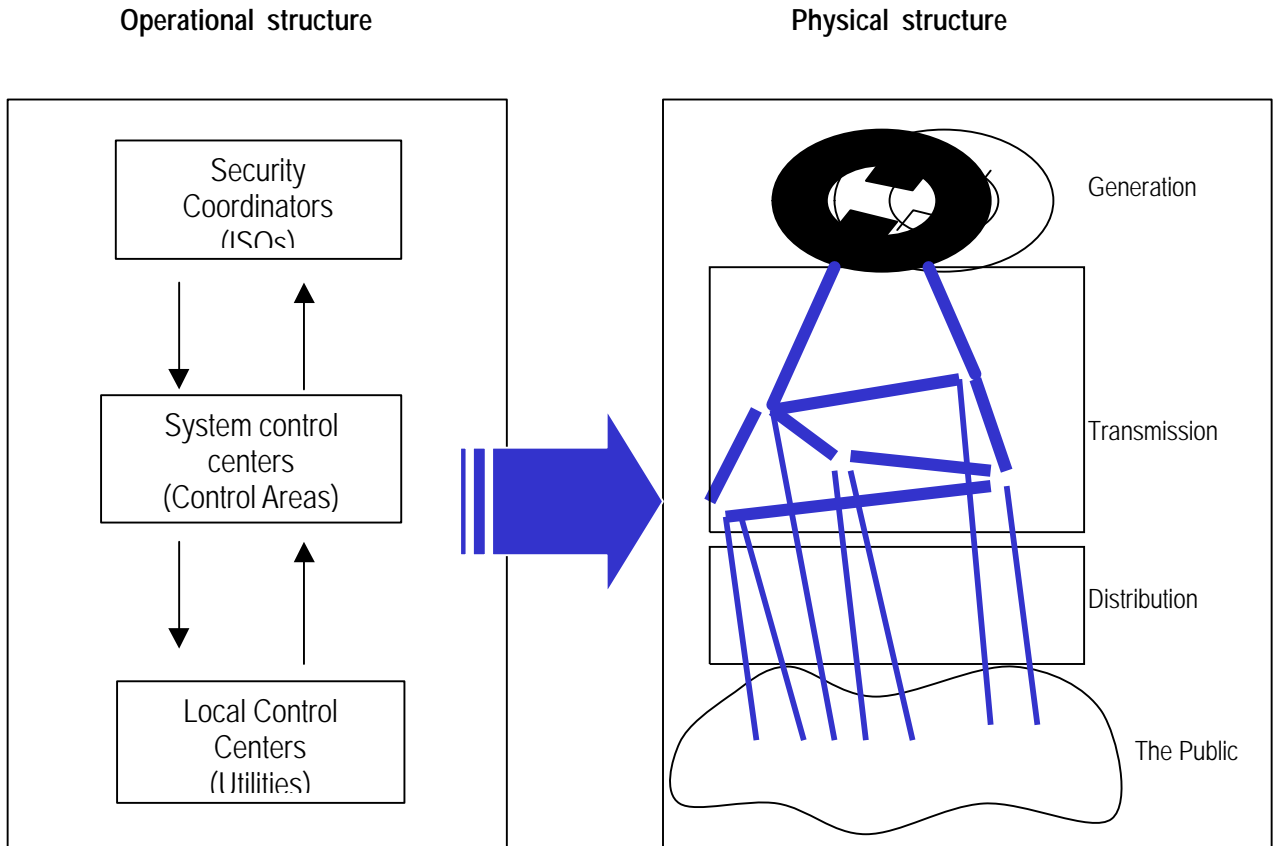
In this chapter, we are going to identify key abstractions of the electric power industry. This is as an essential step in the preparation needed for a simulation of the industry. The abstractions are based on information obtained from [DOE S98, DOE J98, F 97, PJM 99, NE 00]. These current abstractions of the industry can change over time because the industry is itself changing due to deregulation. Therefore, in this chapter, we focus on making a foundation of abstractions from the information obtained from the above public records. The abstractions consist of two structures: physical structure and operational structure. The next section shows an overview of the abstractions. Then the actors of each structure are explained in detail in terms of local actions and neighbor interactions.

4.1. Overview of the abstractions

The abstractions consist of two parts as illustrated in the figure 3: operational and physical structure. The operational structure represents how organizations are structured to make critical decisions for daily operations in the electric power system. The physical structure corresponds to the physical system used for supplying power to the public. These two structures represent points of attack in the electric power system, which could cause problems in supplying electricity if they are attacked or they fail and entities such as the public participating electricity activity. Each actor will be explained in detail in terms of properties, local actions and neighbors. Each structure has the following actors:

Physical structure	Operational structure
<ul style="list-style-type: none">■ Electricity■ The Public■ Generation■ Transmission■ Distribution	<ul style="list-style-type: none">■ Security coordinators■ System control centers (control area)■ Local control centers (utilities)

Figure 3. Overview of abstraction of the electric power industry



4.2. Physical structure

4.2.1. Electricity

Electricity is a power that enables the operation of electronic machines. In our abstractions, electricity accounts for a physical power we obtain from electrical outlets.

- Properties to be captured
 - Watt (W)
 - Frequency
 - Voltage

Table 1. Unit-of-Measure equivalents in electricity

Unit	Equivalent
Kilowatt (kW)	1,000 Watts
Megawatt (MW)	1,000,000 Watts
Gigawatt (GW)	1,000,000,000 Watts
Terawatt (TW)	1,000,000,000,000 Watts
Kilowatt-hours (kWh)	1,000 Watt-hours
Megawatt-hours (MWh)	1,000,000 Watt-hours
Gigawatt-hours (GWh)	1,000,000,000 Watt-hours
Terawatt-hours (TWh)	1,000,000,000,000 Watt-hours
Gigawatt-hours	1,000,000 Kilowatt-hours
Thousand Gigawatt-hours	1,000,000,000 Kilowatt-hours

4.2.2. The Public

The simulation will capture the reaction of the public to policy implementation, because they are the ultimate driving force to change this industry. According to the demand of the public, electricity is generated and is supplied to the places where it is needed. The distribution system is directly connected to the outlets where the public needs electricity, but demand is realized as changes of voltage and frequency in the transmission electricity network.

- Properties to be captured
 - Demand [On, Off]
 - Types of the public [Residential, Commercial, Industrial, Other]
 - Standard voltage range
 - Amount they need
 - The utility to supply power to the customer
- Local actions
 - Demand electricity in safe voltage range
- Neighbors
 - The public
 - The local distribution system
 - The subscribed generation utility

Algorithm

If the public demands electricity, then immediately it causes a drop in the electricity network's frequency and voltage. However, in general, power is continuously produced from generation plants, therefore the drop is not observed easily. In our abstraction, the demand of the public is represented as activating the delivery function.

```

While ( public.demand == on AND public.amount = MW ) {
    Electricity = Deliver (From the distribution, Necessary amount of electricity);
}

```

Related statistics⁸

Table 2. Retail sales, revenue, average price paid and shares by end-use sector in 1996

	Residential	Commercial	Industrial	Other	Total
Retail sales In Million Kilowatt-hours	1,082,491	887,425	1,030,35	97,539	3,097,810
Revenue In Million Dollars	90,501	67,827	47,385	6,741	212,455
Average revenue per Kilowatt-hour in cents	8.4	7.6	4.6	6.9	6.9
Sectoral share by revenue in percent	42.6	31.9	22.3	3.2	100.0

Source : Energy Information Administration, Form EIA-861, "Annual Electric Utility Report" as presented in [DOE O98]

Table 2 shows information about end users of the industry in 1996. As shown in the table, the residential sector accounts for about half of the revenue. However, the price for residential customers is double the price for industrial customers, because industry customers can bargain price based on bulk purchases.

⁸ For more information, please refer to Energy Information Administration (EIA), Annual Electric Power Annual. EIA produces annual reports about electric power industry.

Table 3. Total number of retail customer from 1990 and 1996

Years	Number of Retail customers
1990	110,560,742
1991	111,879,983
1992	113,285,537
1993	114,734,977
1994	116,488,704
1995	118,329,725
1996	120,002,093

Source: Energy Information Administration, Electric Sales and Revenue 1996, DOE/EIA-0540 (96) Table 5 as presented in [DOE 098]

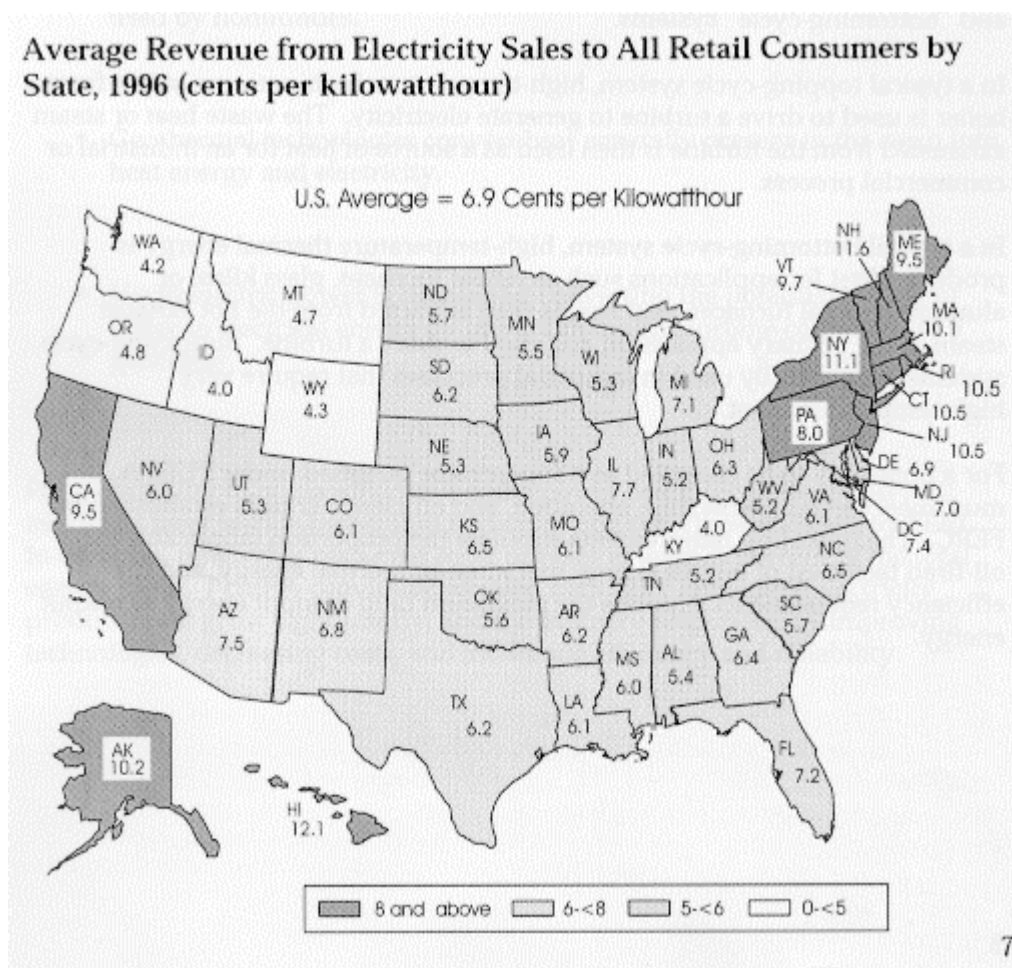


Figure 4. Average Revenue from Electricity Sales to all retail consumers by state, 1996 [DOE J00]

From figure 4, we find that New Jersey, Rhode Island and Connecticut pay the highest price for their electricity in the U.S. with the exception of Alaska and Hawaii. Because of this

unbalance among regions, there are attempts in deregulation to deliver electricity from low price regions to highly priced regions.

4.2.3. Generation system

Generation is a process to manufacture power to meet demand instantly. Because electricity cannot be stored for future load, the capacity of a plant is designed to meet the peak demand of the load they have to serve as well as a margin for emergency. The type of electric current generated is AC because it is easy to change voltage up or down by letting power flow through transformers. Power plants generate electricity voltages of 4,600 to 20,000 volts.

Generated electricity is passed to the transmission system. The generation plants can be controlled by a system control center in the control areas and the owner utility of the plant. Here, a generation system means the generation plant and its local generation control facilities⁹. Some amount of the reactive power should be provided into transmission systems to prevent voltage dropping. The utilities typically own several generators. The generators are dispatched and released in the order of their marginal cost.

- Properties to be captured
 - Maximum generation amount in MW
 - Current generation amount in MW
 - Demand in MW
 - Reactive power to supply to the transmission lines in MVAR

⁹ For more explanation about generation, refer to Policy 1 in the operating manual in NERC [NE 00]. Also, detailed operation practice can be found in dispatching operation manual in the operating manual in PJM [PJM 99].

- Local actions
 - Figure out demand in electricity network
 - Manufacture power to customer for usage
 - Manufacture reactive power to transmission line for security
- Neighbors
 - The public
 - Transmission system
 - Generation system
 - System control center
 - Local control center

Algorithm

The generation amount should be matched to the sum of load and reactive power¹⁰. The unit of generation amount is a Megawatt. If the demand is more than the capacity and it is over the line capacity, then it should ask neighbor generators to provide enough electricity to the customers.

```

Pick generator (generator portfolio that the utility owns)
  {Choose a generator, which is able to supply the demand;
  Select a generator that has least marginal cost among them;}
If (generator failure == False AND (demand + reactive power) < generation capacity AND Available
Transmission Capacity (the transmission system) > load){
  Dispatch Plant (demand + reactive power);
  Current generation = Current generation + demand + reactive power;}
Else
  Ask Neighbor Generator (demand);
  Transmit (demand + reactive power, the transmission line);
If demand is decreasing
  Then release the generator with most marginal cost first
  
```

Related Statistics

Table 4. Gross generation by utilities from 1993 and 1997

Years	Gross generation (million kilowatt-hours)
1993	2,897,815
1994	2,924,961
1995	3,002,304
1996	3,099,945
1997	3,144,768

Source: Energy Information Administration, (EIA) Form EIA-861, "Annual Electric utility Report " as presented in [DOE 098]

¹⁰A transmission line stores some small amount of power, which causes voltage to drop. So to keep the transmission line in a stable voltage range, a generation plant should supply also the amount of reactive power to transmission line.

Table 5. Generating Capability at U.S. Electric Utilities by North American Electric Reliability Council Region and Hawaii, 1993 through 1997 (Megawatts)

North American Electric Reliability Council Region and Hawaii	1993	1994	1995	1996	1997
ECAR	104,818	104,812	104,426	103,360	102,518
ERCOT	52,889	53,110	53,400	53,903	53,711
FRCC	--	--	--	32,751	32,616
MAAC	51,589	51,629	52,083	53,163	53,588
MAIN	50,314	50,863	51,430	52,155	52,093
MAPP	30,915	31,357	31,311	30,610	34,820
NPCC	56,043	55,956	55,967	52,177	51,406
SERC	149,748	151,127	153,434	125,079	155,786
SPP	71,009	71,099	71,375	71,593	42,871
WSCC	129,334	128,937	129,751	131,292	129,232
Contiguous US	696,659	698,890	702,777	706,083	708,641
ASCC	1,711	1,737	1,732	1,734	1,750
Hawaii	1,602	1,602	1,602	1,610	1,499
U.S. Total	699,971	702,229	706,111	709,942	711,889

Notes: Florida Reliability Coordinating Council was created January 1, 1997.

Source: Energy Information Administration, Form EIA-860, "Annual Electric Generator Report" as presented in [DOE O98]

4.2.4. Transmission system

The transmission system includes high voltage lines and transmission substations to maintain the lines. A generator that is far from the point of actual consumption has to reach further to the end of grid through the high voltage lines.

Although the transmission lines do not produce power, if the line is congested (i.e., the line is fully utilized) the generator that uses the lines cannot supply electricity. This limit should be carefully managed; otherwise, it can cause the collapse of a large electric network, i.e., large-scale outages in the networks. In this section, we are going to introduce the technical considerations and the administrative considerations for transmission, together with an abstraction.

Figure 5. A simple, hypothetical power network [F 97]

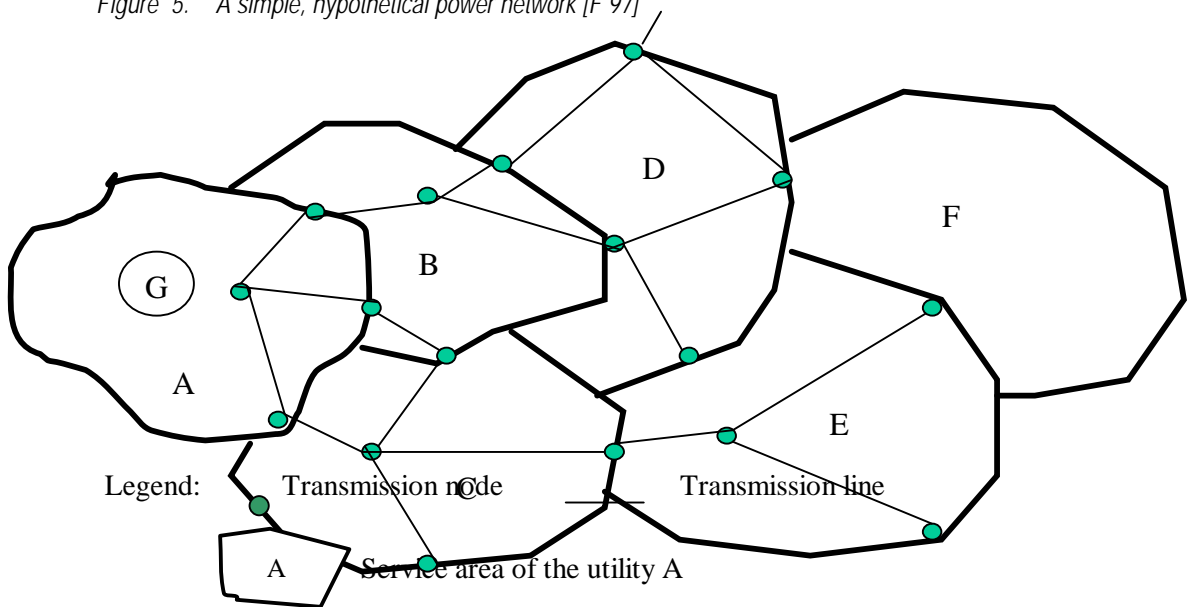


Figure 5 is a simplified picture of the power network and it shows the single transmission grid with one generator labeled G, eighteen transmission nodes, and six utility service areas (A-F).

1) Technical considerations

Loop flow effect

In the Figure 5, if utility A has a contract to provide electricity to the area F. In general, the industry assumes that electricity generated by utility A will flow according to the path A -> B-> D-> F and utility A will give this information to area B, D and F. However, in a real situation, power flows everywhere in the network. When this transaction takes place, power would flow through several paths such as A->B->D->F or A->C->E->F. Therefore, area C or E, which do not know about this transmission, might have some unexpected effect due to this transmission. This phenomenon is called *loop flow effect* or *parallel flow effect*. This effect causes following issues in the industry.

- For reliable operation, the transaction should be publicized and verified before operation because it can adversely affect the operation of other areas.
- It is difficult to charge a cost for parallel flow. Only the contract path can be compensated for the use of their facilities¹¹.
- In deregulation, there will be more transmission requests passing through areas than ever. Because the loop flow effect makes the state of the network harder to predict¹², more attention should be paid to this effect in deregulation [MA 99].

Limitation of line capacity

The transmission line should not hold more than its limit. If it does, then the line is overloaded which causes an imbalance in the transmission network. It implies that even if near neighbors have sufficient or excessive generating power, they may not be able to transmit it to you. This situation is called congestion in a transmission line. The system control center exercises congestion control when a line is about to be overloaded.

Reactive power

The transmission lines store a small amount of power in them. These stored amounts, called reactive power or reactive losses, usually lower the voltage at the other end of a transmission line. To avoid this effect, the reactive power should be injected at the generators

¹¹ Several scheme to price transmission in restructuring are introduced in p. 41 [DOE J98].

¹² PTDF: a matrix for parallel transmission coefficients to figure out how much effect of parallel flows in the specified transmission line. Available at http://www.maininc.org/pubnerc/pubnerc_ptdf.htm

and every transmission substation. The reactive power is specified for each transmission line with unit VAR (voltage amperes reactive)¹³.

Frequency regulation and synchronization

Because the transmission network is interconnected and the operation of one can affect others in the network, the transmission network should be synchronized regularly and maintain a specific range of voltage. If it fails to synchronize with neighbor networks, large-scale blackouts can easily occur.

2) Administrative considerations

Transmission transaction

Every transmission should be registered as a transaction in the electric power system. The transaction is registered to corresponding control areas and the transmission resource is reserved for the transaction. This is classified as a bilateral transaction and it is a dominant type of transaction in the U.S.¹⁴ [DOE J98]. The transmission contract is specified as follows:

- Transmission transaction attributes
 - Sender
 - Receiver
 - Firmness
 - Duration
 - Start time
 - Amount

Firmness

The firmness stands for the possibility to be curtailed in an emergency because the system control center can curtail some transactions due to congestion [NE 00, PJM 99].

- Non-firm: If there is congestion in the transmission, this transaction is likely to be curtailed first.
- Firm: The firm transaction service has highest priority; firm transaction is the last transmission to be curtailed.

¹³ The reactive power amount can have an influence on transmission line capacity. For more discussion, refer to [W 97].

¹⁴ Another type of transmission transaction is a network transaction. Network transaction is used for

Reservation Scheme

In the reservation process, the transmission transaction should be verified by the system control centers. If they decide that it is not appropriate in their area when they verify the transaction's reliability, it is declined. Otherwise, it is accepted. The available transmission capacity (ATC) computation is used to decide whether the transmission system has enough capacity to hold the transaction (Appendix E contains the ATC computation procedure).

Congestion control

When a transmission line is about to reach its line capacity, the control operators should prevent overload of the line. This incident is called congestion of the transmission system. When congestion occurs, the system control center may execute one of following procedures [DOE J98]:

- It can curtail power from certain generators. The priority for curtailment is decided by the transaction firmness.
- It can dispatch another generator outside the congested area to supply power.

3) Abstraction

- Properties to be captured
 - Line capacity
 - The location of ends
 - Reactive power
 - Current availability
 - Corresponding transmission transaction
- Local actions
 - Stepping up voltage to deliver more power
 - Maintain stability of the transmission lines
- Neighbors
 - Generation system
 - Transmission system
 - Distribution system
 - System control centers
 - Local control centers

dedicated lines to some utilities. [PJM 99].

4) Algorithm

This algorithm represents the administration procedure to operate and maintain a transmission network.

Reservation

If (Test transmission request¹⁵ (Amount) == True)

 Schedule transmission request;

Else

 Decline transmission request;

On the day of operation

Case 1: Normal situation

{ As a part of normal operation, transmission will be held according to scheduling. }

Case 2: Contingency situation

If (Amount of emergent transmission Request < Line capacity of the Transmission line)

 Accept request (Amount);

Else

{ Curtail transmission (Transmission line);

 /Or dispatch another available plant that can support load of the request/

 Accept request (Amount); }

Curtail transmission (Transmission line){

 Choose least significant transaction (Transmission line);

 Load relief (Transmission line); }

5) Transmission system in deregulation

The purpose of deregulation is to create competition. The open access to the transmission system is a key to a competitive market. However, as explained above, the electricity operation on the transmission system is very difficult due to the physical characteristics of electricity operation and interconnection. It is possible that utilities take advantage of this complexity to protect their regional market from outsiders [OWP 99].

Independent System Operator (ISO)

In deregulation, it is important to give every utility fair access to the transmission system. Therefore, separate ownership of a transmission system and generation system is required. An independent System Operator (ISO) is a neutral operator responsible for maintaining the generation-load balance of the system controlling the transmission system and some generating units. Because each control area has a different system to facilitate its transmission system and tends to favor their own power generation, a nonaffiliated utility finds it hard to use others' network systems [DOE J98, F 97, DOE S98].

¹⁵ Here “test transmission request” examines the transmission lines using ATC computation in appendix E.

Currently 11 ISOs are either in operation, proposed or under discussion in the U.S. The function of an ISO is a combination of control areas and security coordinator. However, the actual functions of ISOs are different depending on the state. The following are the responsibilities of ISOs as defined in [DOE J98]:

The responsibilities of ISOs [DOE J98]

- Control of the transmission system
- Maintain system reliability
- Provide ancillary service
- Administer transmission tariff
- Manage transmission constraints
- Provide transmission system information

Open Access Same-Time Information System (OASIS)

The Open Access Same-Time Information System (OASIS) is an interactive Internet-based database [DOE J98, DOE S98]. An ISO determines the available transfer capability (ATC) of all transmission systems and posts the information to OASIS. Utilities can reserve a transmission system serviced by an ISO or control center through the OASIS reservation process. Once approved, it is posted on OASIS and then OASIS updates the ATC.

OASIS was created for the interactive computerized market for transmission reservations, along with other transmission-related products and services to support open access to the market. The FERC required the development of OASIS with mandatory participation for those utilities under FERC’s jurisdiction.

6) Related Statistics

Table 6. Distribution of transmission lines by voltage Rating, 1994

Nominal Voltage	
22,000-30,000	82,717
31,000-40,000	96,276
41,000-50,000	34,430
51,000-70,000	111,465
71,000-131,000	95,313
132,000-143,000	68,502
144,000-188,000	24,934
189,000-253,000	67,896
254,000-400,000	47,483
410,000-600,000	26,396
601,000-800,000	3,876

Total	659,289
--------------	----------------

Source: Edison Electric Institute Statistical Yearbook (1994) as presented in [F 97]

4.2.5. Distribution system

The final delivery step of providing electricity to the public is called distribution. The electricity travels through transmission lines and is consumed by the public through distribution lines. The distribution system means distribution lines and distribution substations to control distribution lines. In general, the distribution lines' voltage is set to the safe voltage range for customer usage and the distribution substation manages to keep voltage in the safe range. Most of outages that we experience come from troubles in the distribution system. Nevertheless, the effect is minor compared to the entire electricity network.

- Properties to be captured
 - Line capacity
 - The location of ends
 - The utility to own distribution system
- Local actions
 - Distribute electricity from transmission line to end-customer
 - Stepping voltage down to standard voltage
 - Maintain distribution lines
- Neighbors
 - Transmission system
 - Local control center
 - System control center
 - The public

Algorithm

Step down voltage (the distribution line, standard voltage)
 Deliver (electricity, amount, the public)

4.2.6. Process abstraction for the physical structure

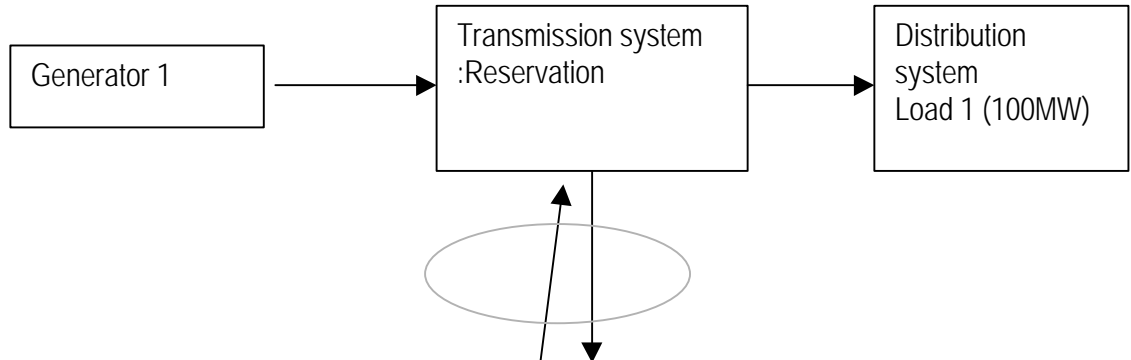


Figure 6. Simplified diagram of the physical structure of the electric power system

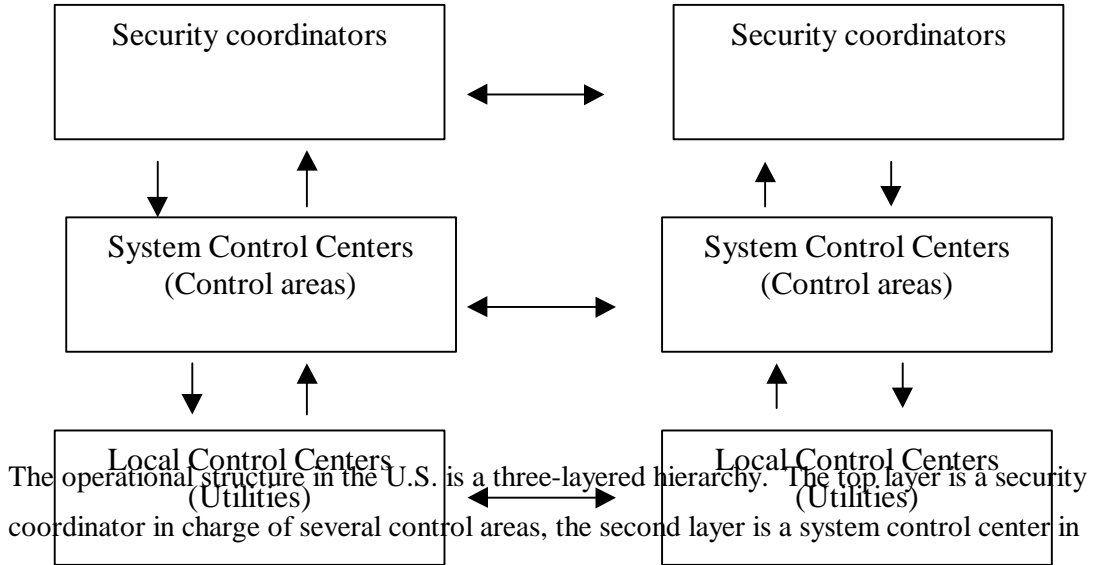
For example, as shown in the Figure 6, the transmission electricity network is connected between generator 1 and 2 and distribution load 1 and 2. Because they are interconnected,

the electricity generated by generator 1, which is responsible for load 1, can flow to load 2. Similarly, the electricity generated by generator 2, which is responsible for load 2, can flow to load 1. On the other hand, the interconnections contribute to preventing an emergency because an area having problems supplying electricity can get electricity through the interconnected electricity networks.

4.3. Operational structure

Most physical facilities are owned by various utilities but for security and economic reasons they form a control area with adjacent utilities. In this section, we are going to explore the operational structure of the U.S. electric power system. Each actor in this operational structure will be explained in the following sections. Then we will show the interchange of electricity between control areas later to see the interactions between these actors.

Figure 7. Overview of the operational structure in the U.S.



A security coordinator monitors a region including several control areas and performs an emergency operation in a region, which is broader than a control area. A system control center is responsible for overall operations in the control area and exchanges between control areas. Sometimes its control over the facilities can override the utilities' control. A local control center has control over its facilities, but the priority of control area operation is higher than a local control area.

There are many types of data exchange between system control centers and local control centers to maintain electricity network stability. Between utilities, in addition to this data exchange, they can purchase electricity from each other. The system control center communicates with other system control centers when there are electricity exchanges between areas. The security coordinators communicate with other security coordinators to

minimize contingency occurrences in its region.

4.3.1. Security coordinators

The security coordinator's main responsibility is to ensure secure operation for the next day in larger area than each control area. Because the electric flow is quickly transported, security coordinators watching a large transmission network can catch a situation and perform emergency operations immediately. This security operator's role is going to be merged into the new entity Independent System Operator (ISO) in deregulation. There are 23 security coordinators in the U.S. electric power industry.

- The properties to be captured
 - Control areas they have to monitor
 - Transmission system information
- Local actions
 - Collect operation data from control areas and evaluate them for the next day for transmission schedule for security
 - Monitor electricity transmission network
 - Provide emergency assistance in contingency situations
- Neighbors
 - Transmission system
 - System control centers
 - Local control centers

4.3.2. System control center (Control area)

A system control center is responsible for uninterrupted and economical electric service in its control area. The main operations of a system control center can be classified as economic dispatch operation and security operation, respectively. In some control areas, it can have a spot market function. The explanation here is mostly based on the PJM control area manual [PJM 99] and [F 97]. This could vary depending on the policy of each control area.

Economic dispatch

For example, suppose a utility, called A, and another utility, called B, are in the same control area and utility A's generation cost is lower than the adjacent utility B. Because the control area is interconnected, the electricity generated by B can flow into the area that A is serving. The unit commitment database (residing in the system control center) stores information about generation units, such as cost and limit, and the information used for

scheduling. All the utilities in the control area submit a 24-hour generation plan to a system control center ahead of time (at least 24 hours ahead). The plan is thoroughly examined for secure operation in the area. According to the plan and unit commitment information, generation is dispatched according to marginal cost.

- Unit commitment database information
 - Variable cost for generation
 - Generation limit
- Plan submitted by utilities
 - Concerning their plants
 - Expected system loads (this is estimated from weather information and historical data)

Security operation

Because every action can potentially affect every other operation in the electric power system, the industry has to check the effects of its decisions. A system control center can determine whether the operation is valid or not, because it has all the information about the control area including real time operating information. Congestion control, load frequency control and recovery from emergency, are part of this service. In the case of the transmission line congestion, a system control center curtails a transaction with lower priority transmission to provide reliable load serving.

Electricity exchange between control areas

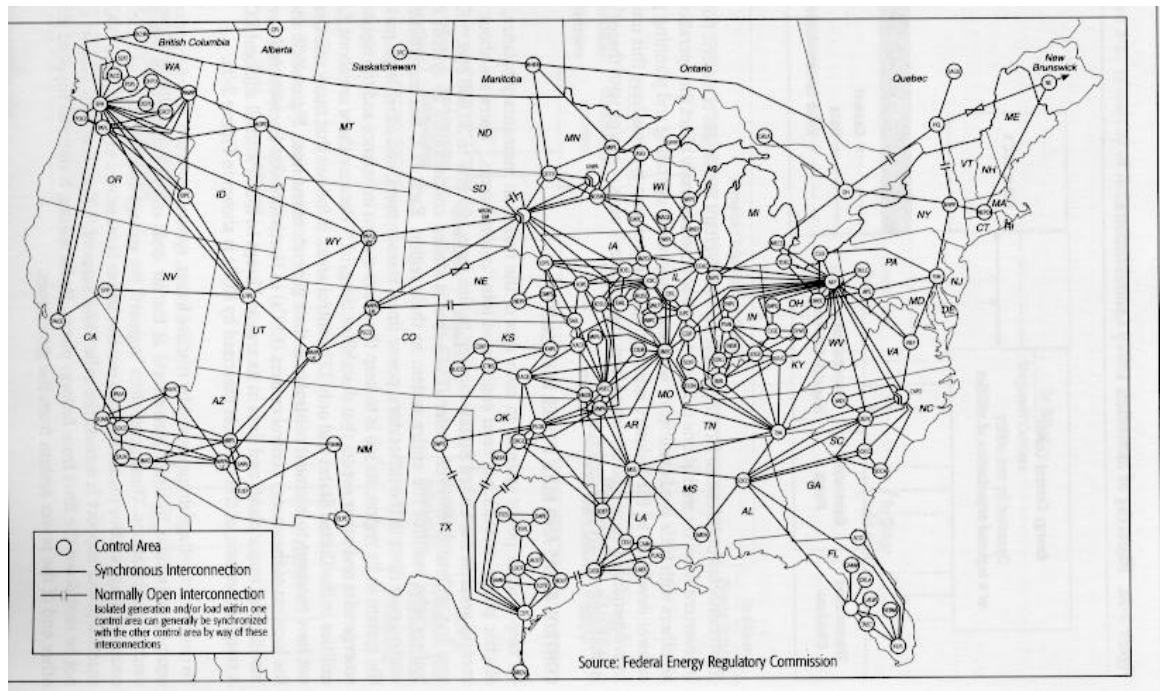
One of the major responsibilities of system control centers is to manipulate electricity exchange between control areas. Each control area defines interfaces (so called tie-lines) between control areas. If a utility wants to provide electricity from one control area to another control area, then electricity is supposed to pass these interfaces between source and destination control areas in the transaction. Once the control areas along the path agree to the transaction, every control area is responsible for this transaction. More explanation about this exchange will be provided in section 4.3.4.

Abstraction

- Properties to be captured
 - Size of the control area
 - Utilities in the control area
 - Generators in the control area
 - Transmission lines in the control area
- Local actions

- Regulate frequency and stabilize voltage
 - Assess and arrange transmission
 - Monitor interface to interchange electricity
 - Perform emergency operation (Prepare backup power, protocol for emergency)
- Neighbors
- Transmission system
 - Generation system
 - Distribution system
 - Local control centers
 - Security coordinators

Figure 8. Interconnected Control Area map in US [F 97]



**Ex
am
ple**

of a system control center: about PJM [PJM m99]

There are total 143 control areas in the U.S. [DOE J98]. The PJM Interconnection, LLC. is one of the system control centers to serve the control area including all or part of Pennsylvania, New Jersey, Maryland, Delaware, Virginia and the District of Columbia. These six states, the district regulatory commissions, and the Federal Energy Regulatory Commission (FERC) have jurisdiction within the PJM control area. The PJM is a largest centrally dispatched control area in North America.

Table 7. Peak load of some control areas and number of generation units. [PJM m99]

Control area	Peak Load (Megawatts)	Number of units
--------------	-----------------------	-----------------

PJM Interconnection	51,550	535
Hydro Quebec	31,530	314
Southern Company Services	27,420	260
New York Power Pool	27,260	455
Tennessee Valley	24,535	109
Ontario Hydro	23,057	300

Table 8. Bulk-power reliability criteria in integrated industry [DOE S98]

Function	Time size	Service
Automatic protection	Instantaneous	Minimize damage to equipment and service interruptions caused by defaults and equipment failures
Disturbance response	Instantaneous to minutes to hours	Adjust generation, breaker, and other transmission equipment to restore system to scheduled frequency and generation/load balance as quickly and safely as possible
Regulation and voltage control	Seconds to minutes	Adjust generation to match scheduled inter-tie flows and actual system load. Adjust generation and transmission resources to maintain system voltages.
Economic dispatch	Minutes to hours	Adjusted committed units to maintain frequency and the generation/load are interchange balance at minimum cost subject to transmission, voltage, and reserve-margin constraints
Transmission loading relief	Minutes to hours	Curtail transactions and redispatch generation to reduce power flows through critical transmission elements
Unit commitment	Hour ahead to week ahead	Decide when to start up and shut down generating units, considering unit ramp-up and -down rates, startup costs, and minimum runtimes and loadings.
Transmission scheduling	Hour ahead to year ahead	Schedule individual transactions and reservations of transmission capacity
Maintenance scheduling	1 to 3 years	Schedule and coordinate interutility sales and planned generating-unit and transmission-equipment maintenance to maintain reliability and to minimize cost.
Transmission const. Planning	2 to 10 years	Design regional and local system additions to maintain reliability and to minimize
Generation planning	2 to 10 years	Develop a least-cost mix of new generating units, retirements, life extensions, and repowering based on long-term load forecasts

4.3.3. Local control center (Utility)

A local control center is a control center in an individual electric service utility. These are the decision-makers about generation, transmission, and distribution. If a utility wants to purchase from the other utilities or deliver electricity to another area, it requires communication with system control centers.

Abstraction

- The properties to be captured
 - Customers to serve
 - Type of service [Generation, Transmission, Distribution]
- Local actions
 - Purchase electricity from other utilities
 - Metering and billing customers
 - Managing their assets
- Neighbors
 - Generation system
 - Transmission system
 - Distribution system
 - System control center
 - Local control center (Other Utility)
 - Security coordinator
 - The public

4.3.4. Operation process abstraction to exchange electricity

Working scenario

These working scenarios are based on Policy 3, Interchange in the operating manual of NERC [NE 00].

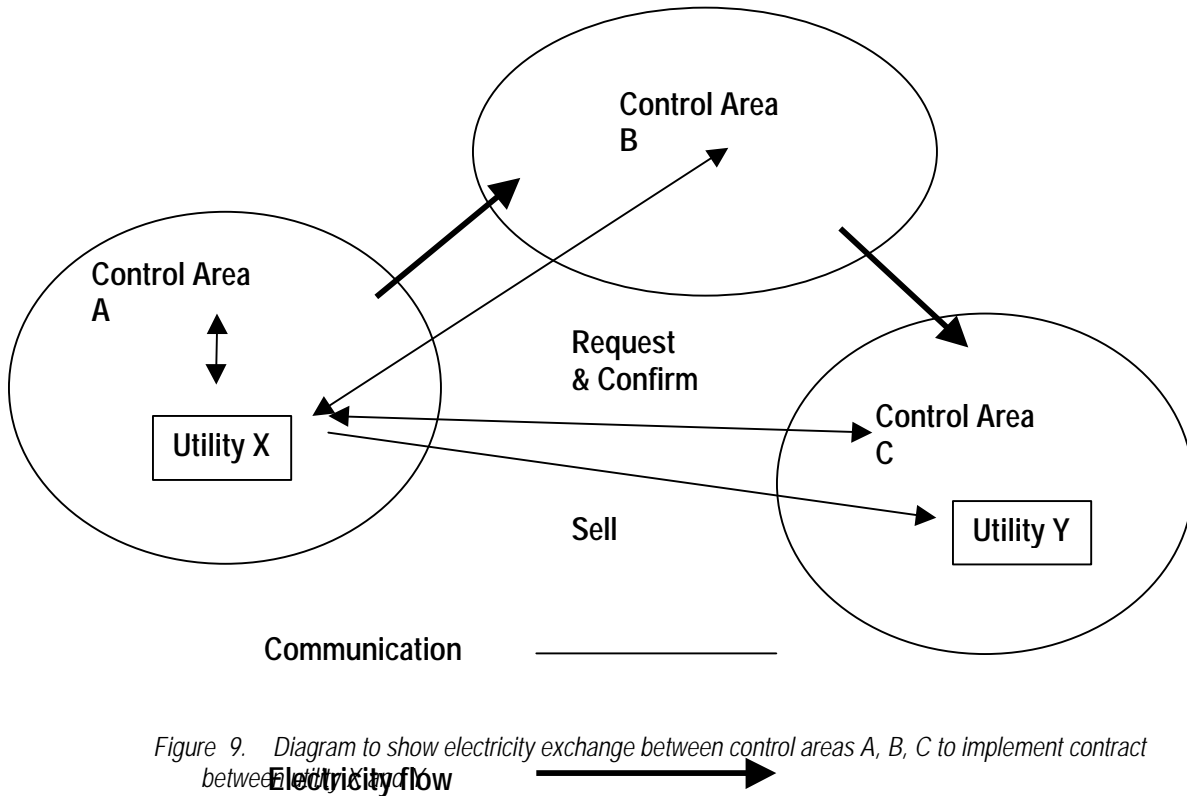


Figure 9. Diagram to show electricity exchange between control areas A, B, C to implement contract between Utility X and Y.

As shown in the Figure 9, suppose that utility X in control area A would like to sell electricity to utility Y in area C and the transmission path in this transaction becomes A->B->C. Then, utility X sends a request to the control areas A, B, and C to approve this transaction from a reliability perspective. If there is one control area among them that declines this request, the transaction cannot be implemented. If they all agree with this transaction, the transmission resource is reserved and the transaction is posted on OASIS. This information will be submitted to a security operator for monitoring purposes. On the

day of the transaction, all the participating control areas watch the interfaces of their control areas to ensure that the net interchange is the same as scheduled. Unless there is a major emergency, the transaction should be implemented, and every participating control area is responsible for this transaction. Although there may be loop flow impacts, the net interchange should be the same as scheduled. A transportation fee will be charged to utility X and Y for this transaction and service [NE 00].

Algorithm

This algorithm has two steps: scheduling and implementation.

Scheduling

```
Utility X, Y; (Assume X is in A and Y is in C)
Control areas A, B, C; (Assume A, B, C is on the path)
Request amount Q;
Schedule {
    Tag =X.request (Q, A);
    Repeat {
        If (one of control area.assess (tag) == OK)    continue;
        Else    Escape loop ( decline transmission request);
    } (until A,B,C is OK);
}
Schedule (Tag);
Post this information to OASIS;
```

Implementation

```
Transmission ( Tag ) {
    X.generation (Q,A);
    While ( Tag is not expired ) {
        All areas (A,B,C) involved in this transaction monitors
        their interface {
            First, A ensures that amount Q is being delivered from X;
            Then B ensures that amount Q is being delivered from area A;
            Finally C ensures that amount Q is being delivered from area B;
        }
    }
}
```

Chapter 5.

Conclusion

In this conclusion chapter, we will summarize our work on the survivability of the U.S. electric power industry. In this thesis, we have achieved our goals described in section 1.2 such as studying the industry's survivability requirements in the environment of deregulation and identifying abstractions of the electric power system for survivability of the electric power industry. However, during this research, more questions about this area have emerged than answers. In this chapter, we are going to summarize our work on survivability requirements and identifying key abstractions of the electric power industry.. In addition, we are going to introduce some findings that can be applied to general survivability research. Finally, we are going to identify topics for future study in this critical research area.

5.1. Survivability requirements of the U.S. electric power industry

The mission survivability requirement of the electric power industry is:

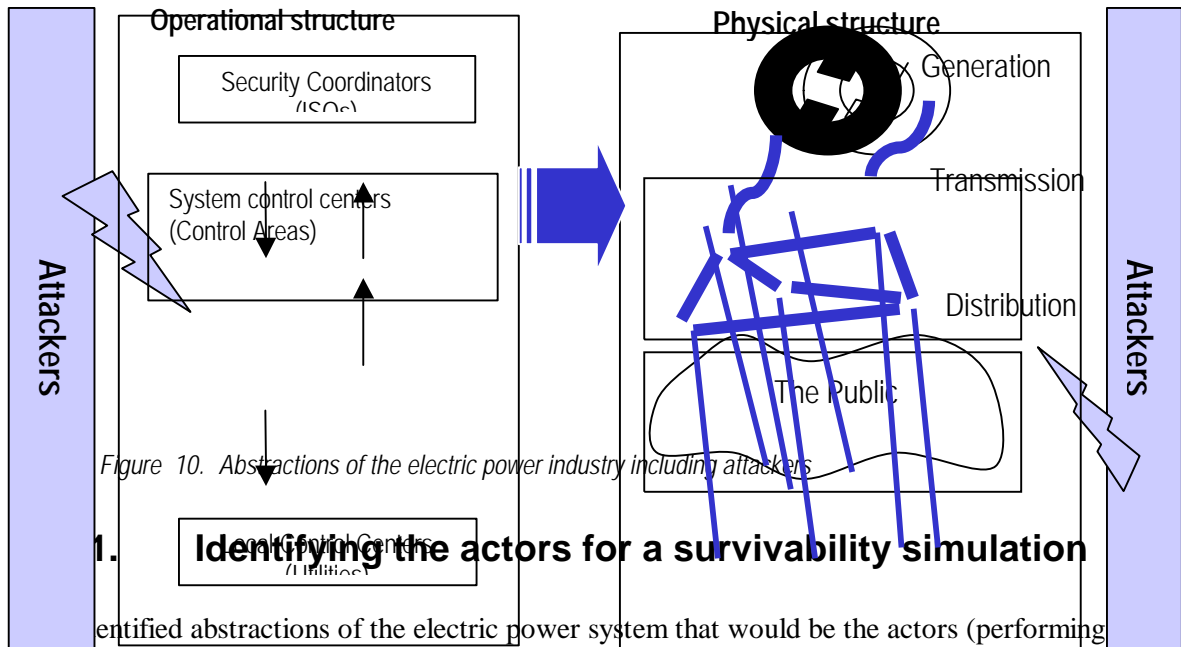
Reliably and profitably generate and supply electricity,
wherever and whenever it is needed in North America.

The reliability requirement is further refined into long term “adequacy planning” and short term “security operation”. Adequacy planning is needed to ensure that there will be enough electric generators and electricity lines to meet future demand. The daily operation in this industry needs special attention, because there are many difficulties in supplying reliable electric power in the presence of sudden disturbances, such as short circuits, or an unexpected loss of system elements. In addition, we discussed some issues that clarify the serious conflicts between the reliability requirements and business requirements in deregulation.

This mission requirement reflects the quality, functional, business and regional requirements of the U.S. electric power system. Reliability is a quality requirement and “wherever and whenever” are additional quality criteria. Generation and supply of electricity are functional requirements. Profitability is a business requirement, which has emerged from deregulation of the industry. These various aspects of the mission should be considered at the same time.

In the situation of deregulation, there will be continual conflicts between profitability and reliability requirements. However, the electric power industry should find a way to satisfy both requirements. Industry participants' compromises between these requirements may decrease the trust of the public in the electric power industry, and the public may seek new solutions that might ignore the current industry structure.

5.2. Identifying key abstractions



local actions and neighbor interactions) in a simulation. We also described the local actions and neighbor interactions of actors in each structure, which is the essential information we need in order to specify emergent algorithms.

As part of future research, the Easel simulation system and language will be used to simulate the electric power system. The electric power system, by its physical nature and control structure, exhibits emergent behavior. Survivability is a highly desirable system-wide emergent property that we want the electric power system to exhibit. Therefore, it is quite appropriate to model the electric power system using emergent algorithms. Because the Easel system is designed to simulate emergent algorithms, the electric power system will be simulated more accurately and efficiently than with other simulators. A primary use of the simulator will be to evaluate and compare the effects on survivability of alternate policies and policy implementations. Furthermore, by including other infrastructures such as telecommunications and transportation as actors in an electric power simulation, we can simulate the interdependencies between these infrastructures and the electric power system.

5.2.2. Survivability scenarios

There could be two types of attackers in the electric power system. One attacker may try to

attack the physical structures by brute force. For example, the attacker could cut major transmission lines or damage one of the generators. The transmission system is considered to be the most vulnerable point in the physical structure because transmission lines are exposed everywhere and even one failure could cause a major outage. As a result of this, coordinated attackers could plan to cut transmission lines supplying power to a targeted organization or region. For survivability, contingency plans must be devised for this type of attack.

The other type of attack could be an attempt to attack one of the entities in a control structure. The most critical part of the control structure is a system control center because this entity is involved in most of the operations to stabilize the electricity network. On the other hand, a security coordinator's role can be simply replaced by one of the control areas nearby. In case of attack, the control center has a backup facility. In the worst case that the backup center cannot function properly, one of the local control centers should serve as a system control center instead and coordinate their operations to minimize adverse affects.

5.3. General survivability

In this thesis, we applied the survivability approach to a specific case, the electric power system. From this research, we found the following methods could be applied to improve the general survivability approach.

5.3.1. Long-term evolution

As discussed above, the survivability of the electric power system needs long-term planning to provide reliable service. Insufficient capacity certainly threatens the survivability of this system. This case implies that survivability may need to consider long-term evolution in general. However, the long-term issues are not discussed seriously in survivability. The concept of evolution should be included in survivability research. In particular, capacity planning should be considered to improve the survivability of a system based on a forecast of future usage.

5.3.2. Measurement of survivability

The electricity power industry has established good operation standards to maintain reliability. Their reliability measurement that includes frequency, duration and magnitude of adverse effects on consumer services is particularly interesting. We can apply this

measurement concept as a measurement of survivability. Survivability relates to fulfillment of mission and continuity of essential services. The reliability measurement we are discussing involves measuring adverse effects on the provision of services, and therefore using this measurement can assess some aspects of a system's survivability. Based on the assessed survivability performance of the system, we can modify the system's features to improve its survivability. This technique can be successfully applied by gathering data on all occurrences of adverse effects on services and then creating quantitative benchmarks that can contribute to improved survivability. This measurement may also be useful in understanding the level of contribution of particular components to the fulfillment of the mission.

5.4. Future study

The environment of the electric power industry is rapidly changing. In particular, the dependency of the electric power industry on information system is increasing. Deregulation is driving a restructuring of the industry from the bottom up, and this restructuring might lessen the industry's ability to fulfill its mission. To continue to fulfill its mission, the industry must use a survivability approach to adapt to the new environment. Survivability takes a business risk management perspective in recognizing and dealing with the vulnerabilities in an organization's information systems [LF 99]. Therefore, a survivability approach should be considered seriously in this new environment. Simulation and abstraction can play an important role in understanding survivability problems and solutions. Here is a list of topics that should be further researched to improve the survivability of the electric power industry.

- Using Easel, develop an emergent algorithm to adapt to the environment of deregulation. The industry is now changing and we expect that it is going to exhibit even more emergent behavior because the competitive market adds an additional source of such behavior. However, in addition to satisfying the business requirement of the mission in the competitive market, the emergent algorithm should guarantee the reliability requirement of the mission.
- Study the increasing dependency of the electric power system on information systems. We need to study the information systems used in the electric power industry. The study of the dependency of the electric power system on

information systems will help the industry to identify the risks and to prepare risk management strategies.

- Interdependency study with the other infrastructures. In the absence of electricity, how survivable are the rest of our society's critical infrastructures? Also, we need to investigate how survivable the electric power industry would be if telecommunications or other critical infrastructures were unavailable. This interdependency study would involve a broad investigation across the critical infrastructures. We need to determine to what extent contingency plans exist for dealing with the unavailability of other infrastructures. The operation manuals existing in each industry will provide a good source to start this research.
- Additional study about the physical structure is necessary. Even though an in-depth study of the details of electricity operation is not in the scope of this thesis, to understand the impact of the implementation of alternate policies further study about the physical structure of the electric power system would be necessary. However, further study of the physical structure requires expertise about the details of electricity operation. We might want to use a simulation to assess the consequences of some behaviors such as whether generating 100 MW from utility "A" is reliable or not. Joint research with a utility might provide the expertise needed to make this simulation better reflect reality.
- Survivability analyses using "what-if" scenario will be necessary. There are many types of disturbances, such as cascade outages, in the electric power system. These disturbances can be represented as survivability "what-if" scenarios and serve to test a proposed policy running on in a simulation. In appendix F, a major disturbance, called a cascade outage, is described as an example of a survivability "what-if" scenario. However, in the future, we will need to illustrate a broad range of cyber-attack scenarios as well.

Bibliography

- [BT 00] Eric Bonabeau, Guy Theraulz, *Swarm Smarts*, Scientific American, Vol. 282, No. 3, March 2000.
- [CNN 00] CNN, “Denial of Service Hackers Take on New Targets”, CNN, February 9, 2000. Available at <http://www.cnn.com/2000/TECH/computing/02/09/denial.of.service.03/>.
- [DOE D99] U.S. Department of Energy, “Directory of energy Information Administration Models” 1999, Energy Information Administration, Washington DC. Available at <http://www.eia.doe.gov/oss/models.html>
- [DOE F98] Energy Information Administration, “The National Energy Modeling System: An Overview 1998”, DOE/DIA-0581 (98), Office of Integrated Analysis and Forecasting U.S. Department of Energy, Washington DC.
- [DOE S98] U.S. Department of Energy, *Maintaining Reliability in a Competitive U.S. Electricity Industry –Final Report of the Task Force on Electric System Reliability*, September 1998, Secretary of Energy Advisory Board. Available at <http://www.hr.doe.gov/seab/electsys.html>
- [DOE M99] U.S. Department of Energy, “Supporting Analysis for the Comprehensive Electricity Competition Act,” DOE/PO-0059, Office of Economic, Electricity and Natural Gas Analysis Office of Policy, Washington DC, May 1999.
- [DOE J98] U.S. Department of Energy, “The Changing Structure of the Electric Power Industry: Selected Issues”, DOE/EIA-0562 (98), July, 1998 Available at http://www.eia.doe.gov/cneaf/electricity/chg_str/.

- [DOE J00] U.S. Department of Energy, “The Restructuring of the Electric Power Industry, A Capsule of Issues and Events”, DOE/EIA-X037, Energy Information Administration, January 2000, Washington D.C. Available at http://www.eia.doe.gov/cneaf/electricity/chg_str/booklet/electbooklet.html
- [DOE O98] U.S. Department of Energy, “Electric Power Annual 1997”, DOE/EIA-0348 (97), October 1998, Washington, DC. Available at <http://www.eia.doe.gov/cneaf/electricity/page/pubs.html>
- [DOE S99] U.S. Department of Energy, “The Comprehensive Electricity Competition Act: A Comparison of Model Results”, SR/OIAF/99-04, Energy Information Administration, Office of Integrated Analysis and Forecasting, Washington DC. Available at <http://home.doe.gov/policy/ceca.htm>.
- [DOE A99] U.S. Department of Energy, “The Comprehensive Electricity Competition Act”, Department of Energy, Washington DC, April 1999. Available at <http://home.doe.gov/policy/ceca.htm>.
- [E 98] Matthew E. Elder, “Major Security Attacks on Critical Infrastructure Systems”, *Topics in Survivable Systems*, Computer Science Report No. CS-98-22, University of Virginia, August 1998.
- [EFL 97] R.J. Ellison, D. Fisher, R.C. Linger, H. F. Lipson, T. A. Longstaff, and N.R. Mead, *Survivable Network Systems: An Emerging Discipline*, Software Engineering Institute Technical Report No. CMU/SEI-97-TR-013, November 1997, revised May 1999. Available at <http://www.cert.org/research/>
- [ELLM 98] R.J. Ellison, R.C. Linger, T.Longstaff, N.R. Mead, *A Case Study in Survivable Network System Analysis*, Software Engineering Institute Technical Report No. CMU/SEI-98-TR-014, ESC-TR-98-014, September 1998. Available at <http://www.cert.org/research/>
- [F 97] Peter Fox-Penner, *Electric Utility Restructuring: A Guide to the Competitive Era*, Public Utilities Reports, Inc., April 1997.
- [F 99] David A. Fisher, “Design and Implementation of EASEL—A Language for Simulating Highly Distributed Systems”, *Proceedings of MacHack 14th Annual Conference*, Dearborn, MI, June 24-26, 1999.
- [FL 99] David A. Fisher, Howard F. Lipson, “Emergent Algorithms – A New Method for Enhancing Survivability in Unbounded Systems”, *Proceedings of 32nd Annual Hawaii International Conference on System Science*, Maui, Hawaii, January 5-8, 1999 (HICSS-32), IEEE Computer Society, 1999. Available at: <http://www.cert.org/research/>
- [ISW 97] *Proceedings of the 1997 Information Survivability Workshop*, San Diego, California, February 12-13, 1997, Software Engineering Institute and IEEE computer Society, April 1997, 83 pp. Available at <http://www.cert.org/research/>
- [ISW 98] *Proceedings of the 1998 Information Survivability Workshop*, Orlando, Florida, October

28-30, 1998, Software Engineering Institute and IEEE Computer Society, 1998. Available at: <http://www.cert.org/research/>

- [LF 99] Howard F. Lipson, David A. Fisher, “Survivability – A New Technical and Business Perspective on Security”, *Proceedings of the New Security Paradigms Workshop*, September 1999, Association for Computing Machinery, New York, 1999.
- [LML 98] R. C. Linger, N. R. Mead, and H. F. Lipson, “Requirements Definition for Survivable Network Systems”, *Proceedings of the International Conference on Requirements Engineering*, ICRE 1998. Available at <http://www.cert.org/research/>
- [M 88] Robert H. Miller, *Power System Operation*, McGraw-Hill Book Company, 1988.

- [M 98] Sean McCulloch, “An Analysis of Non-Security Failures of the Electric, Phone, and Air Traffic Control Systems” *Topics in Survivable Systems*, Computer Science Report No. CS-98-22 University of Virginia, August 14, 1998.
- [MA 99] John D. Mountford, Ricard R. Austria, “Keeping the Lights on!” *IEEE Spectrum*, June, 1999, Vol. 36, No. 6.
- [NE A96] North American Electric Reliability Council, *Glossary of Terms*, Prepared by the Glossary of Terms Task Force, North American Electric Reliability Council, August 1996, Available at <http://www.nerc.com/glossary>.
- [NE 00] NERC, *NERC Operating Manual*, February 15, 2000. Available at ftp://www.nerc.com/pub/sys/all_updl/oc/opman/opman.pdf.
- [O 98] James Odell, “Agents and Emergence”, ACM, *Distributed Computing*, October 1998.
- [OWP 99] Thomas J. Overbye, Jamie D. Weber, Kollin, J. Patten, “Analysis and Visualization of Market Power in Electric Power Systems”, *Proceedings of 32nd Annual Hawaii International Conference on System Science*, Maui, Hawaii, January 5-8, 1999 (HICSS-32), IEEE Computer Society, 1999.
- [PCCIP 97] Presidential Commission on Critical Infrastructure Protection, *Critical Foundations – Protection America’s Infrastructures*, The Report of the Presidential Commission on Critical Infrastructure Protection, October 1997, p. 173.
- [PHT 99] A.G. Phadke, S.H. Horowitz, J.S. Thorp, “Aspects of Power System Protection in the Post-Restructuring Era”, *Proceedings of the Hawaii International Conference on System Sciences*, January 1999, Maui, Hawaii.
- [PJM 99] PJM Interconnection, L.L.C., *PJM Manual*, June 2, 1999. Available at <http://pubs.pjm.com>
- [PJM m99] PJM Interconnection. “About PJM “, May 1999. Available at <http://www.pjm.com>.
- [PW 99] PowerWorld, “PowerWorld Simulator”, PowerWorld Co. Illinois. Available at <http://powerworld.com/simulator/index.html>.
- [S 00] William Sweet, “Power & Energy”, *IEEE Spectrum*, January 2000.
- [SKDG 98] Kevin Sullivan, John C. Knight, Xing Du, Steve Geist, “Information Survivability Control Systems”, University of Virginia, 1998.
- [W 97] James D. Weber, *Implementation of a Newton-based Optimal Power Flow Into a Power System Simulation Environment*, MS Thesis in Electrical Engineering in University of Illinois at Urbana-Champaign, 1997.

Appendix A. Geographic structure of the electric power system

The U.S. electric transmission system is a unified electrical network including most Canada and part of Mexico. As operating convention, it is divided to 5 interconnections and further to 10 regional voluntary councils.

Most of all, the electric transmission system composed of five interconnections¹⁶: Western, ERCOT, Eastern, Quebec and Mexico interconnection (in figure 1). Western, Eastern and ERCOT serve U.S: Eastern Interconnects composing of eastern two-thirds of U.S. and some of Canadian Provinces, the Western Interconnects composing of 12 States west of the Rocky Mountains, some of Texas and some part of Mexican State and the Texas interconnects [DOE J98]. Except Alaska and Hawaii, these major power grids interconnect utilities in US.

Figure a.
Three interconnects and the North American electric Reliability Council Geographic structure

Appendix B. Reliability organizations in the industry

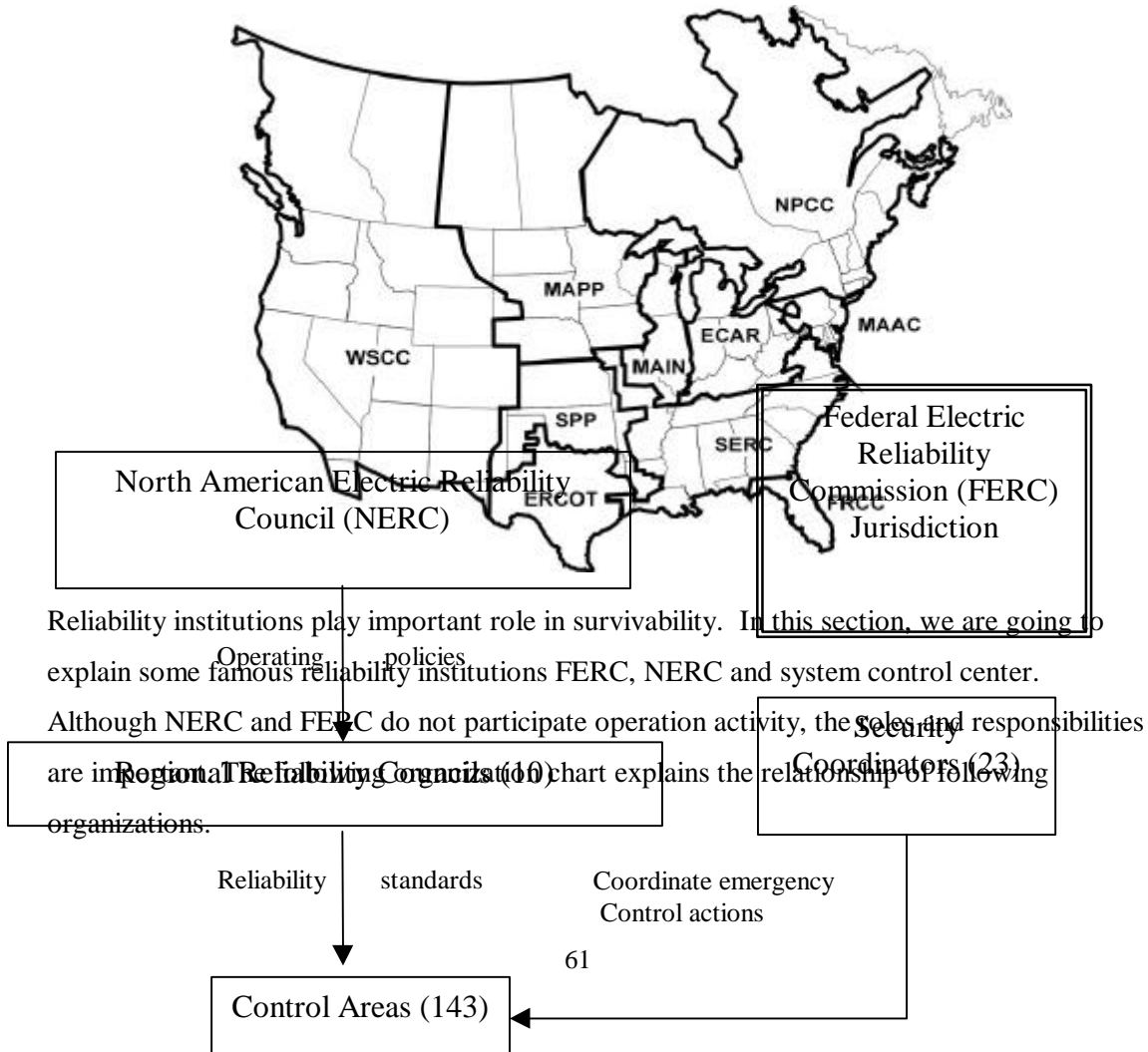


Figure b. Organizational structure for electric system reliability [DOE J98]

Source: Energy Information Administration, Office of Coal, Nuclear, Electric and alternate fuels.

¹⁶ Interconnection is sometimes called as a grid

FERC¹⁷

The Federal Energy Regulatory Commission is the Federal agency with jurisdiction over bulk power market, including interstate transmission systems. As part of these responsibilities, the FERC implements policies to assure that the owners and operators of bulk power transmission facilities under the agency's jurisdiction provide nondiscriminatory service to all power suppliers in wholesale power markets [DOE S98].

NERC¹⁸

NERC's mission has been to promote electrical system reliability and there by prevent further such occurrences. The NERC has been a voluntary, industry-constituted governing body that develops standards, guidelines, and criteria for assuring system security and evaluating system adequacy.

The NERC has been funded by regional reliability councils, which adapt the rules to meet the needs of their regions. Historically, the Reliability Councils have functioned without external enforcement powers, depending on voluntary compliance with standards and peer pressure [DOE S98].

System control centers and security coordinators

Most of the utilities in the U.S. grouped with neighbor utilities and formed a control area. The utilities in a control area cooperate each other as if there is one single utility in a control area. This cooperation in control area helps the utilities to save cost and achieve reliability altogether. This practice is called *aggregating demand* in a control area. For example, because the electric power system is interconnected, the utilities can use back up generators from the interconnected neighbor utility. In addition, if the production cost of one utility is more expensive than the other utilities in control area, they can easily buying request to the other utilities to reduce cost. A system control center in the control areas coordinates such cooperation activities.

Today approximately 143 separate control areas serve the country, each with its own system control center [DOE J98]. The system control centers can dispatch generators, schedule generation and transmission for next day and monitor electricity network for emergency to reduce damage. In addition to the individual control area operators, 23 regional

¹⁷ For more information, please refer to <http://www.ferc.fed.us>

security coordinators monitor the electric network within the regions and across the regional boundaries and take actions in emergency [DOE S98].

¹⁸ For more information, please refer to <http://www.nerc.com>

Appendix C.

Benchmark of other simulators for the energy power system

There are several simulation tools used in electric power system. NEMS and POEMS developed by the department of energy (DOE) help to analyze electric power industry for government policy decision. PowerWorld simulator is a commercial simulator to assess security of an operation. It provides us the insight about electric power industry in terms of economic and electricity flow [DOE F98, DOE D99].

1) NEMS

The National Energy Modeling System (NEMS) is a computer-based, energy-economy modeling system of U.S. energy markets [EIA F98]. NEMS was designed and implemented by the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE). NEMS is used to analyze the effects of existing and proposed government policy, introduction of new technology and change of market situation. In fact, NEMS is used by EIA to produce the annual baseline energy forecasts published in the Annual Energy Outlook. The analysis is represented as collection of numbers such as production, imports, consumption, and prices of energy. NEMS is modular in structure to consist of following components.

Integrating modules of the National Energy Modeling System

- Commercial Sector Demand Module
- Industrial Demand Module
- Residential Sector Demand Module
- Transportation Sector Module
- Coal Market Module
- Natural Gas Transmission and Distribution Model
- Oil and Gas Supply Module
- Renewable Fuels Module
- Petroleum Market Model
- Electricity Market Module
- International Energy Module
- Macroeconomic Activity Module

The electricity market module (EMM), one of components of NEMS, provides analysis about electricity market. The EMM receives electricity demand from the NEMS demand modules, fuel prices from the NEMS fuel supply modules, expectations from the NEMS system module, and macroeconomic parameters from the NEMS macroeconomic module and

then estimates the actions taken by electric utilities and nonutilities to meet demand in the most economical manner. The EMM then outputs electricity prices, fuel consumption, emissions and capital requirements.

2) POEMS

Because the NEMS is designed for a wide variety of forecasting and policy issues, the level of detail provided in each NEMS module is constrained towards this general use. The Policy Office Electricity Modeling System (POEMS), on the other hand, is more narrowly aimed at addressing specific questions surrounding electricity markets [DOE M99]. It substitutes TRADELEC for the EMM in NEMS. The differences between EMM and TRADELEC are in regional detail, pricing methodology, stranded costs, reserve margins and trade style. TRADELEC simulates electricity market more finely because it disaggregates to the control area level than NERC regional level, which includes several power control area in each region. TRADELEC is subdivided with four modules: Demand/Load, Capacity planning, Pricing and Dispatch/Trade. The comparison of these two model results are discussed in [DOE S99]

3) Learning from NEMS and POEMS

Both simulations show that what factors influence electric market in a broad view. For example, profit maximization behavior of industry will affect increase of transmission between control areas. It is represented as decline of price in some area and increase of price in another area as forecast of POEMS and NEMS. Especially detail explanation about input factors will be useful for the simulation for survivability of energy power system.

3) PowerWorld

On the contrary, to the high-level simulators, NEMS and POEMS, the simulator, PowerWorld, simulates electricity flow. This section introduces a simulation tool, PowerWorld, which is developed by PowerWorld¹⁹. PowerWorld simulator is a user interactive power system simulator designed to simulate high voltage power system operation with visualization [PW 99].

The simulator uses a mathematical model, a non-linear Newton algorithm to represent

¹⁹ It is originally developed in a project of UIUC Power System graduate program.

Appendix D.

Information system used in the PJM system control center

This section is to give information about what information systems are used in the electric power system. This information will be useful for future study to investigate information system used in the electric power system. However, it must be difficult to study this part. Because this information is very critical and credential, so it might not be publishable to the public. The followings are computer system used in PJM system control center²⁰[PJM 99].

Mainframe Computer Applications

- Unit Commitment Database (UCDB) – This database resides on the mainframe computer and is used by the Marginal Scheduler and Hydro Calculator programs. Utilities update the UCDB several times per day via computer networks.

PC applications

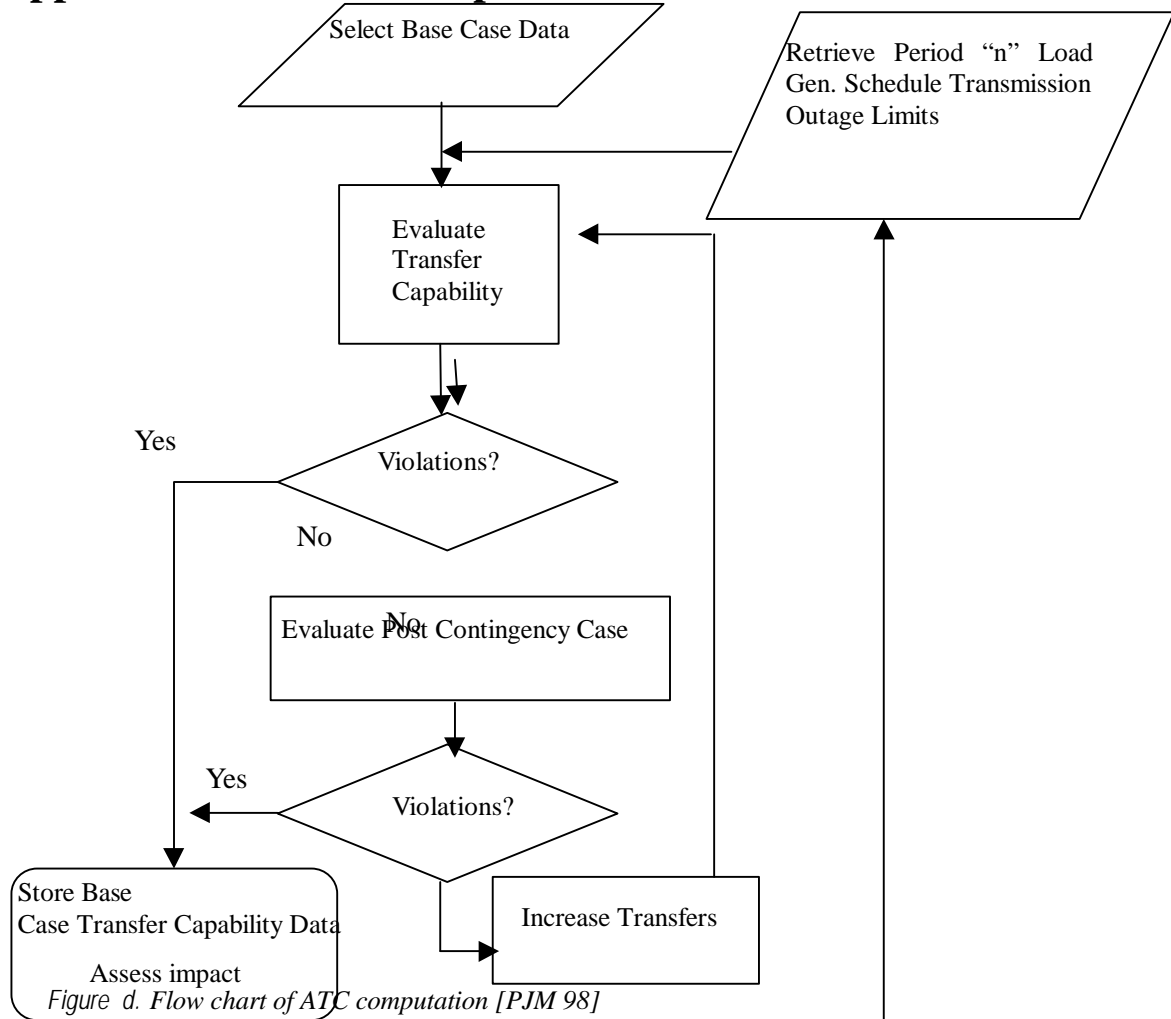
- Generation control system – calculating Area Control Error (ACE), Area Regulation (AR) and economic dispatch.
- Network analysis and SCADA program – monitor network using data gathered through SCADA system
- Resource scheduling and commitment – schedule generation resources for up to a week in advance
- Transaction management system – accounting information
- Hydro calculator – scheduling for hydro generators.
- Regulation logger – accounting and operation information with respect to regulation. Manual input data received via telephone
- Combustion turbine logger – accounting and operation information with respect to combustion turbines
- Interchange distribution Calculator – connected to the IDC server and produces information regarding actual vs. scheduled MW flows. Information is sent to the IDC via the System Data Exchange (SDX) communication link.

Ancillary tools

- Video Graphic Recorders (VGRs) – CRT terminal to display information
- Informational TV – cable TV to obtain weather information
- National Lightning Detection Network (THUNDER) – via satellite
- Weather Data
- Direct phone lines – direct telephone line is available between PJM control center, local control center and utilities and between neighborhood control centers
- ALL-CALL – simultaneous call line to local control center
- Dynamic Mapboard – displays status of lines, transformers, capacitors and results of security analysis of bulk power transmission system
- Racal Recording Device – record all conversations from dispatching and scheduling positions for documentation

²⁰ For more information PJM manual [PJM 99] for dispatching operation section 2.

Appendix E. ATC computation used in PJM



This process is a summarization of description about Available Transfer Capability (ATC) computation in [PJM 98].

1. Here, base case data indicates a status that no transfer is allocated to the transmission path.

According to [W 97], base case shows current load and generation of two areas without exchange of electricity.

Adjustments to Determine ATC&ETC

2. After defining base case data, evaluate transfer capability. If it violates security conditions such as appropriate voltage limit, the transaction is declined and is not scheduled. If it does not, then move on to next time slot.

3. If there is available capacity, then it evaluates post contingency data. It checks whether it is reliable after contingency occurs. If it does not pass this test, also it is rejected.

4. If it does not need next time slot, it updates ATC and TTC (Total Transfer Capacity). At last assess the impact and post the data on OASIS (Open Access Simultaneous Information System) that anybody can see.
5. Input data for ATC computation are base case data, projected loads, transmission outages, reactive and thermal contingency list, firm and non-firm margins and temperature-dependent thermal ratings sets.

Appendix F. Cascade outage

The cascade outage is a major contingency occurred by overload of transmission line. For more information, refer to policy 5, emergency operations in operating manual of NERC [NE 00].

What is cascade outage?

Suppose the system is humming along in balance, and then a large transmission line suddenly fails. Neither generation nor demand has changed, so the system is still in energy balance, demand has not changed, so the system is still in energy balance, but suddenly hundreds of megawatts of power that were traveling on the failed line have rearranged themselves according to the new paths of least resistance across the altered network topology. The new flow pattern will quickly overload some other lines since they were not set up to handle their original flow plus the flow from the broken line. Transmission lines have fuses or circuit breakers to protect them against overloads, so the newly overloaded lines will automatically shut themselves off. This, in turn, may overload and shut off additional lines, and the process may continue if remedial actions are not taken.

Within a matter of seconds, this process sequentially causes dozens of power lines and power plants to shut themselves off in response to one contingency. The pattern of shutdowns will depend on exact electrical conditions all over the network at that moment, and can easily cascade.

Recognition mechanism

The electricity network shows fluctuation of frequency and voltage when it happens. This can be recognized by a security coordinator or system control center.

Resistance mechanism

- Isolation

To reduce cascading failures, power systems are designed to automatically disconnect the rest of the system from the area with a problem. This isolation by shutting down the lines is a reasonable solution because the generation asset and system circuits for transmission system difficult to be recovered once they are damaged.

- Transmission system relief

In some case, as in congestion control, curtailment can be used to resist the disturbance.

Recovery mechanism

Each control area has a protocol to recover a transmission system defined in operating manual for emergency (for example, see the emergency operation in PJM [PJM 99]). If the system is not damaged by overflow, the involved system control center or local control center can restore transmission systems by the order of significance and let them come back to normal operations.

Cascade outage example

In December 1994, the cascading outage happened in western states and two Canadian provinces. In this disturbance, it took one minute and 25 seconds between first failure in S. Wyoming and last failure in Diablo near Los Angeles, 1,000 miles away. Few minutes were taken to restore 40% of customers. 4 hours were taken to restore total system [F 97].

Appendix G. Electricity operation glossary

To make clear meaning of the terms used throughout this paper, the following key terms and definitions are provided based on the NERC glossary [NE A96] and the glossary in the final report of the task force on electric system reliability, Maintaining reliability in a competitive U.S. Electricity Industry [DOE S98]. Online glossary is available at <http://www.nerc.com/glossary/glossary-footer.html>

Adequacy – The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements [DOE S98]

Availability – A measure of time a generating unit, transmission line, or other facility is capable of providing service, whether or not it actually is in service. Typically, this measure is expressed as a percent available for the period under consideration [DOE S98].

Available Transfer Capability (ATC) – A measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses [DOE S98].

Backup Power – Power provided by contract to a customer when that customer's normal source of power is not available [DOE S98].

Bulk-Power system – the portion of an electric system that encompasses the generation resources, system control, and high-voltage transmission system [DOE S98].

Capacity – The rate continuous load-carrying ability, expressed in megawatts (MW), megavolt-amperes (MVA), or megavoltampere-reactive (MVAR) of generation, transmission, or other electrical equipment [DOE S98].

Cascading – The uncontrolled successive loss of system elements triggered by an incident at any location. Cascading results in widespread service interruption, this cannot be restrained from sequentially spreading beyond an area predetermined by appropriate studies [DOE S98].

Contingency – The unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, switch, or other electrical element, A contingency also may

include multiple components, which are related by situations leading to simultaneous component outages [DOE S98].

Control Area – An electric system or systems, bounded by interconnection metering and telemetry, capable of controlling generation to maintain its interchange schedule with other control areas and contributing to frequency regulation of the Interconnection [DOE S98].

Curtailment – A reduction in the scheduled capacity or energy delivery [DOE S98].

Demand-Side management – Programs that affect customer use of electricity, both the timing (sometimes referred to as load management) and the amount (sometimes referred to as energy efficiency) [DOE S98].

Distribution System – The portion of an electric system that “transports” electricity from the bulk-power system to retail customers, consisting primarily of low-voltage lines and transformers [DOE S98].

Electric Utility (used as Utility in this paper)- A corporation, person, agency, authority, or other legal entity or instrumentality that owns or operates facilities for the generation, transmission, distribution, or sale of electric energy primarily for use by the public and is defined as a utility under the statuses and rules by which it is regulated. Types of Electric Utilities include investor-owned, cooperatively owner, and government-owned (Federal agency, crown corporation, State, provincials, municipals, and public power districts) [DOE S98].

Emergency – Any abnormal system condition that requires automatic or immediate manual action to prevent or limit loss of transmission facilities or generation supply that could adversely affect the reliability of the electric system [DOE S98].

Frequency – the rate, in cycles per second (or Hertz, Hz) at which voltage and current oscillate in electric-power systems. The reference frequency in the North American Interconnections is 60Hz [DOE S98].

Generating Unit – Any combination of physically connected generator(s), reactor(s), boiler(s), combustion turbine(s), or other prime mover(s) operated together to produce electric power [DOE O98].

Generation – The process of producing electric energy by transforming other forms of energy; also the amount of electric energy produced, expressed in watt-hours (Wh) [DOE O98].

Generator Governor – The mechanical or electronic device that controls the power output of a generating unit in response to changes in interconnection frequency [DOE S98].

Grid – A system of interconnected power lines and generators that is managed so that the generators are dispatched as needed to meet the requirements of the customers connected to the grid at various points. Gridco is sometimes used to identify an independent company responsible for the operation of the grid [DOE S98].

Independent System Operator (ISO) – A neutral operator responsible for maintaining the generation-load balance of the system in real time. The ISO performs its function by monitoring and controlling the transmission system and some generating units to ensure that generation matches loads [DOE S98].

Interconnected system – A system consisting of two or more individual electric systems that normally operate in synchronism and have connecting tie lines [DOE S98].

Interface – The specific set of transmission elements between two areas or between two areas comprising one or more electrical systems [DOE S98].

Load – A consumer of electric energy; all the amount of power (sometimes called demand) consumed by a utility system, individual customer, or electrical device [DOE S98].

Reactive Power – The portion of electricity that established and sustains the electric and magnetic fields of alternating-current equipment. Reactive power must be supplied to most types of magnetic equipment, such as motors and transformers. It also must supply the reactive losses on transmission facilities. Reactive power is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors and directly influences electric system voltage. It is usually expressed in kilovars (kVAR) or megavars (MVAR) [DOE S98].

Reliability – The degree of performance of the elements of the bulk-power system that results in electricity being delivered to customers within accepted standards and in the amount desired. Reliability may be measured by the frequency, duration, and magnitude of adverse effects on the electric supply. Electric system reliability can be addressed by considering two

basic and functional aspects of the electric system – adequacy and security [DOE S98].

Schedule – An agreed-upon transaction size megawatts, start and end time, beginning and ending ramp times and rate, and type required for delivery and receipt of power and energy between the contracting parties and the control area(s) involved in the transaction [DOE S98].

Scheduling, System Control, and Dispatch Service – The ancillary service that provides for (a) scheduling, (b) confirming and implementing an interchange schedule with other control areas, including intermediary control areas providing transmission service, and (c) ensuring operational security during the interchange transaction [DOE S98].

Security – The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements [DOE S98].

Spinning Reserve – That reserves generating capacity running at a zero load and synchronized to the electric system [DOE O98].

Stability – The ability of an electric system to maintain a state of equilibrium during normal and abnormal system conditions or disturbances [DOE S98].

Synchronize – The process of connecting two previously separated alternating current apparatuses after matching frequency, voltage, phase angles, and so forth (for example, paralleling a generator to the electric system) [DOE S98].

Tie-line – A transmission line that interconnects two control areas or regions [DOE S98].

Transmission – An interconnected group of lines and associated equipment for the movement or transfer of electric energy between points of supply and points at which it is transformed for delivery to customers or is delivered to other electric systems [DOE S98].

Unit Commitment – The process of determining which generation should be operated each date to meet the daily demand of the system [DOE S98].