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Modelling of the Western University Campus Electrical Network for Infrastructural Interdependencies in a Disaster Response Network Enables Platform

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A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science

MODELLING OF THE WESTERN UNIVERSITY CAMPUS ELECTRICAL NETWORK FOR INFRASTRUCTURAL INTERDEPENDENCIES IN A DISASTER RESPONSE NETWORK ENABLED PLATFORM

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ABSTRACT

The interdependencies that exist between multiple infrastructures can cause unexpected system behaviour when their component failure occurs due to large disruptions and natural disasters such as, earthquake or Tsunami. The complexities of these interdependencies make it difficult to effectively recover infrastructure because of the several challenges encountered. To overcome these challenges, a research program called Disaster Response Network Enabled Platform (DR-NEP) was initiated. This thesis deals with the modelling of electrical networks in order to study critical infrastructures interdependencies as a part of DR-NEP project through Western campus infrastructure examples.

In the first module of the thesis, the concept and understanding of interdependencies is presented. For studying the infrastructural interdependencies, three infrastructures are selected at Western campus: electrical power system, steam system and water systems. It is demonstrated that electrical infrastructure is one of the most critical infrastructure as all other infrastructures are dependent on electrical input. This thesis subsequently presents the development of a detailed model of the electrical power system of Western campus. This model is validated with actual measured data provided by the Western facilities management for different loading conditions and different locations in the feeder. Such a model has been developed for the first time at Western University. This model can be used not just for studying disaster scenarios but also for planning of future electrical projects and expansion of facilities in the Western campus.

The second module of thesis deals with different disaster scenarios, critical subsystems and the impact of appropriate decision making on the overall working of the Western campus, with a special focus on electrical power systems. The results from the validated electrical model are incorporated into the infrastructural interdependency software (I2Sim). A total of six disaster scenarios covering Western's various infrastructure systems are studied; three involving electrical power systems in collaboration with water and steam systems, and the other three involving only electrical power system. The study of interdependency during disasters is performed to generate a wiser decision making process. The results presented in this thesis are an important addition to the earlier work done in DR-NEP project, which only involved three infrastructures: steam, condensate return, and water. In this thesis, the information on electrical networks which was earlier missing is provided through the validated electrical power model.

It is demonstrated that decisions to reduce electrical power consumption on campus by evacuating campus areas are effective in stabilizing the hospital operations, but not in maintaining Western business continuity. A decision to accommodate hospital activities according to power availability appears to be the better choice. The results presented in this thesis will help to pre-plan different preparedness strategies in a much better manner to deal with any future potential emergencies in the Western campus.

Keywords: Infrastructure Simulators, Critical Infrastructure interdependencies, Disaster Response Management, Energy management, Integration Software architecture.

Dedicated to my

Family

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Gagandeep Singh Gill

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LIST OF ABBREVATIONS

DR-NEP	The Disaster Response Network Enabled Platform
CIAO	The Critical Infrastructure Assurance Office
SCADA	Supervising Control and Data Acquisition
AIT	Asian Institute of Technology
CANARIE	Canada’s Advanced Research and Innovation Network
IBM	International Business Machines Corporation
EXC	Emergency Expert Center
EMTDC	Electromagnetic Transients including DC
PSCAD	Power System CAD or Computer Aided Design
MV	Medium Voltage
LV	Low Voltage
MCM	Thousand Circular Mils
CAS	Complex Adaptive Systems
EMS	Energy Management System
IIM	The Inoperability Input-Output Model
MATE	Multi-Area Thevenin Equivalent
OVNI	Object Virtual Network Integrator
HRT	Human Readable Tables
MIMESIS	Multi Infrastructure Map for the Evaluation of the Impact of Crisis Scenarios
DSS	Decision Support System
QoSe	Quality of Service Evaluator
CI	Critical Infrastructure
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
CISIA	Critical Infrastructure Simulation by Independent Agents
CIMS	Critical Infrastructural Modelling Software
ESS	East Substation

WSS	West Substation
SSS	South Substation
NSS	North Substation

CHAPTER 1

INTRODUCTION

This thesis deals with electrical power system modelling for the purpose of studying the interdependencies between multiple infrastructures. This is part of the Infrastructure Interdependencies research being carried out at Western University in collaboration with The University of British Columbia (UBC) and The University of New Brunswick (UNB) for the Disaster Response Network Enabled Platform (DR-NEP) project.

1.1 Background

Our national security, economic prosperity, and national well-being are dependent upon a set of highly interdependent critical infrastructures. Examples of these infrastructures include the national electrical grid, oil and natural gas systems, telecommunication and information networks, transportation networks, water systems, and banking and financial systems. Given the importance of their reliable and secure operations, understanding the behaviour of these infrastructures, particularly when stressed or under attack, is crucial [1].

Natural or man-made disasters happen and can cause thousands of casualties. The Asian Tsunami on December 26, 2004 caused a total loss of 229,866 human lives [2]. Another unfortunate incident, Hurricane Katrina, which struck on August 23, 2005, was responsible for a total damage of $81.2 billion and a loss of 1,464 human lives [3]. In 2008, cyclone Nargis, in Myanmar, killed 140,000 inhabitants [3]. On March 11, 2011, earthquake and tsunami occurred in Japan resulting in loss of life of many inhabitants and economical damage to physical properties; followed by a nuclear crisis and shortage of electricity [4]. Researchers, keeping in mind the trends from history, have calculated the numbers of people affected annually by natural disasters up to 2007, as shown in Figure 1.1. These disasters have made the protection and restoration of critical infrastructures such as health care, utilities, transportation, and communication, a serious national concern.

In natural or human-induced emergencies, it is clear that a series of carefully chosen decisions are vital in mitigating death and disaster, following a natural catastrophe such as an earthquake. These decisions must be made on the basis of sound knowledge and experience. However, given that the worldwide frequency of such situations is fortunately low, and that the likelihood of the same command and control personnel encountering similar scenarios over and over again is slim, it can be appreciated that opportunities to build up the necessary experience are severely limited [5]. This is the context of this research work under which the decisions need to be carefully studied and measured before implementation.

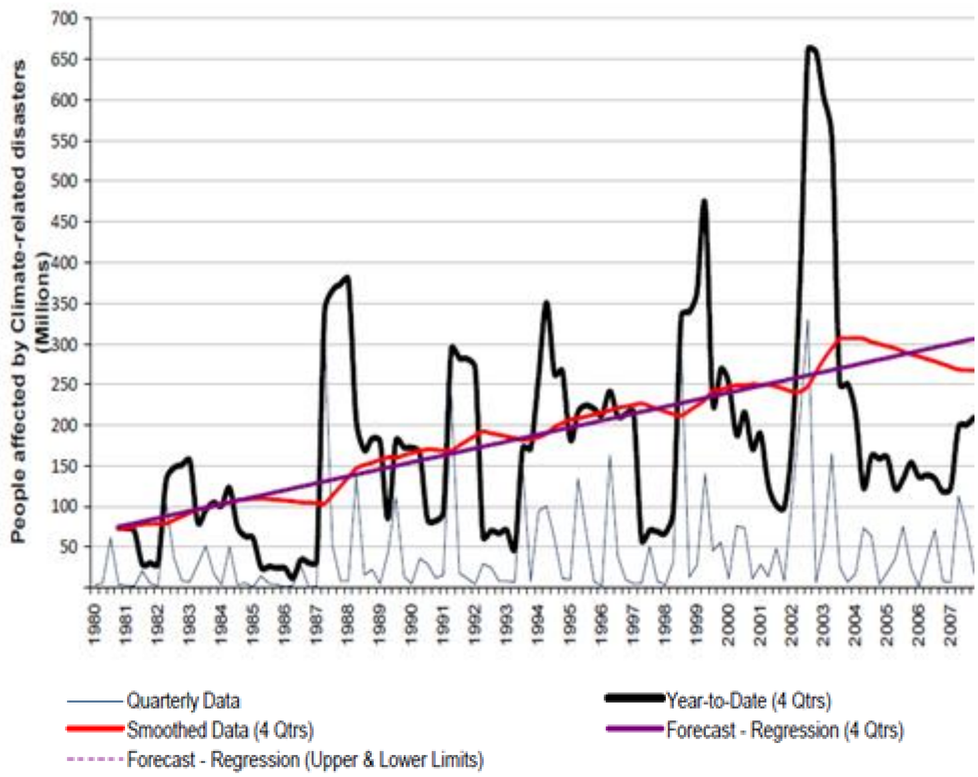

Figure 1.1: People affected by Climate-related disasters 1980 to 2007 (millions, Quarterly & Year-to-Date Actual & Smoothed Trend) [6]

1.2 Infrastructure Interdependencies

The following subsections describe the definition of infrastructures and the need to understand the concept of infrastructural interdependencies. It also mentions the type of interdependencies and related research that has been done in past.

1.2.1 Overview and Definition

The study of infrastructure interdependency is a relatively new concept. As a result, the definition of infrastructures and the classification of interdependencies between them may not be clear to many of us. The Critical Infrastructure Assurance Office (CIAO) defined infrastructure as [7]:

"The framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of the United States, the smooth functioning of governments at all levels, and society as a whole."

This explains that the infrastructures are not limited only to the physical buildings and lifelines. By this definition, infrastructures are an "interdependent" network, which leads to the question of what is the "interdependency" and how it is different from the "dependency" [1][7][8]. The civil infrastructure systems, such as transportation, energy, telecommunications, and water, have become so interconnected, one relying on another, that disruption of one may lead to disruptions in all [7][8]. Interdependencies can be classified into different types depending on their characteristics.

The interdependencies are classified into four categories according to the nature of linkage between infrastructures as physical, cyber, geographic and logical [1][7][9][10]. Modelling interdependent infrastructures is a complex problem. Time scales, geographic scales, cascading, and higher order effects are some of the issues arising from, or related to infrastructure interdependencies that complicate analyses. These factors drive one to a multidisciplinary approach, and may in fact preclude the development of a single, all-encompassing modelling methodology ("one size fits all") for analyzing infrastructures [1].

1.2.2 Literature Review

Disaster situations such as natural disasters, failure of critical systems, or premeditated attacks within infrastructures might result in cascading effects. The dynamic and apparent nature of these effects drives the need to review literature on infrastructure interdependencies and simulations. Infrastructure simulation techniques can take one of two approaches [9], which include (1) integrated models, and (2) coupled models. The integrated models are designed to model multiple infrastructures and their interdependencies within a single framework. The coupled approach takes multiple simulations of infrastructure and connects them together [9].

Based on these approaches some of the modelling and simulation techniques (integrated with electrical power systems) include:

- **Petri-Net –** A graphical and mathematical tool used to model the interdependencies of discretely distributed systems. It is comprised of places, transitions, and directed arcs (connecting places and transitions). Places contain tokens that are transferred between infrastructures to model their states. Petri-Net models have been applied to the modelling of interdependencies between multiple infrastructures including electrical power and its associated Supervisory Control and Data Acquisition (SCADA) system [11]. This tool presents the simple visualisation of interdependencies. However, the drawback of this approach is its inability to model quantitative information and perform scalability analysis under different damage states.

- **System Dynamics –** A continuous integrated modelling approach known as system dynamics was developed which employs differential equations to model internal feedback loops and time delays that affect the behaviour of the entire system [12]. In the output, it creates a picture of how the system or infrastructure changes over time [12]. This technique has been used to study the effects of how policies and regulations are applied in multiple linked infrastructures including energy (electricity, oil, and natural gas), communication, transportation (waterways, highways, and rail), emergency services, banking and finance, agriculture, water, and shipping markets [1].

- **Cell-Channel Model –** The cell-channel model is a unique modelling methodology used in The University of British Columbia I2Sim research. According to this research team [13][14], in the I2Sim implementation of a model, 'service tokens' represent the goods and services produced, consumed, and transferred in and between infrastructures. The entities that perform functions which produce and consume tokens are termed as cells. The means by which tokens can flow between the cells are termed as channels (representation of lifelines such as transmission lines). The cell-channel model is the best approach for mitigating disaster effects for large disaster scenarios through critical decision making [13]. The cell-channel model approach has been chosen to model and simulate critical interdependent infrastructures in this thesis.

- **Agent-Based Model –** This is one of the most popular approaches used for the infrastructure interdependency simulations. It consists of independent decision makers called agents who assess and react to the situations according to their own rules. Infrastructure models developed using an agent-based model include Critical Infrastructural Modelling Software (CIMS) developed by the Idaho National Laboratory [9][10][15], Critical Infrastructure Simulation by Independent Agents (CISIA) [9][16][17], and Next Generation Agent-Based Economic Laboratory (N-ABLE) by Sandia National Laboratories [9][18]. Electrical power is modelled externally in this model whereby the outputs of simulations act as inputs for agents who are responsible for final decision making.

- **Physics-Based Models –** These models are pervasive in the modelling of certain individual infrastructure interdependencies. A wide variety of well-established tools are developed for modelling electrical power systems to various degrees of granularity in time. Modelling interdependencies between infrastructures with this approach in a non-integrated fashion has also been attempted. However, it has not evolved as a popular method [7][19]. This is due to the fact that the amount of processing power required to run these models is high, while the level of detail yielded might not be necessary. Moreover, construction and operation of such models demands an expert knowledge, which is often difficult to obtain for simulations of wide range of infrastructures.

All of these techniques have their own advantages and disadvantages. According to the requirements of the project, one of the above techniques is selected. The scope of this work is based on disaster management and the study of interconnection between various domain simulators and interdependency simulators. The software chosen should be able to serve the purpose of the research study. The decision making alternatives have to be suggested during the simulation of different disaster scenarios and the model has to provide the quantity and scalability of the nature for the system. For the DR-NEP project, according to team members, the most appropriate approach for modelling the system of the Western campus for various disaster scenarios is the “cell-channel model”.

1.3 Disaster Response Network Enabled Platform (DR-NEP) Project

The Disaster Response Network Enabled Platform (DR-NEP) is a project carried out at three different universities in collaboration with two other research agencies**.** The participating universities and agencies are The University of British Columbia, Western University, The University of New Brunswick, ENEA (research agency) in Italy, and The Asian Institute of Technology (AIT) in Thailand. This research project is funded by Canada's Advanced Research and Innovation Network (CANARIE), along with support from IBM. The Disaster Response Network Enabled Platform (DR-NEP) is a system that integrates a set of independently developed infrastructure and disaster simulators.

This section describes some of the architectural choices made for DR-NEP. The overall system uses a master-slave pattern, with one master simulator orchestrating all of the others, based on a central system clock. As the various simulators are developed by different organizations, they each have their own data models with data elements not matching one for one, or with different representations, and not useful for collaboration [20]. To integrate them into DR-NEP, and to avoid developing n^2 distinct translators, a single common data model was devised, akin to the mediator pattern, and therefore only one data translator per simulator was needed [20].

Developing this common data model poses many challenges; containing the right abstractions to communicate with existing and future simulators, in particular the topology of their underlying models. It helps in reducing the overall complexity of the system, and also minimizes the likelihood of many drastic changes when the system will evolve [20]. For effective disaster response, the following are the three major steps [21]:

- Visualization
- Simulation
- Decisions

The DR-NEP project involved different stakeholders, including the Western team. The responsibility of the Western team members was to play the role of a local Emergency Expert Centre (EXC) regarding the simulation of a real-time disaster on its university campus. The role of the Western team was also to make an operational and decision-making function in DR-NEP's networked environment for the Western campus case, and development of a real-time scenario and analysis of best responses (with all stakeholders) [21].

1.3.1 Objectives of DR-NEP Project

Modelling interdependent infrastructures is a complex, multifaceted, and multidisciplinary problem. So under the DR-NEP project efforts were made by the Western team to study, analyze, and understand the disaster events in the presence of different infrastructures.

The research project has various objectives that are mentioned below [21]:

- Simulation of operational scenarios and the state of critical infrastructure before, during, and after an emergency or disaster.
- "Play" with distinct scenarios/strategies of operational decisions and resource allocation.
- Support decision making of multidisciplinary teams during disaster phase.

Under the DR-NEP project, the first and foremost step for the Western team was to develop a study case. In developing a study case, simulation models of all of the infrastructures were to be built using different software applications for various physical entities like water, power, and steam. Also, the study case needed to be built in the infrastructure interdependency simulator (I2Sim). The arrangement of software should be such that software applications representing different entities should be able to interact with interdependency simulator. Operating scenarios needed to be built for a disaster event and needed to be analyzed before and after the disaster event. Essentially, a proper decision support system needed to be developed in order to achieve the above stated objectives.

1.3.2 DR-NEP as an Interdisciplinary Project

As explained earlier, the DR-NEP project in itself is based on analysing and understanding the complexities of different infrastructures. Inclusion of different infrastructures results in involvement of experts from different areas who can perform exceptionally well in visualizing, simulating, and making decisions regarding different infrastructures during various disaster scenarios. Graduate engineering students from different disciplines worked together under one roof towards achieving the goal of successful management of disaster events.

At Western, graduate engineering students were involved from different areas to achieve the objectives of DR-NEP project. Graduate engineering students were involved from four different streams, which are mentioned below:

- **Software Engineering:** The role of the graduate students from software engineering was to combine outputs from different software applications into a common software package: I2Sim. By combining the outputs, it allows output from any one of the software applications to be fed as an input to the I2Sim software, and feedback can then be provided to the originating software.

- **Electrical Power Systems:** The role of the graduate students from electrical engineering was to model the electrical power network for the study case. It also involved load flow studies, fault studies, and load management skills. As an electrical power systems engineer, my role was to develop a validated electrical model of the Western campus for the DR-NEP team.

- **Civil and Environmental Engineering:** The graduate students from civil engineering were involved in the project for modelling and simulating the water networks for the study case. Aspects of drinking water and fire hydrants had to be included while studying the disaster scenarios.

- **Communication Systems:** The graduate students from communication systems engineering were involved in providing algorithms for communication between different software applications.

Thus, the DR-NEP project was an overall interdisciplinary project, with personnel working from different engineering backgrounds. If any one of the disciplines was missing, it would have proved to be a big limitation towards the completion of the project.

1.4 Electrical Network Modelling

Under the scope of this thesis work, modelling of electrical distribution network of the Western campus was a major task. Modelling the electrical networks involved making a simulation model of the Western campus, which should be validated with the actual data [22][23]. In this research work, the study case for disaster management studies is the whole of the Western campus.

There are various steps to be followed in order to build the electrical network model of the Western campus. The initial steps were to gather the accurate data about the various electrical components to be used for the modelling. Then, the next step was to decide on the use of appropriate software applications according to the needs of the project. As the project was about disaster events and scenarios, there was also a need for different types of fault studies according to the nature of the disaster events.

In electrical network modelling, typically three different types of studies are involved [24]. These three types of network studies are as follows:

- **Steady State Studies:** It involves load flow studies [24] that give an idea about the flow of power in the network, the level of voltage available at different buses, and the conditions of feeders, whether they are under normal loading conditions or overloaded. Different software packages are available, such as PSS/E [25] and ETAP [26].

- **Stability Studies:** This type of analysis mainly deals with the short circuit studies. The short circuit studies are done for a short period of time, for example tens of seconds. Different software applications, such as PSS/E [25] and PSS Sincal [27], are available for short circuit studies.

- **Electromagnetic Transient Studies:** These types of studies are done for very short periods of time, to the order of microseconds. Different software applications are used to study electromagnetic transients in the power network such as EMTP [28] and EMTDC/PSCAD [29].

In this work, steady state studies are performed on Western Campus electrical networks. Detailed modelling methodology for Western campus electrical networks has been presented in chapter 3.

Once the electrical network is modelled, efforts have to be made to validate the model based on the actual data acquired by various measuring devices. The validation of electrical network is the most difficult part if the data required for making the electrical network is not available. The methodology for validating electrical power network has been presented in detail in chapter 4. The last step is combining the results from the electrical model into the I2Sim model, which was developed by DR-NEP team members. In the end, the objective is to run the both software applications on same time scales and synchronize the results.

1.5 Motivation of the Thesis

It is clear that the delivery of goods and services to people through infrastructures is essential to modern society and that the systems of components constituting these infrastructures are large and complex. In a case when a disaster has occurred, the delivery of goods and services is very difficult or sometimes even impossible. The delivery of services requires the efficient working of every infrastructure or subsystem involved in that particular infrastructure.

During normal times, every infrastructure such as a power grid, a telecommunication system, or water systems, etc. knows very well how to respond to the problems in its own system and can send out repair crews or readjust operation [6][7][21]. Earlier, the disaster response plans were normally developed assuming the other infrastructures will be available. However, the opposite occurs during large-scale disasters; multiple infrastructures are damaged simultaneously and individual response plans are not sufficient [7][8][21]. For example, in March 2011, earthquake and tsunami occurred in Japan followed by a nuclear crisis and shortage of electricity [4]. This disaster scenario led to large destruction of physical and economical infrastructures affecting overall interconnected multiple infrastructures [4]. Major threats like tornados, earthquakes, or floods impose great disorder, and many times, human lives are lost. Therefore, it is important to prepare an emergency plan in advance, to respond during a disaster event and recover as quickly as possible after hazards have occurred.

From the previous disaster events, it has been learnt that the study of inter-operability between multiple infrastructures is very crucial. Research work on identifying, understanding and analyzing these interdependencies is extremely important and has significant challenges. Realizing these facts, efforts have to be made in understanding these inter-relationships in a better way, and to enhance decision-making during disaster events by doing significant research to overcome the challenges. The objective of the DR-NEP project was to develop effective decision-making tools, which will be used by policy makers and infrastructure service providers to maximize the number of human lives saved during natural or man-made disaster scenarios, which was a vital motivation for this study. Efforts have to be made to collect the information about power infrastructures, as electrical power is the most crucial infrastructure, and all other infrastructures are dependent on it.

1.6 Objectives and Scope of the Thesis

The work presented in this thesis is part of the study carried out under the DR-NEP project. The goal of this research is to use the cell-channel and other related methods to model interdependencies among electrical power systems and other infrastructures, to take them into account during the response and recovery stages of an emergency involving during different disaster scenarios on the Western campus. The main focus of this thesis will be on electrical power systems.

The objectives and scope of this thesis are as follows:

i. To develop an electrical distribution network model of the entire Western campus for use in disaster management studies.

ii. To validate the developed Western campus electrical distribution network model by comparing the simulated model outputs with actual measured quantities.

iii. To integrate the steady state study results of the validated electrical network model into the Infrastructural Interdependency Simulator (I2Sim).

iv. To develop different disaster scenarios based on different infrastructures, in order to simulate different emergency situations with main focus on electrical power systems. To further understand and analyze the different disaster scenario resultsin order to accomplish the optimal decision making during any disaster situation.

1.7 Outline of the Thesis

The remainder of the thesis is organized as follows:

- Chapter 2 presents the basics of the infrastructural interdependency and the various subsystems involved. It then introduces the concepts of the infrastructural interdependency simulator, web-service, and basics of the Western disaster scenario case study. It also presents the significance of electrical infrastructure for the working of other infrastructures in overall study of infrastructure interdependencies.

- Chapter 3 describes the methodology of modelling of different electrical components utilized in electrical power distribution systems with respect to the software applications used for simulation.

- Chapter 4 presents a methodology to validate the electrical distribution model of Western University developed in EMTDC/PSCAD software.

- Chapter 5 presents and analyzes three different disaster scenarios, with and without collaboration with other engineering disciplines, which were created at the Western campus. It then presents a discussion of the results and alternatives regarding decision-making during the disaster scenarios. The results are presented with respect to electrical power infrastructure as the main focus of study.

- Chapter 6 provides the conclusions and future work.

CHAPTER 2

CONCEPT OF INFRASTRUCTURAL INTERDEPENDENCIES

2.1 Introduction

Modern society relies greatly upon an array of complex national and international infrastructure networks such as transportation, utilities, telecommunication, electrical power systems, and even financial networks [10]. The society also depends on the operations of civil infrastructure systems, such as transportation, energy, telecommunications, and water. These systems have become so inter-connected; one relying on another, that disruption of one may lead to disruptions in all [7][8][30]. As shown by the 1998 failure of the Galaxy 4 telecommunications satellite [1][7], the north eastern blackout in 2003 in USA [31], and many other recent infrastructure disruptions like the Japan earthquake and tsunami in 2011[4], what happens to one infrastructure can directly and indirectly affect other infrastructures, impact large geographic regions, and send ripples throughout the national and global economies [7].

Interdependencies are facilitated by advances in technology and driven by economics, causing them to become more and more commonplace [30]. With the advancements in technology, infrastructures are becoming more and more complex. The different infrastructures such as electrical power systems, communication systems, water systems, and transportation systems are often called as subsystems (system of systems) or lifelines [30]. All of the aforementioned critical infrastructures have one property in common—they are all complex collections of interacting components in which change often occurs as a result of learning processes. That is, they are complex adaptive systems (CASs) [7].

Figure 2.1 illustrates interdependencies between different subsystems. The concept of complexity and interdependencies of the subsystems can be understood well from Figure 2.1. There are five different planes in the diagram representing different infrastructures such as power systems, transportation systems, and communication systems. Each plane has several points, or sectors, starting and ending with an arrow. The spheres or point represent key infrastructure components within that plane. For example, the electric power infrastructure contains the sectors of electrical power plant, electrical generation and distribution, etc. Ties and dependencies exist within each infrastructure between the different sectors. The arrows represent the infrastructure interdependencies. The example in the figure is a simple attempt to relate the complexity of dependencies that may exist between different components. In chaotic environments such as an emergency response to a catastrophic event, decision makers should understand the dynamics underlying the infrastructures.

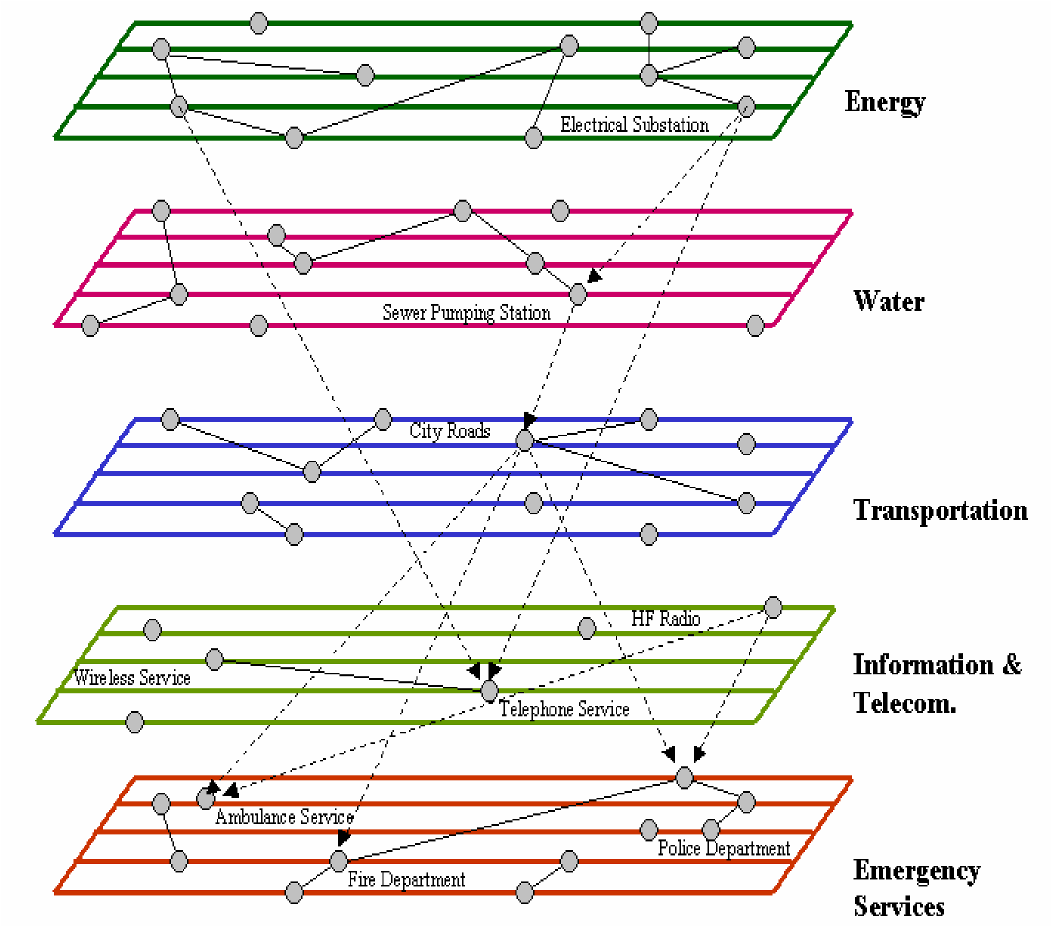

Figure 2.1: Interdependencies between different subsystems [10]

When investigating the more general case of multiple infrastructures connected as a “system of systems,” it is essential to consider interdependencies. Infrastructures are frequently connected at multiple points through a wide variety of mechanisms, such that a bidirectional relationship exists between the states of any given pair of infrastructures. That is, infrastructure *i* depends on *j* through some links, and likewise *j* depends on *i* through other links [1][7][8][21]. So the infrastructural interdependencies can be bidirectional as well as unidirectional in which *j* does not depend on *i* through the same link.

This research work is carried out to study the electrical power systems of the Western campus for the purpose of understanding the interdependencies between multiple infrastructures that exist within the campus. The focus of this research work is to model the electrical power system of the Western campus and incorporate the results into the I2Sim model, which was developed by the DR-NEP team, along with other infrastructures such as steam, water and condensate return systems.

In this chapter, the definition, concept, and understanding of interdependencies is presented along with their types. Section 2.3 and 2.4 of this chapter provides details about various subsystems in infrastructures and their interconnection techniques and analysis. Section 2.5 gives a brief idea about the interconnecting software I2Sim and its architecture. Also a new concept called web service and quality of service is presented in section 2.6. Section 2.7 presents brief description of the federated critical infrastructure simulators. Section 2.8 describes Western disaster case study. Significance of electrical infrastructure in overall interdependency study is presented in section 2.9 followed by conclusions in section 2.10.

2.2 Definition of Interdependencies

In this section, the definition of infrastructure interdependencies and their types are discussed. As Interdependencies give rise to numerous challenges that do not exist in single infrastructure models, it is very important to discuss some definitions.

Interdependency: A bidirectional relationship between two infrastructures through which the state of each infrastructure influences by, or is correlated to, the state of the other [1][10]. More generally, two infrastructures are interdependent when each is dependent on the other [7][9][11]. For example, the electric power grid and natural gas network are interdependent; Natural gas fuels many electrical generators, and elements of the natural gas infrastructure require electricity to operate. A disturbance in the electrical system can cascade into the natural gas system, and the loss of natural gas pressure can shorten the generation of electricity. So the term interdependency is conceptually very simple, as observed from the previous example. It also shows the connections between different agents in different infrastructures in a general system of systems. As the number of agents and infrastructures increases, the overall system complexity increases proportionally. Figure 2.2 illustrates the interdependent relationship among several infrastructures. These complex relationships are characterized by multiple connections among infrastructures, feedback and feed forward paths, and intricate branching topologies [7].

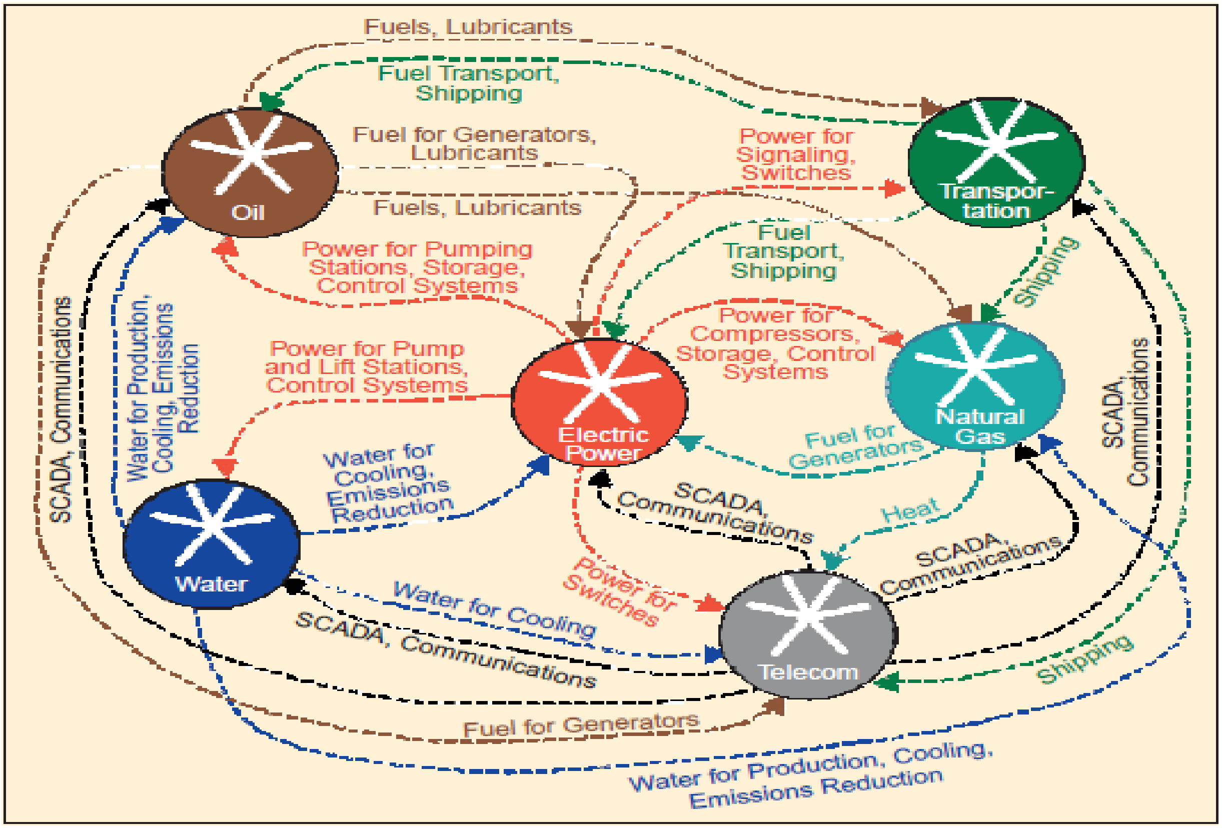

Figure 2.2: Representation of interdependent relationship among different infrastructures [7]

2.2.1 Types of Interdependencies

Infrastructure interdependencies refer to influences that an element in one infrastructure imparts upon another infrastructure. Interdependencies vary widely, and each has its own characteristics and effects on infrastructure agents. Although each has distinct characteristics, these classes of interdependencies are not mutually exclusive. In the following text, four principal classes of interdependencies are defined and discussed in detail [1][7][10][31][32]:

- **Physical Interdependency:** Two infrastructures are physically interdependent if the state of each depends upon the material output(s) of the other. Physical interdependencies arise from physical linkages or connections among elements of the infrastructures [1][10]. A physical interdependency arises from a physical linkage between the inputs and outputs of two agents: a commodity produced or changed by one infrastructure is called an output, and one which is required by another infrastructure for it to operate is called an input [1][13][23]. For example, a transportation network and a coal-fired electrical generation plant are physically interdependent, given that each supplies commodities that the other requires to function properly [33]. Figure 2.2 illustrates the physical interdependency between transportation and electrical power infrastructures.

- **Cyber Interdependency:** An infrastructure has a cyber-interdependency if its state depends on information transmitted through the information infrastructure [1][10][31]. The computerization and automation of modern infrastructures and the widespread use of supervisory control and data acquisition (SCADA) systems have led to pervasive cyber interdependencies [33][34].

- **Geographic Interdependency:** Infrastructures are geographically interdependent if a local environmental event can create state changes in all of the infrastructures. This implies close spatial proximity of elements of different infrastructures, such as co-located elements of different infrastructures in a common right-of-way [7][10][30]. For example, an electrical line and a fiber-optic communications cable slung under a bridge connect elements of the electric power and telecommunications. Traffic across the bridge does not influence the transmission of messages through the optical fiber or the flow of electricity.

- **Logical Interdependency:** Two infrastructures are logically interdependent if the state of each depends on the state of the other via a mechanism that is not a physical, cyber, or geographic connection [1][7][10][31]. In other words, a dependency that exists between infrastructures that does not fall into one of the above categories [10]. Some examples are various policies and legal or regulatory regimes that can give rise to logical linkage among two or more infrastructures. For better understanding, an example is the power crisis that occurred in California in late 2000 [7].

2.2.2 Coupling Characteristics and Behaviour

This section deals with the coupling and response behaviour of various infrastructures. There is a need to understand the characteristics of the couplings among infrastructures and their effects on infrastructure responses to perturbations or disturbances. A disruption in an infrastructure is said to occur when one or more of the physical components, or one or more of the activities needed to operate a physical component cannot function at prescribed levels. Disruptions may or may not result in service degradation. Service degradation is said to occur when the service itself cannot be provided at its prescribed level [30].

From an analytic perspective, infrastructure interdependencies must be viewed from a "system of systems," perspective. Failures affecting interdependent infrastructures can be described in terms of three general categories [31]:

- **Cascading failure:** A disruption in one infrastructure causes a disruption in a second infrastructure (e.g., the August 2003 blackout led to communications and water supply outages, air traffic disruptions, chemical plant shutdowns, and other interdependency-related impacts) as illustrated in Figure 2.3.

- **Escalating failure:** A disruption in one infrastructure aggravates an independent disruption of a second infrastructure (e.g., the time for recovery or restoration of an infrastructure increases because another infrastructure is not available).

- **Common cause failure:** A disruption of two or more infrastructures at the same time is the result of a common cause (e.g., Hurricane Katrina simultaneously impacted electric power, natural gas, petroleum, water supply, emergency services, telecommunications, and other infrastructures) [3][31].

2.3 Subsystems in Interdependency Studies

Modern society relies on the operations of a set of human-built systems and their processes. The set of systems that are investigated in all interdependencies related research are denoted to as civil infrastructure systems. There are several types of infrastructures and subsystems included in the infrastructures itself which arise while dealing with interdependencies and studying inter-relationships between different subsystems. A subsystem is a set of elements that is a system itself, and is that is also a component of a larger system. The systems or infrastructures can be classified as follows:

- Energy and Utilities

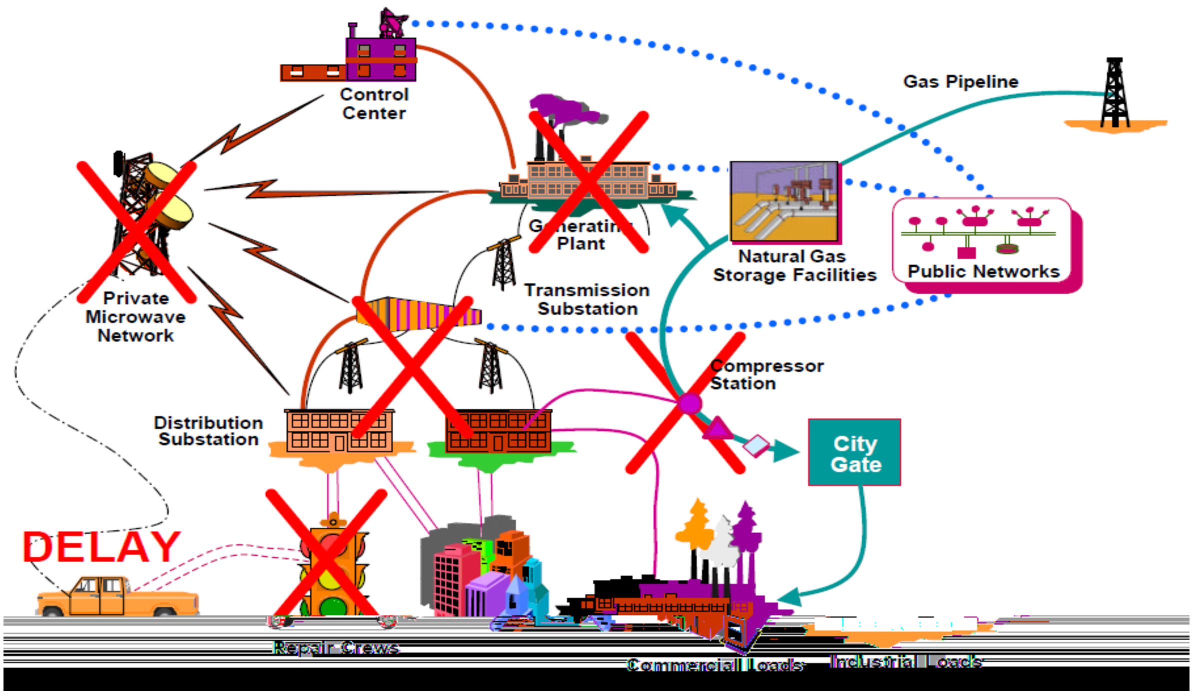

Figure 2.3: Failures in interconnected infrastructure system [35]

- Communications and Information Technology
- Finance
- Healthcare
- Food
- Water Supply
- Transportation (Road transportation, railway, air transportation, marine transport)
- Safety
- Government Services
- Manufacturing

Figure 2.4 illustrates that infrastructures cover a large number of sectors, including the national electric power grid, oil and natural gas production, transportation, and distribution networks, telecommunications and information systems, water systems, transportation networks, the banking and finance industry, the chemical industry, agriculture and food systems, and public health networks.

Understanding the operational characteristics and providing a sufficient level of security for these infrastructures requires a system-of-systems perspective, given their interdependencies [1][32].

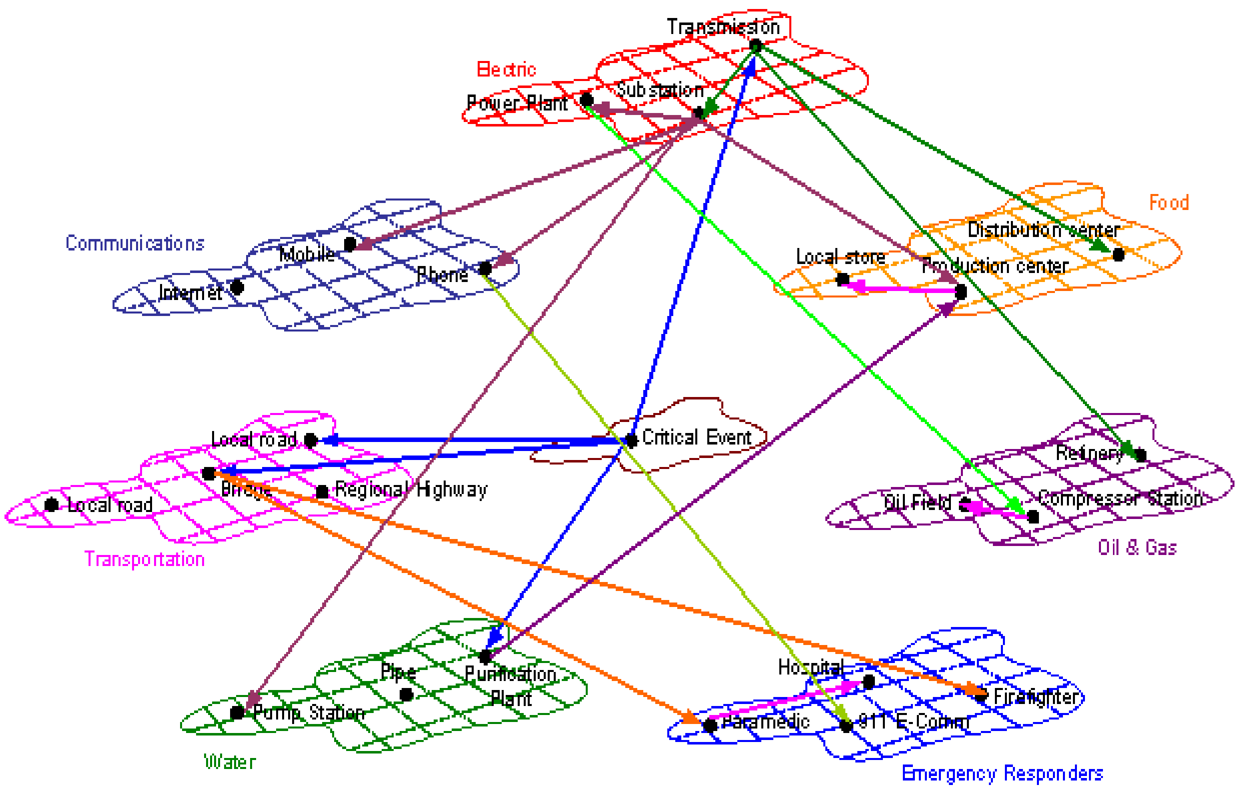

Figure 2.4: Representation of different subsystems in Interdependencies Studies [21]

Instead of giving details about all the infrastructures, this section will present a discussion on selected infrastructures and subsystems which fall under the scope of this thesis.

- **Energy and Utilities:** The energy and utilities sector includes electrical power, natural gas, oil production, and electrical power systems. Sufficient information for the electrical infrastructure for performing interdependency estimates can be collected easily. The electrical infrastructure has three major components for its operation. These are electrical power generation, transmission, and distribution. In this work, only the distribution systems are included. The communication infrastructure services play an important role in all three phases. Supervisory Control and Data Acquisition (SCADA) systems are necessary for the reliable operation of electrical generation equipment [36]. Energy

Management Systems (EMS) is important for transmission and distribution network management [37].

- **Water Supply:** There are two important components in most water supply networks: the drinking water network and the waste water management network. In recent years, new systems have been built to monitor and manage water reservoirs and distribution networks using different kinds of sensors technologies [38]. There are three aspects to online drinking water network monitoring: monitoring of water sources, monitoring of water treatment facilities, and monitoring of the distribution network [38]. These monitoring concepts are related to those in the electrical infrastructure as everything is based on software based programs. All of these communication based systems are installed in modern water station control stations. Within the DR-NEP project, the water system of the campus was modelled with the help of simulator software called EPANET [39]. The simulation provides knowledge about water pressure at various points in the buildings, and also at the various fire hydrants installed on the campus.

- **Communications and Information Technology:** Reliable operation of the communications based systems depends on effective service to many of their core components. These include software services (e.g. web server, email gateway, virtualization system, database system), low level operating system tools, protocol and device drivers, communication devices and links, and different supporting utilities (e.g. firewall, virus scanner, spam filter) [36]. Any typical organization that has a modern information system infrastructure has all of these services in use every day. From each of the core components, software services are crucial as, nowadays, each and every function is based on software applications.

2.4 Interconnecting Subsystems

This section discusses the interrelationships and interconnections between subsystems and infrastructures presented in section 2.3. The main focus will be on complex adaptive systems (CAS)[1]. Holmgren et al. [40] present issues in power control systems and the associated communication systems. Jha and Wing [41] develop a constrained Markov decision process method to investigate survivability within infrastructures systems that rely on computers and computer networks. Haimes and Jiang [37] also presented a Leontief-based input–output model called the inoperability input–output model (IIM) that enabled the accounting for interconnectedness among infrastructure systems. However, this approach worked only at a macroscopic level, and was useful for vulnerability calculation; but it would be difficult to extend this approach to restoration activities. In a more recent work [42], Haimes and others continued the development of the IIM and its ability to measure economic impact among various sectors in the economy by analyzing both the initial disruption and the ripple effects. Carullo and Nwankpa [43] presented experimental studies in electrical power systems with an embedded communication system for the transmission of network conditions.

Other CAS models, such as SMART II+ and SymSuite, have been developed to analyze large scale, interconnected infrastructures with complex physical architectures [31]. Argonne Labs is also developing a next generation drag-and-drop simulation building platform that offers a unique, comprehensive, and unified modelling environment with capabilities for developing and integrating dynamic physical systems models, agent-based simulations, real-time data flows, advanced visualization, and post-processing tools [31]. Broadly, five types of interrelationships between infrastructure systems have been identified [30] and are described below.

- **Input dependence:** The infrastructure requires as input one or more services from another infrastructure in order to provide some other service.

- **Mutual dependence:** At least one of the activities of each infrastructure in a collection of infrastructures is dependent upon each of the other infrastructures. An example of mutual dependence involving two infrastructures occurs when an output of infrastructure A is an input to infrastructure B, and an output of infrastructure B is an input to infrastructure A. An example of this type of dependence is electrical power systems and the railroad mode of transportation. Railways transport fuel for electrical generators and electrical power systems provide signals for useful operation of railways.

- **Shared dependence:** Some physical components or activities of the infrastructures used in providing the services are shared.

- **Exclusive OR dependence:** Only one of two or more services can be provided by an infrastructure. Exclusive OR dependence can occur within a single infrastructure system or among two or more systems.

- **Collocated dependence:** Components of two or more systems are situated within a prescribed geographical region.

2.5 Interconnecting Software I2Sim

People are largely dependent on continued services from interdependent critical infrastructures such as telecommunication, electricity, transportation, water supply, oil and gas networks, and financial services. A system of interdependent infrastructure sectors is highly nonlinear and complex in nature. To ensure stable and reliable operation of these interconnected infrastructures, it is important to know their interdependencies. Well-designed simulation frameworks can provide significant insight into the interdependencies of these interconnected networks [13]. In the DR-NEP project, for the purpose of simulating all of the participating infrastructures together on a single platform, Infrastructure Interdependency Simulator (I2Sim) is used. This project is a combined effort between three universities and research agencies, thus major work regarding I2Sim was already done at The University of British Columbia under the guidance of Dr. J. Marti (UBC). In this section, the I2Sim system, its definition including its critical components, is explained. I2Sim's critical components, cells, channels, and tokens are also described.

2.5.1 I2Sim Definition and Overview

The research objective of the DR-NEP project was to study the decision making processes in the context of critical linkages within multiple infrastructure networks and to develop better policies to mitigate disaster situations. The present volatile world situations combined with the rising trends of natural hazards have raised concerns for the smooth operation of these critical infrastructures. However, until now, only a few computational frameworks have been developed to assist researchers, decision makers, and infrastructure service providers to understand the operational characteristics of these infrastructures during disaster scenarios [21][44]. These frameworks and methods have already been discussed in Section 2.4.

Infrastructure Interdependency Simulator (I2Sim) software is based on a matrix partition-based technique called Multi-Area Thevenin Equivalent (MATE) [13][14]. The MATE model has been used for large scale real-time power system simulations and is an efficient alternative to the existing agent-based critical infrastructure simulation frameworks. Another distinguishing feature of I2Sim is that it is based on the cell-channel model, where interdependencies among different infrastructures can be represented through a formal technique based on the extension of the Leontief input-output model [37]. Figure 2.5 depicts the block diagram of working of I2Sim simulator.

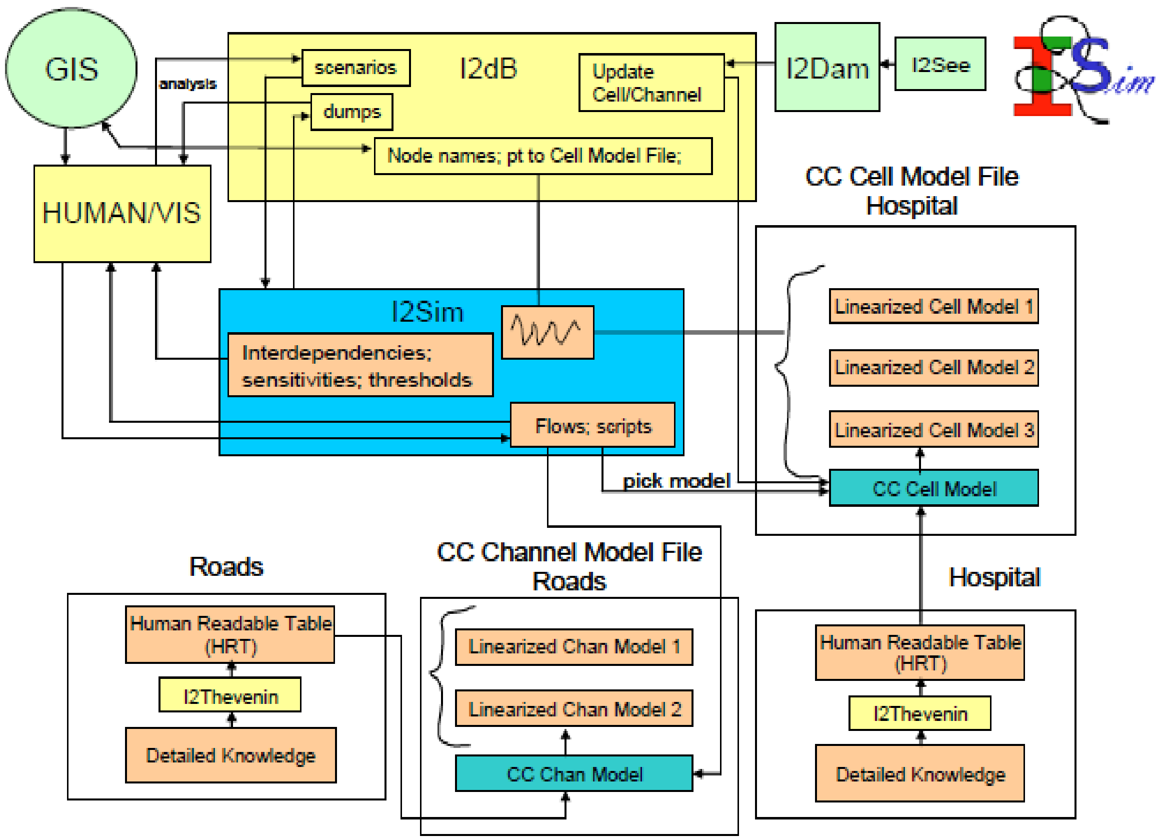

Figure 2.5: Block diagram of working of I2Sim simulator [14]

I2Sim uses a cell-channel model where cells, channels, and tokens are the main modelling entities. Cells perform the function of transforming inputs to outputs. Tokens are units transported from one cell to another, and include entities such as electricity, gas, and people. Channels are links between cells through which tokens may flow, such as pipes, wires, and streets [13].

2.5.2 The Cell-Channel Model

The cell-channel model proposed by Dr. Marti, J. Hollman, C. Ventura and Jatskevich [45] captures physical interdependencies among different critical infrastructures using precise mathematical descriptions [13][44]. Components defined in the physical layer can interact with the decision making layer through an event forwarding mechanism. The model has the following five components [13][21]:

- **Cell:** A cell is an entity that performs a function. For example, a hospital is a cell that uses input tokens, such as electricity, water, medicines, etc. and produces output tokens, such as beds served.

- **Channel:** A channel is a means through which tokens flow from a generator cluster to a load cluster.

- **Token:** Tokens are goods and services that are provided by some entity to another entity that uses them. These tokens can be water, electricity, medical supplies, etc.

- **Cluster:** A cluster is a group of one or more cells (also called node). Clusters reduce the modelling granularity and give a mapping to the MATE model. Two clusters are separated in time or space and are connected by channels. Each cluster generates and/or consumes tokens [13]. In an electrical network, a token can be a generator or a motor which generates or consumes electrical power.

- **Control:** These are distributor and aggregator units. They change their state based on the events received from the decision making layer. In terms of electrical power, the amount of power available for distribution can be changed with the help of distributor units.

2.5.3 I2Sim System Architecture

I2Sim (Infrastructures Interdependencies Simulator) is a tool used to achieve a time-domain simulation of disaster scenarios affecting large scale systems of infrastructures [13]. In particular, it is concerned with the simulation of both the physical layer and the human layer of infrastructures consisting of a large number of functional units [13][44][45]. A number of modules are designed to support the functionality of the I2Sim simulator, such as the database and the visualization modules.

The I2Sim simulator solves cell-channel model based infrastructure networks using the MATE solution algorithm [13]. The MATE algorithm is originally implemented in an OVNI (Object Virtual Network Integrator) power system simulator [13]. I2Sim extends the OVNI solution procedure for multiple infrastructure cases. The I2Sim framework can be described as time-driven, discrete event simulation architecture [13], where simulation states change due to a sequence of chronological events. In the following section, the components of I2Sim framework and architecture are explained briefly in five different steps [13].

- **Model of Cell, Channel and Infrastructure Networks:** Cells and channels are the basic infrastructure elements that form the core of cell-channel model (Section 2.5.2). Examples of cells are different physical infrastructure entities that can include power houses, substations, steam-stations, and hospitals, etc.

- **Representation of Interdependencies between Critical Infrastructures:** The interdependencies between different infrastructures are nonlinear relationships. To establish benchmark cases for I2Sim, UBC researchers studied interdependency among different infrastructures within the UBC campus for the last two years; and these results were discussed with Western researchers during the DR-NEP project [21].

- **OVNI Solution Model:** The design philosophy of OVNI simulation framework is to partition the solution of large scale power system networks into the solution of smaller subsystems plus the solution of the links joining the subsystems.

- **I2Sim Event Scheduling:** The I2Sim solution model is extended from OVNI by introducing two types of decision elements: aggregators and distributors. The aggregators and distributors are linear elements in a power station cell, and the range of their values is between 0 and 1 [21].

- **I2Sim Solution Model:** The I2Sim solution model, to some extent, is different from OVNI due to the differences between critical infrastructure networks and electrical networks. The difference is also due to the introduction of the nonlinear blocks and decision elements in the I2Sim cell model.

2.6 DR-NEP Infrastructure Architecture

DR-NEP is an interdisciplinary project in which five different organizations worked towards a common goal. In this project, different civil infrastructures such as electrical systems, water systems, and communication systems were analyzed at UBC and Western with the help of different simulators. I2Sim was used as the common software for understanding and analysing the results from all other domain simulators.

In this thesis, two different software applications were used with respect to the electrical systems. For the purpose of validating the electrical model, EMTDC/PSCAD [29] is used; for combining the results with I2Sim, PSS Sincal [27] is used, with the help of ENEA in Italy. Figure 2.6 illustrates the DR-NEP infrastructure architecture in terms of the Western campus, showing the Western electrical systems, and the steam and water systems which were developed by DR-NEP team members.

- **Physical Entities Layer:** The lower most layer in the architecture of integrating the subsystems is the physical entities layer. The words ‘physical entities’ are used for different lifelines or infrastructural physical quantities which are critical to the working of a domestic or commercial infrastructure. Examples of these physical entities or quantities are electricity, drinking water, steam, etc. Without the physical entity, the survival of the infrastructure is not possible. With respect to the disaster scenario created on one of the buildings on the Western campus, the physical entities are mentioned in Figure 2.6. Knowledge and data about all of the entities was provided by the Western Facilities Management department. The data was converted into useful information by the various engineers and students from the different disciplines participating in the project.

- **Domain Simulators Layer:** The second layer in the architecture of integrating the subsystems is the domain simulators layer. When studying the behaviour of interdependencies during disaster events, it is mandatory to get information about input and output data for various physical entities.

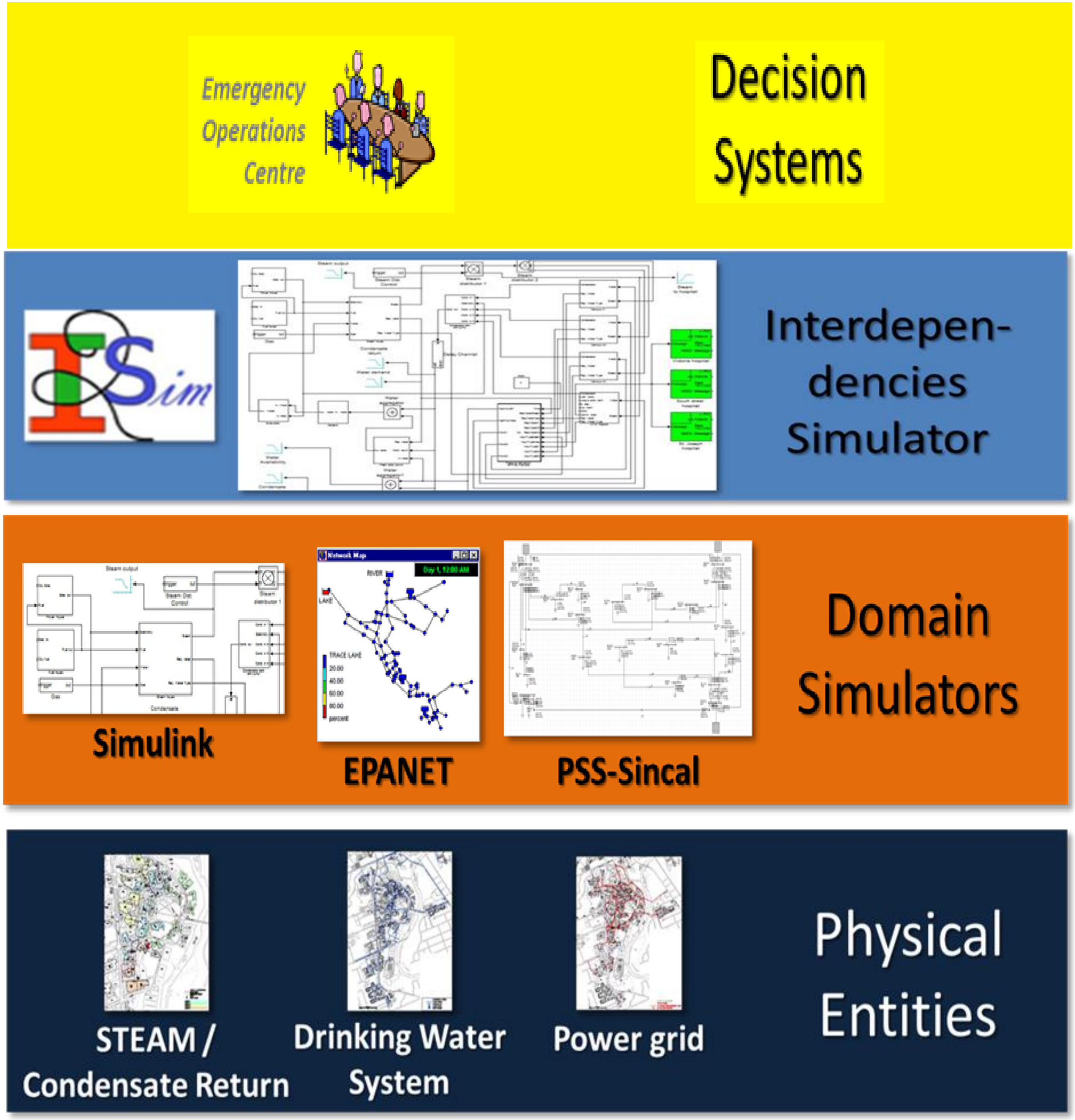

Figure 2.6: DR-NEP Infrastructure Architecture [21]

For getting the exact input-output data information about the physical entities utilized in the lowermost layer, it is necessary to use domain simulators to model and simulate all of the physical entities such as power, water, and steam. For the disaster scenario created on the Western campus, four physical entities were utilized. Three different domain simulators were also used to model the physical entities. PSS Sincal (Load flow simulator) [27] was used to model the power network of the campus. The water system was modelled using the software called EPANET [39] by a student from The Civil and

Environmental Engineering Department. The steam and condensate returns were simulated in MATLAB [46] based Simulink, jointly by team members. The contribution of this thesis was to make a detailed electrical model of the campus that can be used for the interdependency study.

- **Infrastructure Interdependency Simulator (I2Sim):** The third layer after the domain simulator layer is the infrastructural interdependency simulator layer. This layer is the most important layer and the most crucial to the events. This layer deals with combining all of the domain simulators. Combining implies that all inputs and outputs from all of the domain simulators should be incorporated into the common software - I2Sim. The incorporation of inputs and results from domain simulators should be based on the same time steps and based on the same disaster scenario. It should be possible to manage inputs and outputs of domain simulators through one common channel or platform, i.e. I2Sim. This was the task of the entire DR-NEP team to make the I2Sim model.

- **Decision Layer:** The fourth and uppermost layer is the decision layer. As explained in the previous section, the outputs of the physical entities from the domain simulators are fed into the common simulator I2Sim. The outputs of the physical entities are then plotted in the form of graphs. The next step is the decision making process, under which the demand management of physical entities has to be done based on the disaster scenario. Different demand management decisions are taken based on the availability or non-availability of critical entities. The decisions are taken by team members in such a manner that the supply of physical entities has to be maintained above critical values to maintain the working condition of the infrastructure and to achieve the desired objectives during the disaster event.

2.6.1 ENEA- Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

ENEA is the ' National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) [47]. Its activities cover the following topics:

- Energy efficiency

- Renewables
- Nuclear
- Environment and climate
- Health and safety
- New technologies
- Electric system research

On these issues, the agency ENEA [47][48]:

- performs basic research, mission-oriented and industrial skills using broad-spectrum and experimental facilities, specialized laboratories, and advanced instrumentation;
- develops new technologies and advanced applications
- disseminates and transfers the results encouraging their use for productive purposes;
- provides to public and private high-tech services studies, measurements, tests, and evaluations;
- conducts training and information tailored to increase the skills and knowledge of the public sector.

ENEA provides a multidisciplinary expertise and vast experience in managing complex projects. ENEA is carrying out a project called MIMESIS (Multi Infrastructure Map for the Evaluation of the Impact of Crisis Scenarios) [49]. This project aims to build a Decision Support System (DSS) that, by coupling meteorological-climatic and geophysical predictions with the knowledge of all critical infrastructures in a given region, is able to provide a dynamic risk assessment of the elements of all critical infrastructures and to estimate the impact that a specific crisis scenario could produce [48][49].

The evaluation of the impact of crisis scenarios on critical infrastructures is performed through a simulative approach based on a distributed simulation platform that integrates a set of critical infrastructures domain simulators (also known as Federated simulation) [50].

In the context of the DR-NEP project, ENEA joined the CANARIE network in order to provide the critical infrastructures domain simulators services that are used by UBC and Western, to be integrated into the I2Sim simulation platform. On the other hand, ENEA will be using I2Sim to simulate crisis scenarios models that ENEA have developed in the research activity [21].

2.6.2 Web Service

A web service is an effort to build a distributed computing platform for the web [51]. Also, a web service is a software system designed to support interoperable machine-to-machine interaction over a network.

A web service is an abstract notion that must be implemented by a concrete agent. The agent is a piece of software or hardware that sends and receives messages, while the service is the resource characterized by the abstract set of functionality that is provided. For example, we can implement a particular web service using one agent one day (perhaps written in one programming language), and a different agent the next day (perhaps written in a different programming language) with the same functionality [47][48][49]. Although the agent may have changed, the web service remains the same.

2.6.3 Quality of Service

Quality of Service (QoS) is an index of a network which relates to its “technological” efficiency in delivering the required power load, expressed in terms of the operating conditions under which the network is called to operate [48][49].

QoS is defined below:

$$QoS_{tech} = 1 - \frac{N_{ol}}{2N} - \frac{N_d}{N}$$

$$0 \leq QoS_{tech} \leq 1$$

Where,

N = the total number of lines

N_{ol} = the overloaded lines (i.e. where a larger than expected power flows)

N_d = the lines which must be disconnected

In the event that the QoS_{tech} is lower than a fixed threshold due to some failures occurring in the network, the operator should somehow reduce the electrical power available to the load points (e.g. through load shedding policies). To keep into account the quality of serviced perceived by the user, a new index QoS_e is defined in terms of the difference between the delivered and the expected loads [48][49]:

$$QoS_e = 1 - \frac{\sum_{i=1}^{k}(L_i - L_i')}{\sum_{i=1}^{k} L_i}$$

where L_i are the loads expected to be supplied by the different "*k*" load points, and L_i' are the effectively delivered loads. MIMESIS performs a load reconfiguration on the different loads, aiming at maximizing QoS_e and QoS_{tech} as well.

2.7 Federated Critical Infrastructure Simulators

The behaviour of each critical infrastructure can be observed and analyzed through the use of domain simulators, but this does not account for their interdependency [50]. To explore CI interdependencies, domain simulators need to be integrated into a federation where they can collaborate [50].

Under the DR-NEP project, members of the team explored three different simulators: the EPANET [39] water distribution simulator, the PSCAD/EMTDC [29] power system simulator, and the I2Sim infrastructure interdependency simulator. Each simulator's modelling approach was explored and their similarities and differences with respect to the modelling approaches were determined. Core ontology for each simulation engine was created. Ontologies and their mapping will support collaboration of simulators by enabling exchange of information in a semantic manner [50].

2.8 Western Disaster Case Study

For the purpose of fulfilling the objective of the DR-NEP project, different disaster scenarios were created on the Western campus by the team members. For this study, the Western campus was divided into four different parts, or cells, namely A1, A2, A3, and A4 as illustrated in Figure 2.7 [21].

Different cell divisions of the Western campus represent the following:

- A1: South campus
- A2: University community center & Social Science
- A3: Central campus
- A4: University hospital

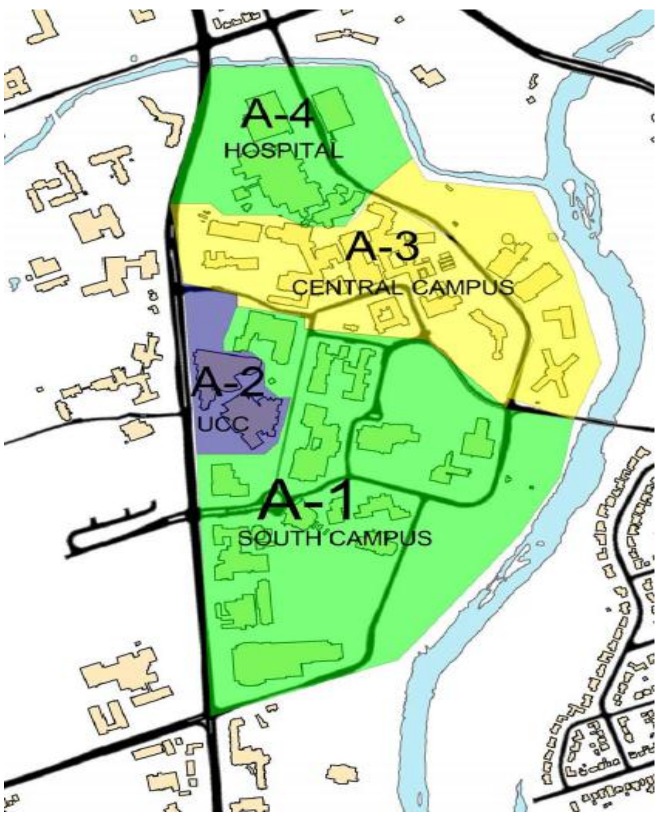

Figure 2.7: Cell division of Western campus for studying disaster scenario [21]

The disaster scenarios were created in buildings in the different cells. There is a high voltage substation close to the building chosen for each event. For example, the south substation supplies electrical power to the south part of the Western campus. The disaster scenario events are listed below.

2.8.1 Disaster Scenario Events [21]

1. Time of disaster event: winter time.
2. Fire started in one of the building in the campus.
3. Electrical substation is located very close to the selected building.
4. Forced shut down of the high voltage (HV) substation due to fire.
5. Three of the nearby fire hydrants were started.
6. Starting of fire hydrants results in reduction of water pressure available for the campus.
7. Leakage occurred in the condensate return system.

2.8.2 Simulated Events [21]

Below is the list of the controllable and uncontrollable events during the disaster event simulation:

Uncontrollable events

- Fire
- Power, water, steam, and condensate return leakages

Controllable events

- Hydrants usage
- HV substation operation
- Steam production and distribution
- Evacuating people

2.8.3 Objectives of Disaster Scenario Simulation

The disaster scenario was simulated using I2Sim software, with the following objectives, during the DR-NEP project.

- The critical task was to keep the University Hospital operational
- The critical operational cell is the Power/Physical Plant where the electrical power and water pressure must be kept above the cut off level.
- Electrical power should also be provided to keep the critical buildings operational
- Minimization of human injuries and casualties
- Speedy recovery (ensuring continuity of the campus activities)
- Best utilization of resources

2.8.4 Study Subsystems

There are several types of infrastructures and subsystems included in the infrastructures itself which arise when dealing with interdependencies and studying interrelationships between different subsystems. In the disaster scenario case study of the Western campus, team members included the following subsystems:

- **Water System:** Within the DR-NEP project, the water system of the campus was modelled with the help of simulator software called EPANET [39] by a team member from The Civil and Environmental Engineering Department. The entire campus water distribution system was modelled to obtain the desired values of water availability and pressure values. These values were calculated from the simulated model. Also, different disaster scenarios were modelled to get the optimum water availability values in case of emergencies. The output of the water networks is dependent on the type of disaster event and the availability of other infrastructures, such electrical power, which is necessary in order to run the water pumps and motors on campus.
- **Steam and Condensate Return Subsystems:** These are two other subsystems which are directly related to water system. These two major subsystems are also modelled in the disaster scenario along with the water subsystem. During the disaster simulation, all of the water related components like the water treatment plant were simulated.

- **Electrical Power:** The second major subsystem used in this study along with the water system is the electrical power subsystem. The electrical power systems can be categorized into the generation, transmission, and distribution of electrical energy. In the context of the Western campus, the disaster study mainly deals with distribution of electrical power. There are three main substations supplying power to the campus. Details regarding the electrical systems are provided in Chapters 3 and 4.

It is clear from the above discussion that the disaster scenario simulated is based on four different entities. Every building is simulated on the basis of a combination of entities. The combination of entities can be called a function for a building, which involves different critical lifelines such as power, steam, water, etc., as below:

- Physical Plant: function (water, power, condensate return)
- University Hospital: function (steam)
- Campus buildings: function (water, power, steam)

2.9 Significance of Electrical Infrastructure in Overall Interdependency Study

This section presents the importance of electrical system modelling and the inputs provided by the electrical model, in the overall study of infrastructural interdependency. The outputs from various domain simulators for different entities such as water, steam, and electricity will be used as inputs into the interdependency software I2Sim.

The following subsections provide details about the different infrastructure networks and their characteristics. In the end, the need for, and importance of, the electrical network study will be discussed in detail, followed by a conclusion.

2.9.1 The Electrical Power Network

The energy and utilities sector includes electrical power, natural gas, and oil. The electrical infrastructure has three major components for its operation. These are the electricity generation, transmission, and distribution. The working of an electrical infrastructure depends upon various other infrastructures. For example, communication systems, such as Supervisory Control and Data Acquisition (SCADA), systems are necessary for the reliable operation of electrical generation equipment [36]. Both Energy Management Systems (EMS) and SCADA systems are critical components in power system control centers, which are essentially based on communication infrastructure.

Malfunction of the SCADA or the Energy Management Systems (EMS) system has a major impact on electrical energy generation and distribution [36][37]. However, these systems are normally well designed and carefully implemented. Thus, they provide reliable operation in normal operating conditions. In the case of emergencies, more than one infrastructure is involved. There is, therefore, a need to study all of the different infrastructures together during a disaster event. In terms of other infrastructures, all of the infrastructures need electricity to perform day-to-day operations. For example, all of the different infrastructures such as water, steam, etc., work on equipment like water pumps or motors which need electric power to perform their operation. To understand the importance of electrical power as a critical input, the water, steam, and condensate return systems are discussed in detail in the following sections.

2.9.2 The Water Network

There are two important components in most water supply networks: the drinking water network and the wastewater management network. There was a need to include the water systems in the interdependency studies, as water is an extremely crucial physical entity in the life of human beings. In a general sense, it is used for drinking and household purposes. But in the context of emergency services, water is used in fire hydrants for fighting against fire during a disaster event. Water is also used for generating steam, which is used as a heating source during the winter [21].

At Western, steam is generated from water in the steam plant, located in the southern part of the campus. The steam produced is distributed to the campus buildings and to University Hospital. It was important to include this system in the interdependency studies as an incident had already occurred in 2006, in the steam plant. In 2006, during winter operations, Western’s steam plant experienced a failure in operations due in part to an unobserved anomaly in the municipal water supply [21][52]. The subsequent explosion, which disabled campus heating, caused building closures and nearly resulted in an evacuation of a major hospital [21][52]. The representation of the campus municipal water distribution system was built with external stresses applied to produce system conditions equivalent to those during the failure. The water model was built in EPANET (water modelling software), by a graduate student from The Department of Civil and Environment Engineering.

EPANET is a program that analyzes the hydraulic and water quality behaviour of water distribution systems. The EPANET Programmer's Toolkit is a dynamic link library (DLL) of functions that allows developers to customize EPANET's computational engine for their own specific needs [39].

The campus has two feeders for water supply: the eastern and southern feeders [21]. Water is needed as an input on four parts of the campus as well as for University Hospital. The available amount can be evaluated by performing a water simulation study, similar to an electrical power simulation study. Then, the input is entered into the interdependency software, which in turn, provides information about relationship between supply and demand.

The water model depends mainly upon the functioning of water pumps. The water pump takes water and electricity as inputs and the output of the pump is water with higher pressure. The water with high pressure is used to feed the boilers in the steam plant to produce steam during the winter. Thus, the electric power supply plays a crucial and life sustaining role in the case of water networks.

2.9.3 The Steam and Condensate Return System

The steam and condensate return systems are part of the water networks. In a broad sense, water systems are directly related to steam and condensate systems. During the winter, one of the major requirements is the availability of heat in the buildings, whether a residential building or a commercial building. In the case of the Western campus and hospital, both of these systems receive heating in the buildings by steam produced at the physical plant situated within the campus [21].

To produce the steam for heating purposes, five boilers are installed in the physical plant [21]. To produce steam, water and electrical power are needed as inputs to the boilers. The boiler in

I2Sim is equivalent to the super heater that produces steam for the campus and University Hospital. Water is needed for producing steam, but it is noted that to provide steam and water, one common entity is required: an electrical power supply.

The second physical quantity that is directly related to water is condensate return. Both steam and condensate return are related to water networks, as these three can be interchanged by simply varying the temperature of the physical entity. In the Western physical plant, all three entities are present for ensuring the university and campus activities remain operational.

A condensate aggregator is used for adding all of the condensate return quantities from all the three buildings A1, A2, A3 (Figure 2.7) as well as the hospital building, which is pumped out using an electric motor or pump. Electricity is again used as an input in the condensate return system, as was used in the steam and water networks.

2.9.4 Importance of Electrical Network Study

Different entities were modelled in I2Sim for the DR-NEP project, but this section focuses on how important the input provided by the electrical network study in the overall system can be. Figure 2.8 depicts two different decision-making scenarios for distribution of electrical power on the Western campus during a disaster event.

In Figure 2.8 four separate rectangles represent different physical infrastructures:

- Electrical Power Substation
- Water Station
- Physical Plant
- Hospital

In Figure 2.8 out of four blocks representing infrastructures, the hospital is considered to be the most critical. For its normal working conditions, it needs different physical entities such as electrical power, water, and steam. If all of the entities are available above threshold value, the hospital is not considered as a critical infrastructure. During a disaster event the entities available can decrease below threshold values. These situations can be handled using optimal decision-making scenarios. Optimal decision-making depends on the appropriate distribution of available resources. This has been discussed in detail with examples as noted below.

Figure 2.8 is presented to show two types of decisions during a disaster scenario. These two types are described as follows:

- ***Worst decision making scenario:*** In this scenario, the physical entities (electrical power, steam, and water) availability is zero for every infrastructure except for the hospital. During a disaster event the output of the electrical substation is decreased to 250 MW from 550 MW. Considering the hospital to be the most critical infrastructure, the available power (250 MW) is fed only to the hospital, leaving all other infrastructures without any electrical power input. Thus, this decision resulted in the shutdown of the water station and physical plant, further resulting in zero water and steam supply for the Western campus and hospital.

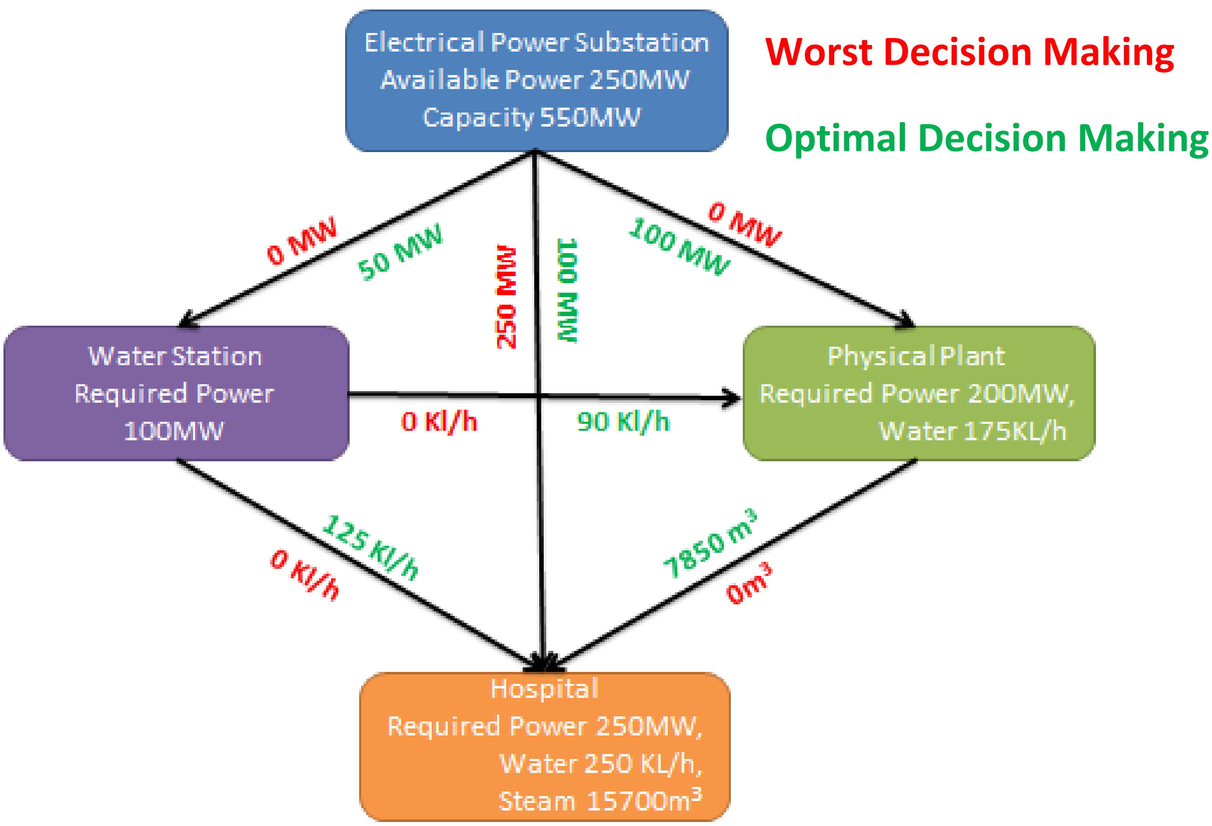

Figure 2.8: Power distribution decision making scenarios

- ***Optimal decision making scenario*: In this scenario, the physical entities (electrical power, steam, and water) are available for every infrastructure but in reduced quantities. During a disaster event, the output of the electrical substation is decreased to 250 MW from 550 MW. Out of the available 250 MW of electrical power, 100 MW is fed to the hospital, 100 MW is fed to physical plant and 50 MW is fed to the water station. Every infrastructure is receiving electrical power as input, which results in availability of water and steam for both hospital and the entire Western campus. This demonstrates a better and optimal decision-making scenario.

Figure 2.9 depicts infrastructures as a function of different physical entities such as water, steam, and electrical power. The importance of power network modelling can be easily seen from Figure 2.9. Four different infrastructures are illustrated, which are within the scope of this research work.

These infrastructures are electrical substations, the water station, steam plant and hospital. The symbols within the brackets show the physical entities on which a particular subsystem is based on. It is clear from the Figure 2.9, that every subsystem has one entity in common as input, which is electrical power. For efficient working of all the infrastructures electricity needs to be provided water station, steam plant and hospital.

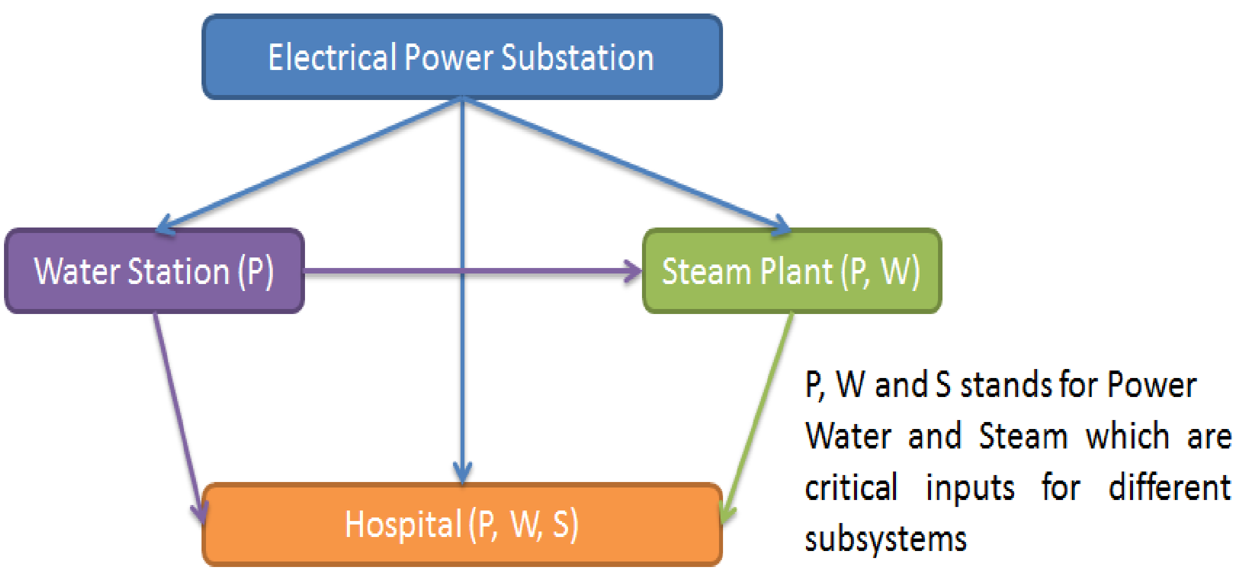

Figure 2.9: Infrastructures as a function of different physical entities (water, steam, electrical power)

For getting the knowledge about how much electrical power will be available during emergency situations, it is necessary to include power system modelling studies into the disaster response studies, as all of the infrastructures are dependent on electrical power.

Thus it can be stated that, while all the network models are important for the disaster response studies, an indispensable network to be studied is the electrical network. Power is the only entity which is needed by all other subsystems. If a disaster response study is done without including a power network model as input, it is simply incomplete and inadequate. The electrical network study performed in this thesis is therefore vital for studying the different subsystems under multi-infrastructure interdependency approach.

2.10 Conclusion

In this chapter, the concept of infrastructure interdependency is discussed in detail. All of the possible subsystems are discussed, but the main focus is on the subsystems that are under the scope of this research work. The principles of interconnection of these subsystems are presented. The main concept used for interconnection is a cell-channel based approach that is executed by the I2Sim software. I2Sim software architecture was presented along with the presentation of the DR-NEP software architecture. The interconnection of domain simulators and interdependency software I2Sim is based on software architectures Quality of Service Evaluator (QoSe) technique of measuring power quality based on fault studies during disasters is presented through the use of Web Services at ENEA Italy. The details of the disaster case studies for the Western campus developed under the DR-NEP project are presented. The significance of electrical infrastructure in overall interdependency study was also presented.

CHAPTER 3

MODELLING OF ELECTRICAL NETWORK OF WESTERN UNIVERSITY

3.1 Introduction

The concept of electrical power network modelling involves the understanding of the structure of power systems. The basic structure of electrical power system can be divided into three main subsystems: namely Generation, Transmission, and Distribution. This thesis has its main focus on Western University Distribution Systems. Power distribution systems are considered as a final stage in delivering the power to consumer loads. The distribution systems generally consist of feeders, distributors and service mains. London Hydro is the utility, which supplies electrical power to Western University. The power voltage levels as defined by the utilities are medium voltage (MV) levels operating between 13.8 kV and 60 kV, and low voltage (LV) levels operating less than 13.8 kV. The incoming power feeders to the substations at Western are at medium voltage level, operating at 27.6 kV. Medium Voltage distribution can be further categorized as a radial type distribution network in which only one circuit is used to supply the consumer loads, and as ring type distribution network in which the primaries of distribution transformers form a loop [24].

The distribution system begins as the primary circuit and then leaves the sub-station and ends as the secondary service enters the customer's meter socket. Distribution circuits serve many customers. Distribution circuits are fed from a transformer located in an electrical substation, where the voltage is reduced from the high values and is used for power transmission [24]. At Western there are three main substations, each having two different transformers connected to different bus bars with same voltage level.

In distribution systems, power may be carried through either overhead lines or underground cables. Also, only large consumers are fed directly from distribution level voltages. Most of the utility customers are connected to a transformer, which reduces the distribution voltage to very low voltage (120V-208V) used by lighting and household loads. The transformers used may be pole-mounted or set on the ground in a protective enclosure [24]. At Western most of the distribution of power is carried out through underground cables. At each substation, two transformers are installed to step down medium level voltage (kV) to low level voltage (kV).

In order to study the nature and different issues of the power distribution system, the electrical network is modelled using different simulation software applications. This chapter describes a detailed modelling of elements of the power distribution system at Western.

3.2 Software Determination

The first and foremost step while making an electrical power model is the selection of appropriate software. The software can be chosen on the basis of the requirements of the study that has to be done. The present research work is based on the modelling of the electrical network for the study of infrastructural interdependency. In this work, the software used for modelling should be able to predict different loading conditions during different disaster scenarios. It should be able to perform load flow studies [24] and predict the different voltage levels at different network levels. In disaster scenarios, the fault studies can generate valuable inputs for interdependencies studies. Thus, according to the above mentioned needs, two different software applications were chosen for modelling the electrical network of the Western campus. One is EMTDC/PSCAD [29] and the second is PSS Sincal [27]. PSS Sincal is appropriate software for load flow studies [24] and EMTDC/PSCAD can be used for fault studies, especially for temporary overvoltage and network transients.

3.3 Modelling of Study System

This section describes the modelling of the elements which are used during the electrical modelling of the study network. This section describes the modelling methodology used in section 3.3.1. The system under study is the power distribution network of Western University. The different subsections of section 3.3 explain the modelling of the substations, transformers, and cables, etc. with regards to both software applications used.

3.3.1 Modelling Methodology

- Softwares like EMTDC/PSCAD and PSS Sincal are commercially available for doing various electrical power systems studies.

- Various component models for transformers, motors and generators etc. are built-in the software and are utilized worldwide for modelling electrical power networks. The models for different components are internationally accepted and used globally.

- Single line diagram for the Western campus was obtained from the facilities management at Western, which gives the information about the various components associated with Western campus electrical distribution networks.

- Different electrical components of Western electrical distribution system network are modelled using the built-in models in the electrical power software EMTDC/PSCAD. By connecting different models, the whole electrical network of Western campus was modelled.

- To make the developed model meaningful, it was necessary to put the accurate data for each and every component in the electrical network. Getting the accurate data was really a tough job. After a time period of more than four months, accurate data was compiled from Western facilities management and transmission and distribution handbooks.

- Finally, the Western electrical distribution network model is developed using the accurate data for each component model in EMTDC/PSCAD. The next step after the electrical network modelling is to validate this model by comparing the calculated values with the actual values.

The validation of the developed Western electrical distribution model has been done in Chapter 4.

3.3.2 System Description

Figure 3.1 depicts the block diagram of the Western campus. The campus consists of three different substations that receive an incoming power supply of 27.6 kV. There is another substation that receives a power supply internally from other two campus substations. At each substation, step-down transformers are installed, which step down the voltage level to 4.16 kV.

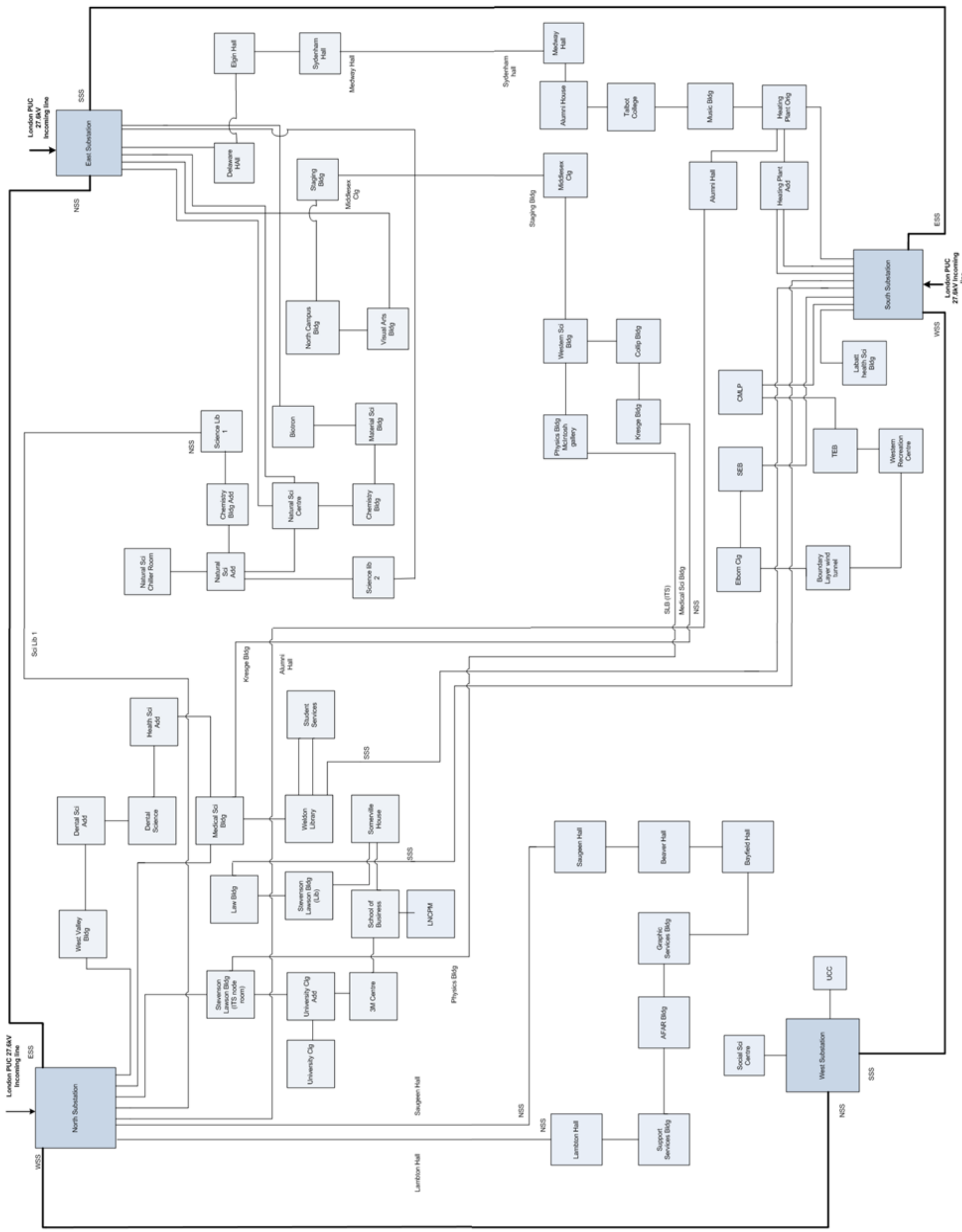

Figure 3.1: Block diagram depicting the Western campus power distribution systems

Every substation has two step-down transformers, which can be seen as redundancy measures to meet emergency situations. Circuit breakers are installed between the bus bars, connecting the two transformers. There are other important components installed on campus such as fuses, capacitor banks, fans and boilers.

Different components present in the above single line diagram are used in the simulation model. These are explained in detail in the following subsections.

3.3.3 Substation Modelling

The main component in any electrical distribution network is a substation where voltage is transformed to a lower level for local distribution [24]. A distribution substation transfers power from the transmission system to the distribution system of an area. Substations contain one or more transformers, and have switching and protection elements such as fuses and circuit breakers, voltage control elements, and power factor correction elements. At Western University, there are three substations at the north, south, and east ends of the campus. The input to these substations is provided by the local utility London Hydro. The input voltage to the substations is 27.6 kV, which is stepped down further to 4.16 kV at all the three substations. There is also a fourth substation at the west end, which supplies two of the major buildings. The west substation is not really a substation in terms of incoming supply, as it is supplied power by two other substations on campus, instead of receiving power from the utility. The basic circuit of the substations at Western University is shown in Figure 3.2.

At each substation, there are two types of bus bars on each side of the transformers. One is the high voltage (HV) bus bar, for which the voltage level is 27.6 kV, and the second is the medium voltage (MV) bus bar, for which the voltage level is 4.16 kV.

In Figure 3.2, there are two different medium voltage bus bars which are connected through a power circuit breaker (2000 A), normally open. Each medium voltage bus bar is connected to a different secondary transformer. Also, each of the medium voltage bus bars supplies 4.16 kV to different buildings across the campus. Each of the buildings at Western has its own small step-down transformers situated along the electrical power circuit, which steps down the 4.16 kV medium voltage level to 240/120 V low voltage level. The low voltage level is used to supply power to different electrical equipment such as fans, lights, and computers in the various buildings. Each of the buildings can be supplied from two different substations providing a redundancy during an emergency or a disaster event.

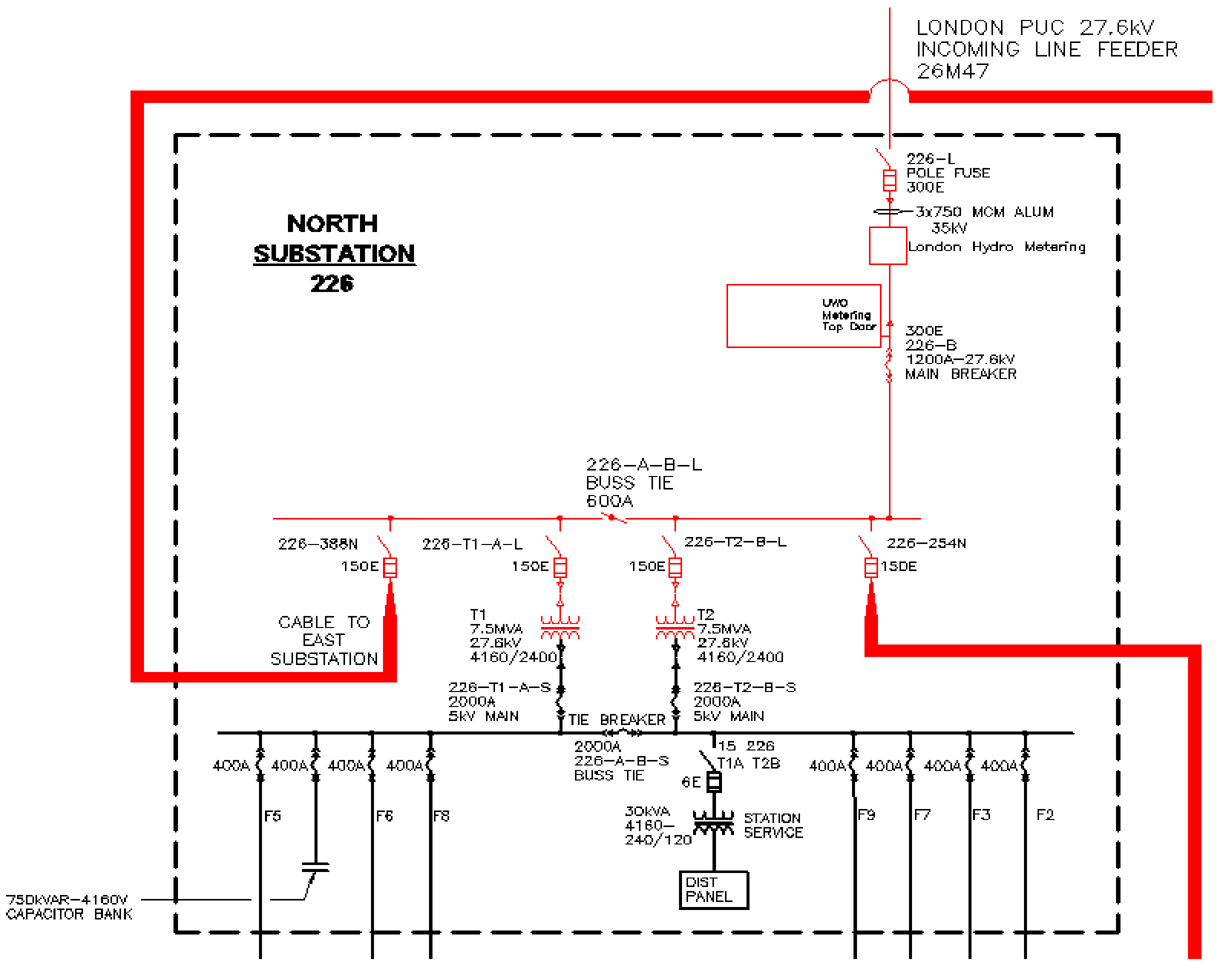

Figure 3.2: Single line diagram depicting details of north substation of campus [53]

Figure 3.3 describes the modelling of the substation in EMTDC/PSCAD software. The incoming power supply from London Hydro is modelled as a voltage source with high voltage level. In actual simulation, a measuring device is used on the primary side of transformer for measuring active and reactive powers. Breakers are used for connecting and disconnecting power between bus bars, substations, and various buildings.

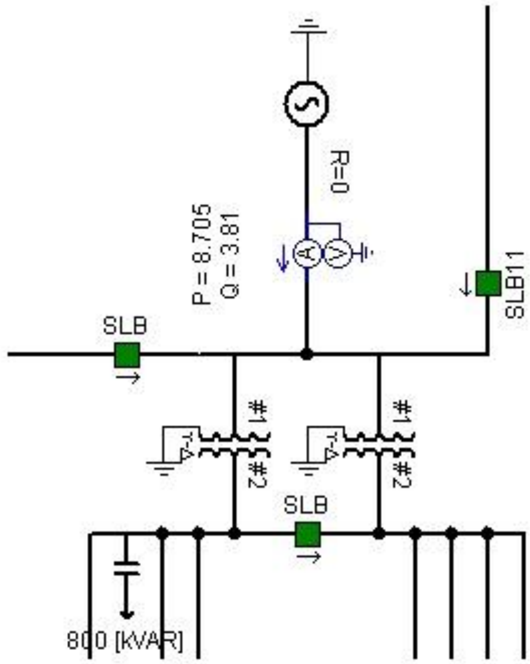

Figure 3.3: Substation modelling in EMTDC/PSCAD

3.3.4 Transformer Modelling

A distribution transformer is a static device constructed with two or more windings, used to transfer alternating currents by electromagnetic induction from one circuit to another, at the same frequency, but with different values of voltage. The purpose of a distribution voltage transformer is to reduce the primary voltage of the electric distribution system to utilization voltage [24]. Mathematically, for a transformer, the product of primary voltage and primary current is equal to the product of secondary voltage and secondary current. The transformers used in the Western University distribution network are typically the dry type, and step down voltage from 27.6 kV to 4.16 kV in the distribution substations as well as stepping down voltages from 4.16 kV to either 600 V or 208 V in campus buildings. In the substations, the transformers are connected in a wye-grounded to delta configuration on a bus line which has a tiebreaker switch between them. This step up allows one transformer to take on the load of the other transformer in the event that one of the transformers requires maintenance and de-energization is required.

The transformer model adopted for simulation in EMTDC/PSCAD and PSS Sincal for the study system is based on the theory of mutual coupling as illustrated in Figure 3.4 [29]. This concept of mutual coupling is illustrated with the help of equivalent circuit of the transformer, as shown in Figure 3.5 [29].

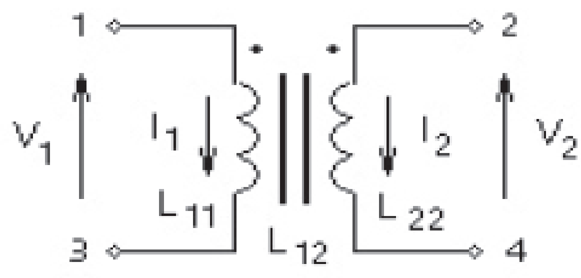

Figure 3.4: Transformer model used for simulation in EMTDC/PSCAD [29]

where,

L_{11} = Self-inductance of winding 1

L_{22} = Self-inductance of winding 2

L_{12} = Mutual inductance between windings 1 & 2

The voltage across the primary winding is V_1 and the voltage across the secondary winding is V_2. PSCAD computes the inductances based on the open-circuit magnetizing current, the leakage reactance, and the rated winding voltages [29].

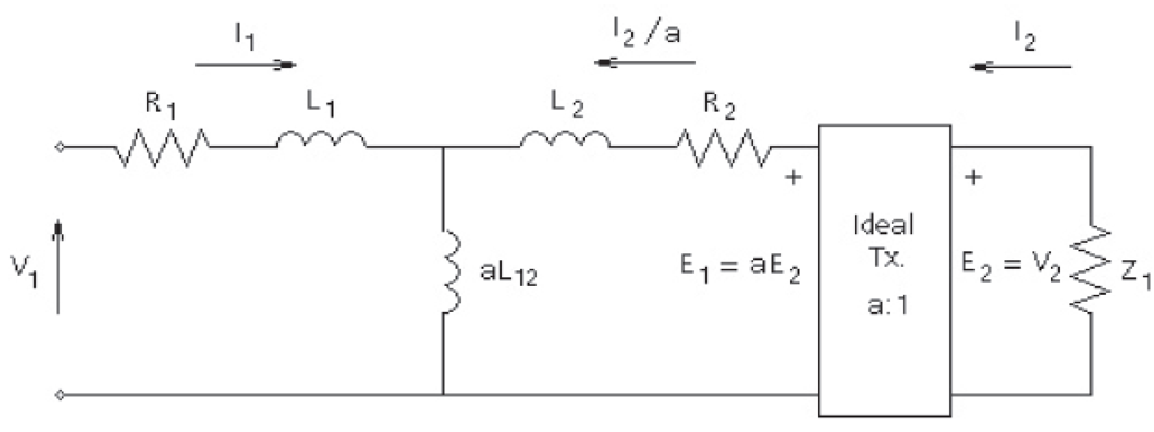

Figure 3.5: Equivalent circuit of transformer model [29]

$L_1 = L_{11} – a* L_{12}$

$L_2 = a_2* L_{22} – a* L_{12}$

Using the above methodology, all transformers are modelled for the study system. At each substation, two transformers are installed to step down the distribution voltage. In addition, transformers are used to further step down voltage to supply power to buildings from the substation. But in the study system, these transformers are not modelled at building level to avoid complexity.

3.3.5 Underground Feeders

An underground feeder is a buried power cable system used to distribute power to consumers. Western University utilizes the underground feeder system to distribute power to various buildings across the campus. There are two types of cables used in the study system depending upon voltage levels. The standard cable used for 27.6 kV side is 750 MCM overhead aluminum cables with an ampacity rating of 385 A, and with a temperature rating of 75 ^{O}C. However, for the 4.16 kV side, a 500 MCM underground copper cable system with an ampacity rating of 380 A and a temperature rating of 75 ^{O}C is used. The reason for using copper cables on the secondary side, instead of aluminum, is that secondary side currents are higher and copper offers less resistance than aluminum. The high conductivity of copper allows for the easy passage of electricity without heating the wire [54]. Copper wiring is three times heavier than identical aluminum wiring. As such, depending upon the requirement of the study system, an underground cable can be used. Both the copper and aluminum cables used are illustrated through pictures in Figure 3.6.

Figure 3.6: Aluminum and copper cables used for underground feeders [54]

In PSCAD the cables are modelled using standard pi-section models, as they are suitable for very short lines where the traveling wave models cannot be used as shown in Figure 3.7. Coupled pi-section in PSCAD is formed by user defined values for lumped R, L, C elements. Overhead lines or cables are presented as series reactance, resistance, and shunt admittance (Line charging capacitance). Accurate data for the cables was obtained from the Westinghouse transmission and distribution book [55].

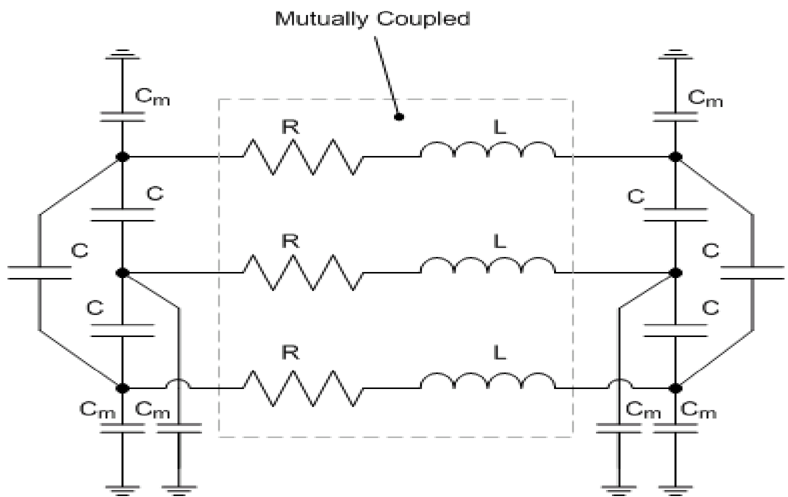

Figure 3.7: Coupled pi model used for underground feeders in EMTDC/PSCAD [29]

In order to obtain the feeder lengths of the network, an updated AutoCAD [53] map of the Western distribution underground network was used. The AutoCAD map was obtained from engineering facilities at Western who assured that the scaling of the components and distances was accurate. AutoCAD possesses tools that can measure the exact lengths between two points on a map using the accompanying scaling legends. The initial step was to determine the exact location of each building's electrical room with the AutoCAD map. Feeder lengths were calculated as the distance between the electrical rooms for each building or substation, depending on the type of connection. The distances were measured using AutoCAD map and the data is provided in Appendices D and F.

3.3.6 Circuit Breaker

A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit [24]. The circuit breaker can also be defined as a piece of equipment that can

- Make or break a circuit, either manually or by remote control, under normal conditions
- Break a circuit automatically under fault conditions

Thus, a circuit breaker incorporates manual (or remote control) as well as automatic control for switching functions. The latter control employs relays and operates only under fault conditions. In the study system, circuit breakers are used in modelling both buildings and substations. As a redundancy every building can receive a power supply from two or more substations, so there is a switching phenomenon going on routinely in day-to-day operations. Thus circuit breakers are used in the simulation of study case, which is modelled in both PSCAD and PSS Sincal, to create the different scenarios.

There are different methods for representing a simple switching element in time domain simulation programs. The most accurate approach is to represent them as ideal that possesses both a zero resistance in the ON state and an infinite resistance in the OFF state [29]. Figure 3.8 illustrates a simple RLC network. In this diagram let the resistance R_{12} represent a simple switch. If R_{12} is considered ideal, then two different networks can result, depending on the state of the switch. These two states of the switch are ON and OFF states. When R_{12} is connected, the switch is in ON state and in OFF state if R_{12} is disconnected.

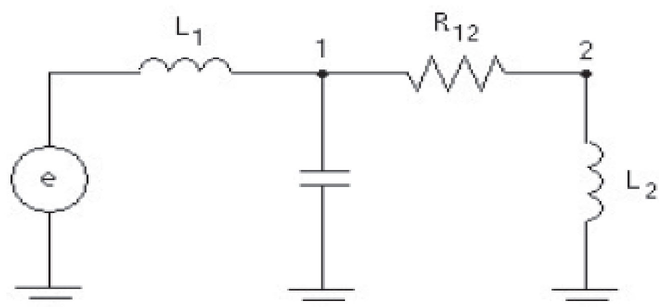

Figure 3.8: RLC equivalent network in EMTDC/PSCAD [29]

In EMTDC/PSCAD, simple switching devices are represented as a variable resistor, possessing an ON resistance and an OFF resistance. Although this type of representation involves an approximation of both the zero resistance (ON) and an infinite resistance (OFF) of an ideal switch, it is advantageous in that the same circuit structure can be maintained, and the electric network will not need to be split into multiple networks, as a result of each switching event [29].

3.3.7 Modelling of Buildings (Load)

The term 'load' refers to customer equipment that needs electrical power to operate. In the campus study case, various buildings represent different kinds of loads. The load of the campus is different during different time periods during the day. For example, the load at night is much lower than the load at daytime. Also, load affects the performance of circuits that provide output voltages or currents, such as sensors, voltage sources, and amplifiers. When a high power appliance in the campus building is switched on, it reduces the load impedance. Also every time a new department or building comes into the picture, it leads to the addition of new load which impacts the bus voltage. It, therefore, becomes necessary to perform the load flow analysis for existing loads and plan the future addition of loads.

Figure 3.9 shows the original configuration of the buildings, as provided by the Physical Plant personnel. The loads are modelled as constant power load. Two buildings or loads are separated by a power circuit breaker. For the distribution of electricity, cables are used in the simulation, which is equivalent to a “pi” circuit model of transmission line. The data for the power cables is taken from Westinghouse Transmission and Distribution (T&D) book [55]. Figure 3.10 presents a network segment model EMTDC/PSCAD software. It shows how these buildings are modelled in EMTDC/PSCAD. These buildings are modelled as a single node and a single load.

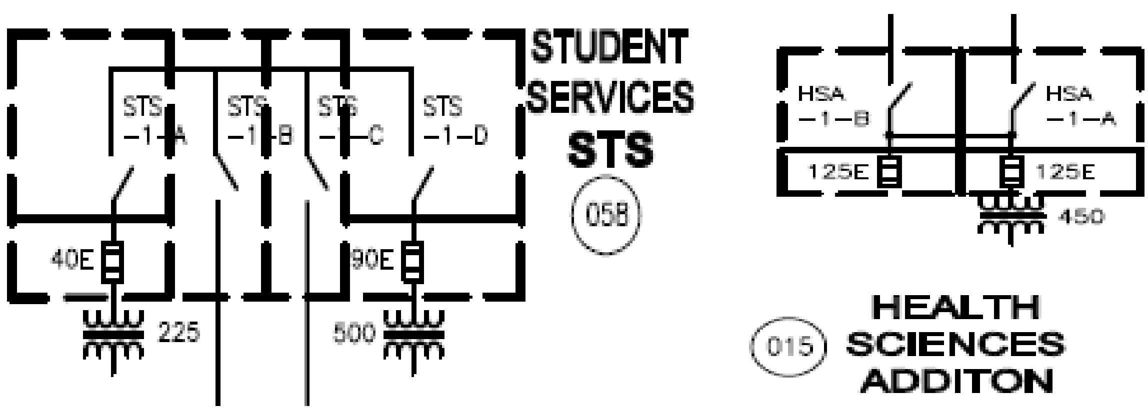

Figure 3.9: Single line diagram of student services buildings and health science building [53]

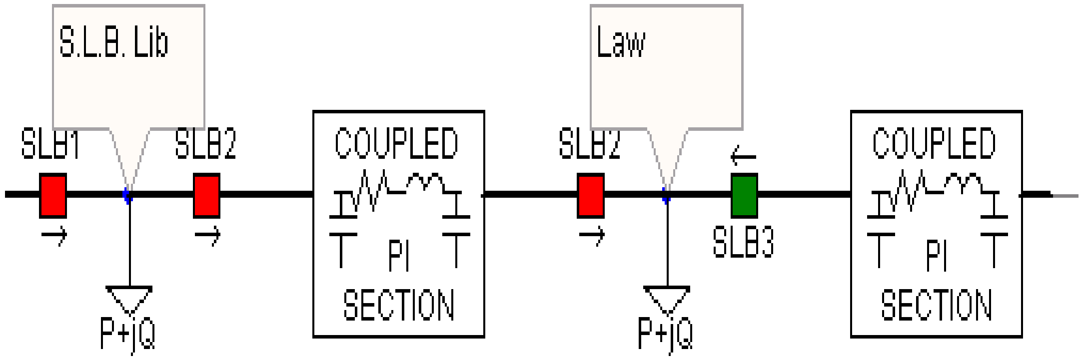

Figure 3.10: Software simulation subset of Western campus in EMTDC/PSCAD

3.4 Conclusions

This chapter has presented the description of the major components of the electrical system model of the Western campus. The modelling of these components in both EMTDC/PSCAD software and PSS Sincal software are described.

CHAPTER 4

VALIDATION OF ELECTRICAL SYSTEM MODEL OF WESTERN UNIVERSITY

4.1 Introduction

The Western University electrical distribution system is modelled for performing the infrastructural interdependency studies. The University campus receives an incoming power supply from the local utility, London Hydro. For the validation of interdependency studies, it is important that the infrastructures participating in these studies should be correctly modelled. This chapter deals with the validation of the electrical system model so that its outputs can be reliably used for the DR-NEP project studies. For validating the electrical system model, EMTDC/PSCAD [29] software is used for simulation of various substations and buildings.

In this chapter, three different scenarios are investigated for the validation of the campus electrical system model. These scenarios deal with three different power levels during different time periods during the day, in a week when the power goes from minimum level to peak level. For this purpose, a single line diagram of the campus electrical systems is taken from the Western Facilities Management website. The data for the validation is also provided by the Western Physical Plant. This validated model will be useful for studying different disaster scenarios. Various faults can be created to represent the disaster, and analysis can be done with respect to the objectives of this work. In the next section the methodology used for validation will be described.

4.2 Methodology for Validation

To best demonstrate the reliability of the campus power system during a disaster, the worst case scenario has to be identified and selected. This worst case scenario corresponds to the maximum loading condition (highest power consumption) that has occurred in the past. This way, by simulating for the worst case scenario we could see how system would react in extreme conditions during a natural disaster. A historical study of the overall trend on each of the building and substation was done including the seasonal load data that Western Facilities

Management provided. It is seen that peak power demands occur mainly during the months of January and July.

January has a high power demand due to fact that it is one of the coldest months and students are returning from a holiday break. For this reason, electricity consumption trends are much higher as compared to other months. July has been historically the hottest month and the increase in electricity use is primarily caused by the increased usage of the campus chillers. Both cases present equal likelihood of a worst-case scenario in terms of total power consumptions.

In this research work, for validating the model, three scenarios have been selected for steady state analysis in EMTDC/PSCAD. Each of these three case studies has the same system diagram, but different data is used for the load flow studies. These three case studies represent different loading conditions of the Western campus electrical systems, as follows:

- Peak Load Conditions
- Light Load Conditions
- Medium Load Conditions

For all the three loading conditions, following steps were followed for validation.

- Once the model was developed in EMTDC/PSCAD, the model is executed for getting the values of different electrical quantities.
- For all the three different loading condition, active power (P), reactive power (Q) and voltage (V) values are calculated from the model developed in EMTDC/PSCAD.
- For each of the three loading conditions, the values for different electrical quantities were calculated at three different locations, start, middle and end of the feeder.
- The actual measured values for same electrical quantities (P, Q and V) were obtained from the Western facilities.

- Comparison is done between the actual and measured values obtained from EMTDC/PSCAD.
- For the validation, the values for three different electrical quantities (P, Q and V) are compared and percentage error is calculated for nine different cases.

4.2.1 Peak Load Conditions

For modelling the peak load conditions, the data provided by the campus physical plant was studied and analyzed. The data provided for all three substations was studied on a weekly basis, analyzing the trends of different days of the week. Physical Plant personnel also provided data for all of the different buildings on the Western campus, from the year 2002 to present. After analysis, it was observed that different weeks of a particular month had a common trend from Monday to Sunday. For the majority of the weeks, the load of campus reaches its peak value for Mondays and then the load gradually decreases day by day as the weekend approached. The peak value on a particular Monday was observed as 22.9 MW. Figure 4.1 presents a typical total power curve for the Western campus for a particular week in 2011. It illustrates that the campus uses more power during the day as compared to night time.

The seven peaks in the Figure 4.1 represents seven days of a week. The first peak represents Monday and the last two lowest peaks represent Saturday and Sunday. Another factor, which was included, is the concept of critical buildings and critical electrical devices that require electrical power 24 hours per day. The critical buildings of the campus include the power plant, the hospital, medical science building, animal care, etc. As such, it was made sure that during the modelling of campus, critical buildings should receive power above the threshold value. The data used for the modelling of the Western campus during peak load conditions is provided in Appendix A. Table 4.1 represents the buildings which have a peak load, more than 5 MW.

4.2.2 Light Load Conditions

The second scenario used for validating the campus electrical model corresponds to the light load conditions. The light load scenario was determined by analysing the total substation data, which is the combination of north, south, and east substations. The basic concept of analyzing the data remains the same as in peak load conditions. As explained in Section 4.2.1, different weeks of a particular month had a common trend from Monday to Sunday.

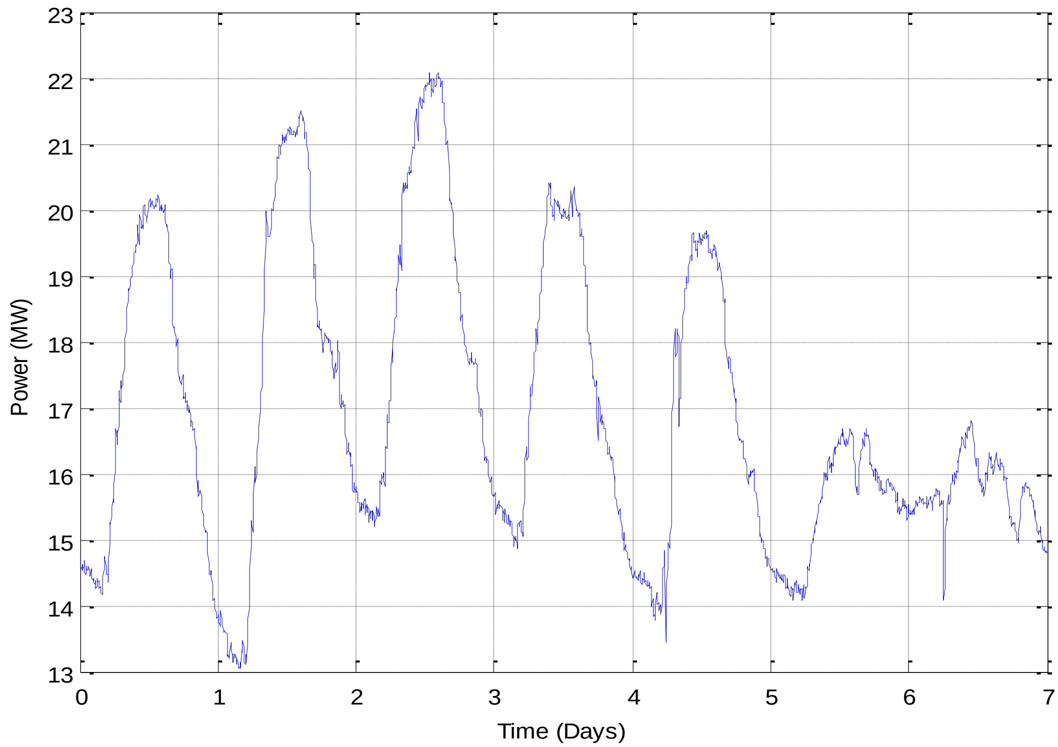

Figure 4.1: Typical total power curve for Western campus for a particular week in 2011 (On x-axis 0-7 represents Monday to Sunday).

Table 4.1: Campus buildings having peak load more than 5MW

Serial Number	**Building Name**	**Average Peak Load (KW)**
1	Social Science	1833.8194
2	West Valley	942.2667
3	Support Services	881.3778
4	Recreation Centre	722.6389
5	Medical Science	670.3364
6	Spencer Engineering Building	654.0648
7	Dental	614.1991
8	Weldon	599.1821
9	Biotron	572.3241
10	University Community Centre	556.1389

For all of the weeks, the load of campus reaches its lowest value for nighttime mainly on Wednesday and Thursday, during the weeknights. For the light load case study, the simulation diagram remains the same, but the data is different, which is provided in Appendix B. Also, one of the major worst load conditions was observed in November 2011 for approximately two weeks. This is the incident when the south substation was shut down for roughly two weeks and the north substation was compensating for the closing of the south substation.

4.2.3 Medium Load Conditions

The third scenario used for validating the campus electrical model relates to medium load conditions. Both the building and substation data was analysed to determine the appropriate medium loading conditions. By analyzing different maximum and minimum loading conditions, an average value for medium loading conditions was obtained. In addition, the corresponding loading conditions were obtained from the building load data provided by the physical plant. In actual practice, medium load conditions represent the late afternoons and early evenings during the weekdays. Also, at times the medium loading conditions can be represented by the peak load values during Saturdays and Sundays. In this scenario, the same system diagram is utilized during the simulation except with changed load values, as provided in Appendix C.

4.3 Simulation Results

In this section, the simulation results of steady state analysis of the Western campus electrical systems are presented. These results are divided into three subsections based on three case studies selected for validation of the Western campus electrical system. In support of the validation of the three case studies, appropriate graphs and tables are presented. Different comparison techniques are used to find the percentage error between the actual and simulated results. The results are validated under the following assumptions:

- The load power factor for the simulation is assumed to be 0.9 lagging.
- The data for some of the residence buildings are calculated based on the assumption that an increase in load of one building has the same ratio as the increase in the load of another residence building with almost same load in 2002. For example: Saugeen Hall residence had data from 2002-2006, but Perth Hall residence had data for all years from

2002-2011. So, the data for Saugeen Hall is calculated based on the assumption that the ratio of the increase of load is same for both the halls.

- Some of the building loads are added together as one if the connection data is missing in the single line diagram provided by Facilities Management. For example, in the single line diagram of the Western campus, if the connection data between any two closely situated buildings is missing, the load data for both buildings is added together and presented as one building in the simulation.

- Every building on the Western campus can be supplied power by two different substations. Facilities Management did not provide the connection data for a particular building to a substation for a particular time of the day. Thus, the connection of a particular building has been done keeping in mind the historical load distribution values of different substations. For example, the Weldon Library building can be supplied power by both the north and south substations. However, as per historical data, in the simulation diagram, Weldon Library is receiving its power supply from the south substation.

According to the data provided by Facilities Management for the three different substations, graphs have been plotted depicting the actual measured data by the substation meter.

A large set of data was provided by Facilities Management in an Excel spreadsheet. This data was sorted according to the needs of the study. The relevant data was then plotted, with the help of MATLAB software [46]. For generating the data, a code was written in MATLAB, and is provided in Appendix E.

The data provided gave information about the active power consumed by the all three substations. Information was also provided about the power factor, currents on the secondary sides of the transformers, and voltage on secondary side of the transformers. To obtain the total data values for the entire campus, data for the individual substations was added manually.

Figure 4.2 depicts the actual active power consumed by the entire Western campus. Figure 4.3 depicts the actual active power consumed by individual substations during a particular week. The week that has been selected measures the average peak loading of the campus. The peaks of the seven curves in Figure 4.2 represent the maximum load during the day for all seven days of the week. For example, on the x-axis, Monday starts from value 0 and ends on value 1 and from 1 onwards the load curve starts for Tuesday, which ends at 2. According to Figure 4.2, the peak loading of the Western campus occurs on a typical Monday and is around 22.84 MW. Among the individual substations, the south substation supplies the largest power, as seen in Figure 4.3.

Figure 4.4 presents the total actual reactive power for the individual substations on the Western campus. As meters cannot measure reactive power, the reactive power was calculated using the power triangle illustrated in Figure 4.5. When the active power is known, using a power factor of 0.9, reactive power can be calculated. The power factor in all of this research work is assumed to be 0.9.

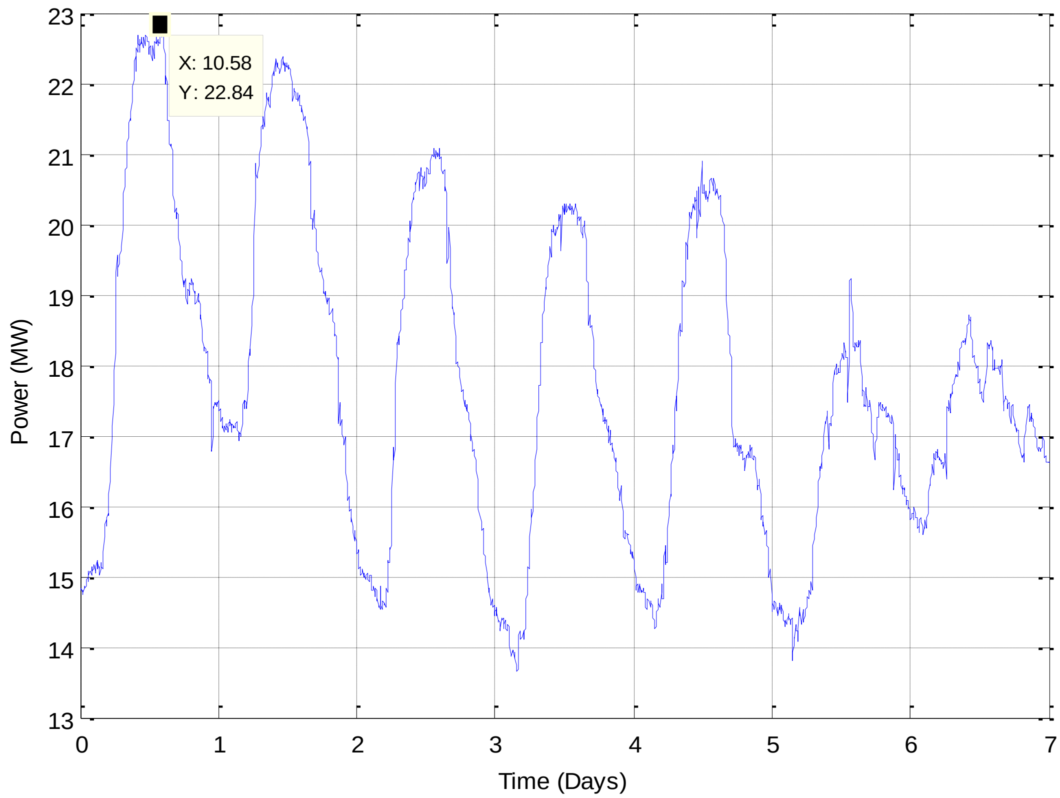

Figure 4.2: Total actual active power measured at Western substations (On x-axis 0-7 represents Monday to Sunday).

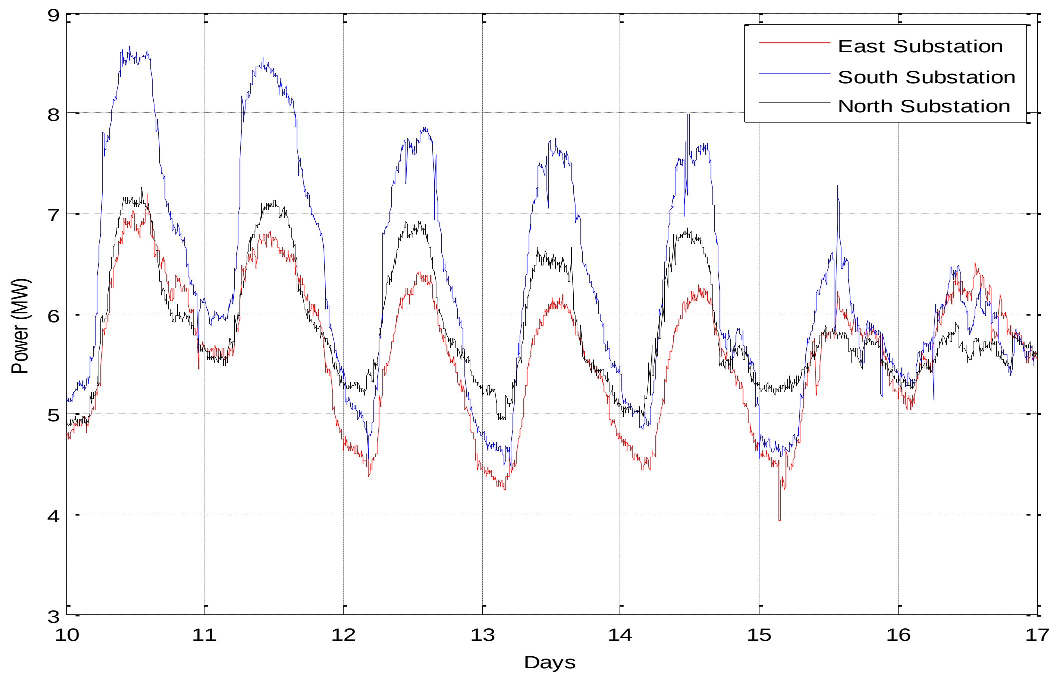

Figure 4.3: Individual actual active power measured at three substations in Western campus (On x-axis 0-7 represents Monday to Sunday).

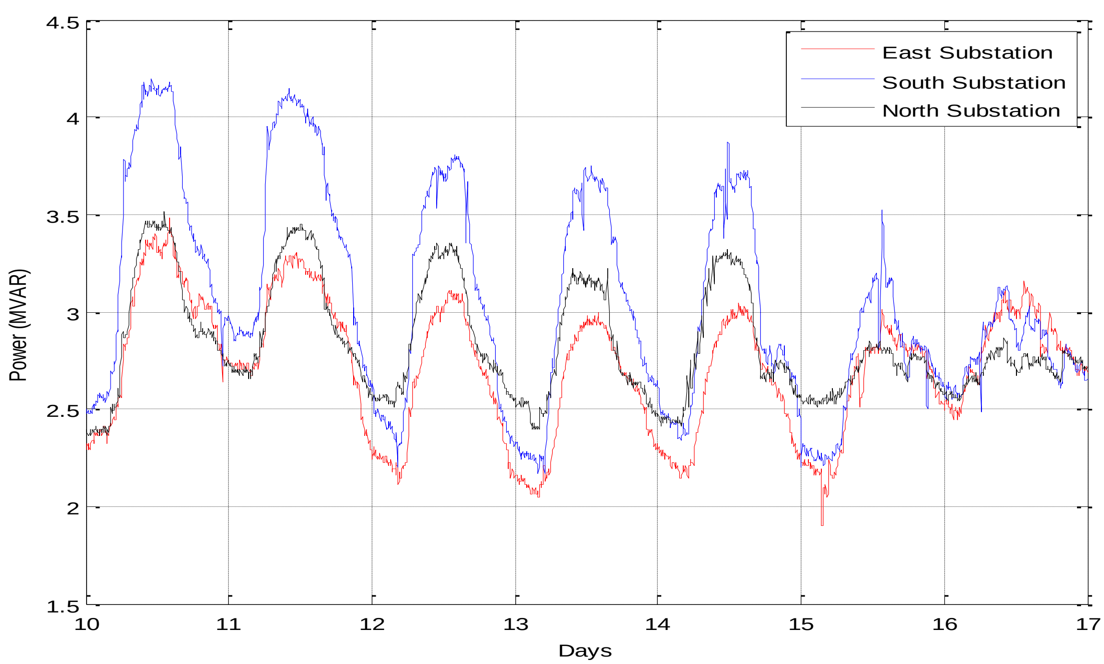

Figure 4.4: Total actual calculated reactive power for three Western substations (On x-axis 0-7 represents Monday to Sunday).

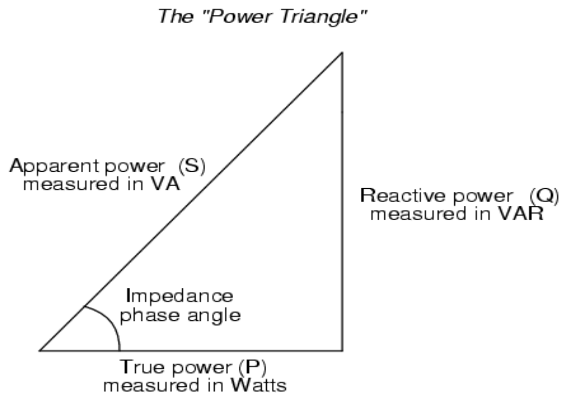

Figure 4.5: The power triangle [24]

4.3.1 Peak Load Conditions

The model of the Western campus is implemented for steady state analysis by the electromagnetic transient software EMTDC/PSCAD. In order to validate the campus electrical model, three different loading conditions have been simulated. This section deals with model validation using the simulated results for peak loading conditions. For this purpose, the values of voltage, active power, and reactive power are compared at the start of the feeder, middle of the feeder, and at the end of the feeder, with the help of graphs and tables.

The data recorded or measured by Facilities Management personnel have been plotted using MATLAB [46] software. The simulated results are transferred from EMTDC/PSCAD to MATLAB in order to get similarity in graphs, as plotted for the actual data. These graphs are compared with respect to the total active and reactive power flow for the Western campus. Graphs are also plotted individually for all three substations that collectively supply electrical power to the campus.

The actual data has already been presented in Figures 4.3 and 4.4 which provide the actual readings of active and reactive power of all three substations. Figures 4.3 and 4.4 presented the peak power demand for the seven days in a week. However, Figure 4.6 plots the maximum power over the entire week. For validating the results, comparison of the highest peak (Monday) in Figure 4.2 is done with the maximum value depicted in Figure 4.6.

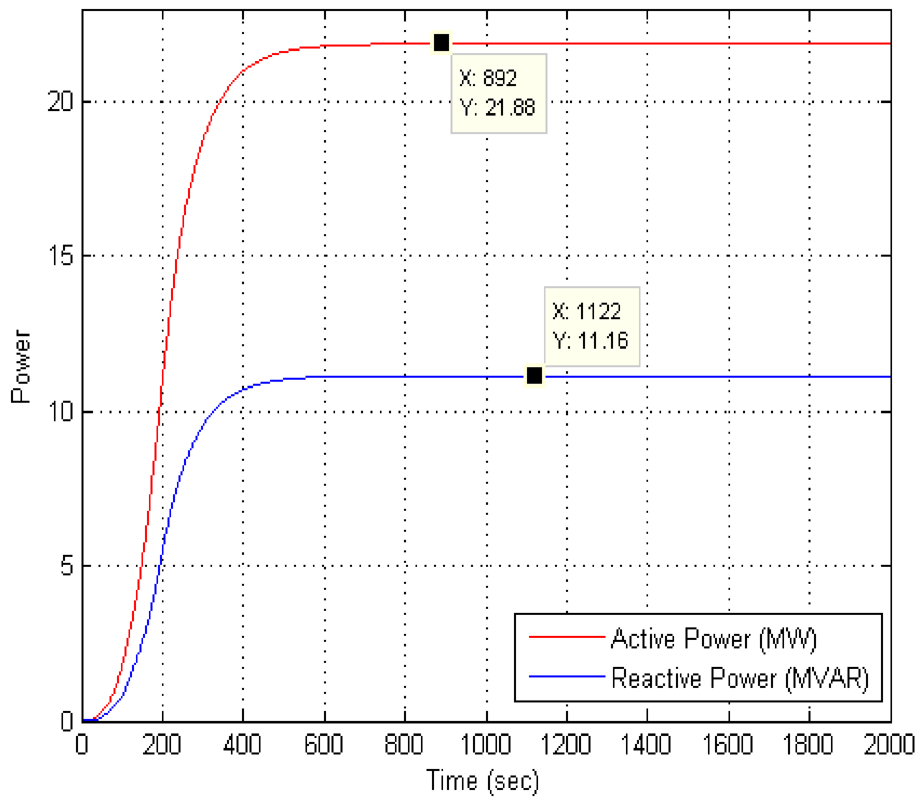

Figure 4.6: Simulated total power consumption during peak loading conditions

This comparison is done at three different locations in the simulation model. The three different locations are:

- Start of Feeder
- Middle of Feeder
- End of Feeder

Table 4.2 presents the comparison of measured and simulated quantities for peak loading conditions with error calculation at the start of the feeder. Table 4.3 presents the comparison of measured and simulated quantities for peak loading conditions, with error calculation at the middle of the feeder. Table 4.4 presents the comparison of measured and simulated quantities for peak loading conditions with error calculation at the end of the feeder.

Table 4.2: Comparison of Measured and Simulated Quantities for peak loading conditions at start of feeder

Start of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.654	0.642	1.835%
Reactive Power	0.317	0.311	1.893%
Voltage	0.988	0.995	0.697%

Table 4.3: Comparison of Measured and Simulated Quantities for peak loading conditions at middle of feeder

Middle of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.410	0.394	3.902%
Reactive Power	0.199	0.191	4.070%
Voltage	0.979	0.988	0.959%

Table 4.4: Comparison of Measured and Simulated Quantities for peak loading conditions at end of feeder

End of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.070	0.066	4.686%
Reactive Power	0.034	0.032	4.765%
Voltage	0.971	0.985	1.399%

It is noted that the simulated values of real power, reactive power, and voltage match very well with the measured values, with an error less than 5%, which is within acceptable limits. This validates the EMTDC/PSCAD model of the Western campus for peak loading conditions.

4.3.2 Light Load Conditions

The simulations for the light load conditions are done with the same EMTDC/PSCAD model but with different load values. The actual values for the light loading conditions were calculated with the help of data provided by Facilities Management. The curves were plotted for actual active and reactive power with the help of a MATLAB program that is provided in Appendix E. Figure 4.7 depicts the total actual active power consumption over different days of the week (Monday to Sunday) on the Western campus. It also illustrates the light loading conditions for a typical week. The seven dips in Figure 4.7 show the nighttime power loading from Monday to Sunday. The lowest dip in the graph occurs on Wednesday night with respect to light loading conditions. The actual value of active power during light loading conditions is 13.65 MW.

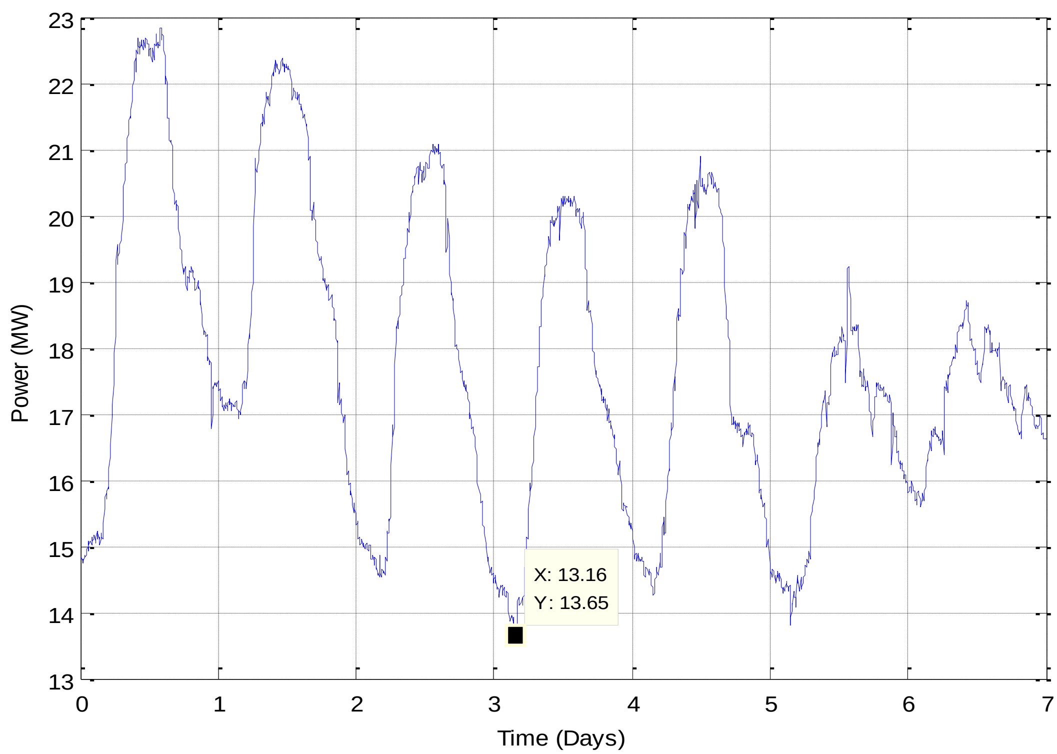

Figure 4.7: Total actual power consumption during light loading conditions
(On x-axis 0-7 represents Monday to Sunday).

Figure 4.8 depicts both active and reactive power values for a particular time of night on the Western campus during light loading conditions. In contrast to the seven dips in Figure 4.7, which represent the seven days of a week from Monday to Sunday, Figure 4.8 has only one quantity which represents the value of light loading conditions observed on a Wednesday night.

For light loading conditions, a comparison of the actual measured quantities is done with simulated quantities at three feeder locations in the simulation model. These three locations are start, middle, and end of the feeder.

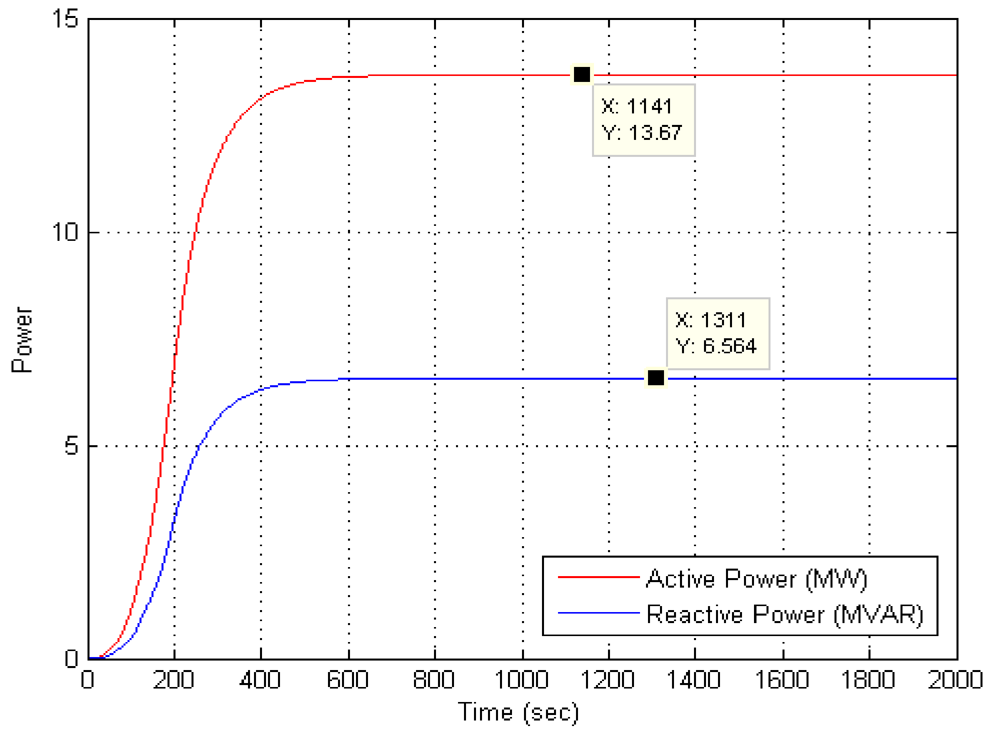

Figure 4.8: Total simulated power consumption during light loading conditions

Table 4.5 presents the comparison of measured and simulated quantities for light loading conditions with error calculation at the start of the feeder. Table 4.6 presents the comparison of measured and simulated quantities for light loading conditions with error calculation at the middle of the feeder. Table 4.7 presents the comparison of measured and simulated quantities for light loading conditions with error calculation at the end of the feeder.

Table 4.5: Comparison of Measured and Simulated Quantities for light loading conditions at start of feeder

Start of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.392	0.386	1.531%
Reactive Power	0.190	0.186	1.684%
Voltage	0.988	0.997	0.930%

Table 4.6: Comparison of Measured and Simulated Quantities for light loading conditions at middle of feeder

Middle of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.024	0.023	2.724%
Reactive Power	0.119	0.115	3.025%
Voltage	0.979	0.994	1.521%

Table 4.7: Comparison of Measured and Simulated Quantities for light loading conditions at end of feeder

End of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.042	0.040	3.357%
Reactive Power	0.020	0.019	3.400%
Voltage	0.971	0.992	2.120%

It is noted that the simulated values of real power, reactive power, and voltage match very well with the measured values, with an error less than 5%, which is within acceptable limits. This validates the EMTDC/PSCAD model of the Western campus for light loading conditions.

4.3.3 Medium Load Conditions

The simulation for the medium load conditions is done with the same system model as both the light and peak loads, but with different data values. The actual loading values for the medium loading conditions were calculated with the help of data provided by Facilities Management. The curves were plotted for actual active and reactive power, with the help of a MATLAB program provided in Appendix E. Figure 4.9 depicts the total actual active power consumption over different days of the week (Monday to Sunday) on the Western campus. The seven peaks and dips in the Figure 4.9 shows the daytime and nighttime power loading, from Monday to Sunday respectively.

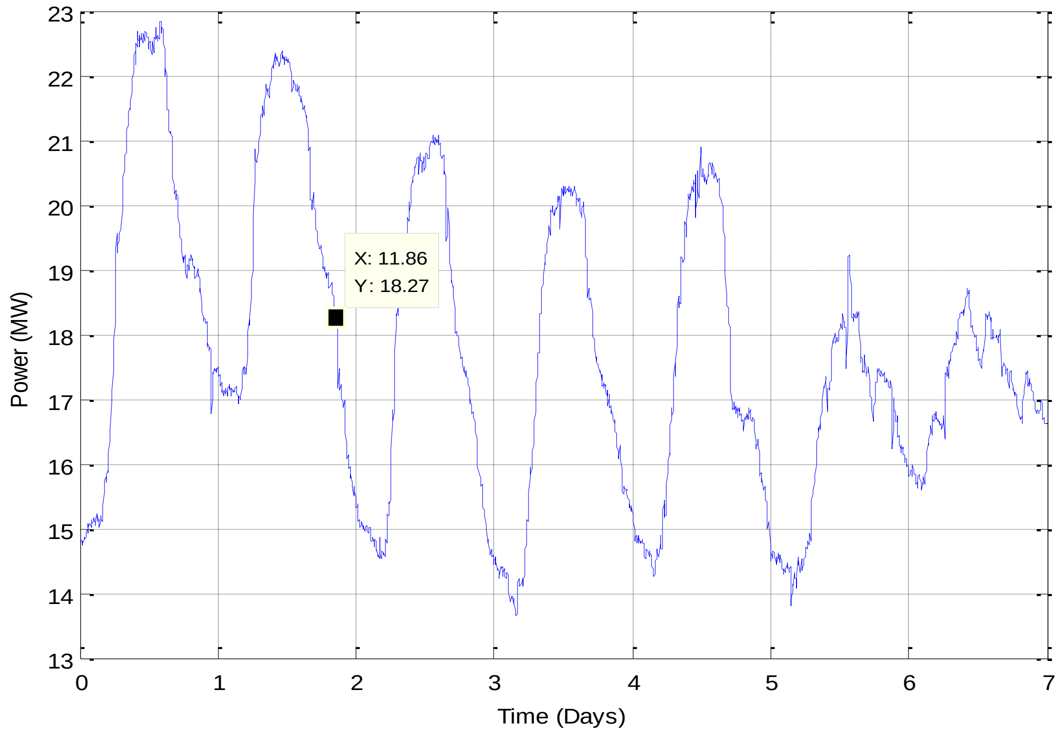

Figure 4.9: Total power consumption during medium loading conditions (On x-axis 0-7 represents Monday to Sunday).

For modelling the medium loading conditions, an average value in between the maximum and minimum values was chosen from Figure 4.9. The medium loading values normally represent the late evening or early morning time of the day. The actual value of active power during medium loading conditions is obtained as 18.27 MW.

Figure 4.10 depicts both active and reactive power values for a particular time: a Tuesday evening on the Western campus during medium loading conditions. In contrast to the seven peaks and dips in Figure 4.9, which represent the seven days of a week from Monday to Sunday, Figure 4.10 have only one quantity, which represents the value of medium loading conditions observed on a Tuesday evening.

For medium loading conditions, comparison of actual measured quantities is done with simulated quantities at three feeder locations in the simulation model. These three locations are the start, the middle, and the end of the feeder.

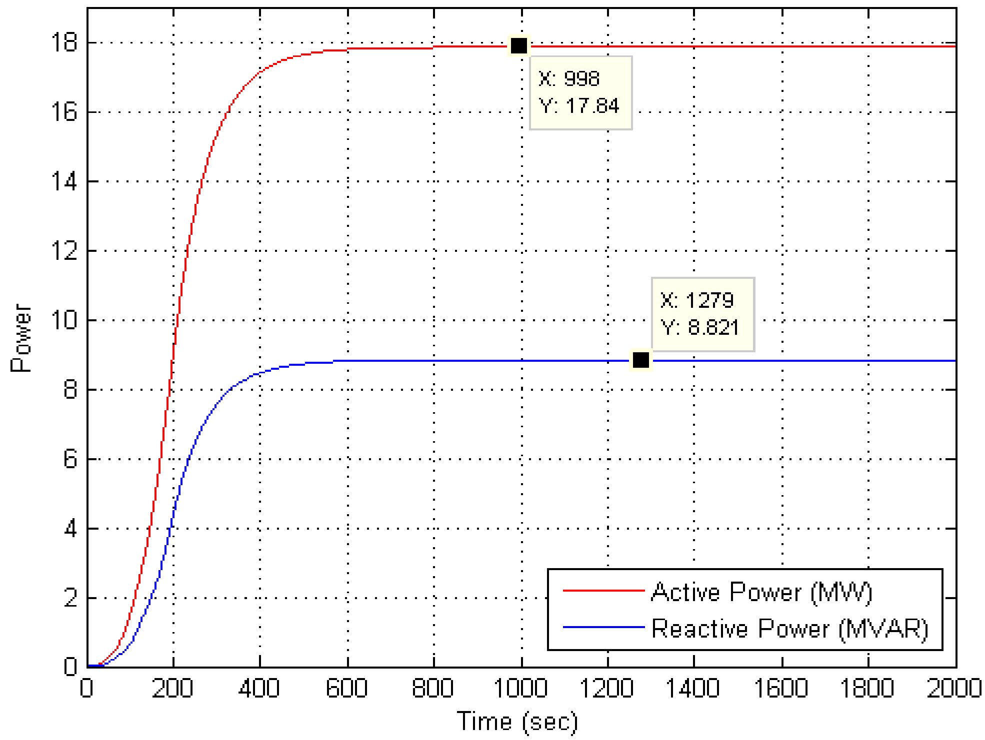

Figure 4.10: Simulated total power consumption during medium loading conditions

Table 4.8 depicts the comparison of measured and simulated quantities for medium loading conditions with error calculation at the start of the feeder. Table 4.9 depicts the comparison of measured and simulated quantities for medium loading conditions with error calculation at the middle of the feeder. Table 4.10 depicts the comparison of measured and simulated quantities for medium loading conditions with error calculation at the end of the feeder.

Table 4.8: Comparison of Measured and Simulated Quantities for medium loading conditions at start of feeder

Start of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.523	0.512	2.103%
Reactive Power	0.253	0.247	2.372%
Voltage	0.988	0.997	0.910%

Table 4.9: Comparison of Measured and Simulated Quantities for medium loading conditions at middle of feeder

Middle of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.328	0.315	3.963%
Reactive Power	0.159	0.152	4.088%
Voltage	0.979	0.988	0.959%

Table 4.10: Comparison of Measured and Simulated Quantities for medium loading conditions at end of feeder

End of feeder			
Quantity	**Measured Value**	**Simulated Value**	**Percentage Error**
Active Power	0.056	0.053	4.571%
Reactive Power	0.027	0.025	4.630%
Voltage	0.971	0.986	1.451%

It is concluded that the simulated values of real power, reactive power, and voltage match very well with the measured values, with an error less than 5%, which validates the EMTDC/PSCAD model of the Western campus for medium loading conditions.

4.4 Conclusions

In this chapter, the electrical model of the Western campus has been validated in EMTDC/PSCAD software for three different loading conditions namely, peak load condition, medium load condition, and light load conditions. For each of these conditions the model is validated within some reasonable assumptions or limitations as discussed in section 4.3. For all three different loading conditions, the model is also validated at three different feeder locations. The validation has been performed for three quantities namely active power, reactive power, and voltage. For all of the cases studied, the error in the simulated quantities as compared to actual measured quantities is less than 5 %, which is considered acceptable.

Such a validated model as developed in this research work has never been attempted earlier at Western. Within the presented assumptions, this validated Western model can be used in the future for the following purposes:

- **To study the disaster events:** This model can simulate different faults during any emergency situations and provide information on the available electrical power on the campus for meeting the needs of other infrastructures such as water pumps in the water network, various machines in the hospital, computers in data acquisition systems in the communication systems, etc. During the disaster management studies involving various infrastructures, it is important to have a validated electrical power model.

- **Installation of renewable energy resources:** At Western, some photo-voltaic (PV) panels are already installed at the top of the Claudette MacKay-Lassonde Pavilion building (Green building). In the future, plans can be made to install more PV panels or other renewable generating sources across the campus. The validated electrical model can be used to perform feasibility studies of the installation of such renewable resources on Western's campus.

- **Future expansion studies:** Western is expanding its activities daily. Based on the demands of campus activities, it is necessary to build a new infrastructure at present, and in future. For example, a new building is being constructed for The Richard Ivey School of Business on Western Road. Also, a new construction site has been started behind Perth Hall residence. Keeping in mind construction of new buildings, it is necessary to get information about various power system components and availability of electrical power for these buildings. The validated system model can be used for both steady state and transient studies for future expansions of the Western campus.

CHAPTER 5

DISASTER SCENARIOS FOR INTERDEPENDENCY STUDIES

5.1 Introduction

The word *disaster* implies a sudden, overwhelming and unforeseen event [56]. At the household level, a disaster could result in a major illness, death, or substantial economic or social misfortune. At the community level, it could be a flood, a fire, a collapse of buildings in an earthquake, the destruction of livelihoods, an epidemic, or displacement through conflict. When occurring at district or provincial level, a large number of people can be affected. Most disasters result in the inability of those affected to cope without outside assistance.

Thus, in order to deal with these disasters in a better way, it is necessary to prepare an emergency plan in advance. When preparing an emergency plan, it should be confirmed that all of the necessary infrastructures are included in the plan. This plan would be best if the coordination of all of the infrastructures such as power, water, steam, and communication systems is ensured.

In earlier chapters, the concept of infrastructural interdependencies was presented in the context of natural disasters occurring around the world. The scope of the DR-NEP project was to define new alternatives to analyze, model, and manage disaster scenarios in the context of infrastructural interdependencies in an efficient manner, and in order to achieve its objective - maximum human survival during a disaster event. Within the scope of the DR-NEP project, the Western campus model is used to study interdependencies between various entities or lifelines of the campus and University Hospital. When performing an interdependency study on the Western campus, certain entities need to be selected from available infrastructures and specific disaster scenarios have to be designed and analyzed.

This chapter deals mainly with the disaster scenario analysis based on the results from the electrical network case study. The subsections in the chapter explain in detail, the disaster scenario, critical subsystems (power systems), and the impact of appropriate decision making during these disasters on the overall workings of the Western campus. The disaster scenarios are simulated using PSS Sincal, which is a load flow software. The results from PSS Sincal generate different values of the Quality of Service (QoS) indicator which are used for decision making during the disaster. The final results are presented in the following subsections.

5.2 Electrical Network Case Study

According to the scope of this research work, one of the physical entities chosen for detailed analysis is the electrical power system. The basics of the electrical power systems with respect to Western campus have already been discussed in Chapters 3 and 4. In support of the DR-NEP project, the disaster scenario was created with the inclusion of different physical entities such as electrical power, water, steam and condensate returns. However, in this thesis, only the electrical model case study has been presented with results. The electrical models were created in separate softwares EMTDC/PSCAD and PSS Sincal. The final results were fed manually into the infrastructural interdependency software I2Sim. The electrical network case study is discussed in brief with respect to the two softwares used.

5.2.1 EMTDC/PSCAD Electrical Model

The main purpose of the EMTDC/PSCAD electrical model was to make a validated electrical model of Western campus distribution systems. The validated model has already been presented with simulation results in Chapter 4. In Figure 5.1, the EMTDC/PSCAD model is presented only for the south substation. During DR-NEP project the focus of the disaster scenario is on the Physical Plant. The Physical Plant is close to the south substation and in normal times it gets incoming power supply from south substation. In case of any emergency, if the south substation has to be shut down, the other two substations in the campus can substitute for the south substation. In the process of substitution of power supply, it is likely that some of the buildings might need to be shut down due to insufficient amount of power available.

Based on the disaster scenario, different fault conditions were created, such as connecting and disconnecting a number of buildings/loads to analyze different operating conditions in the presence of a disaster scenario. These fault conditions are created in PSS Sincal, and then on the basis of obtained results the information was used in I2Sim software.

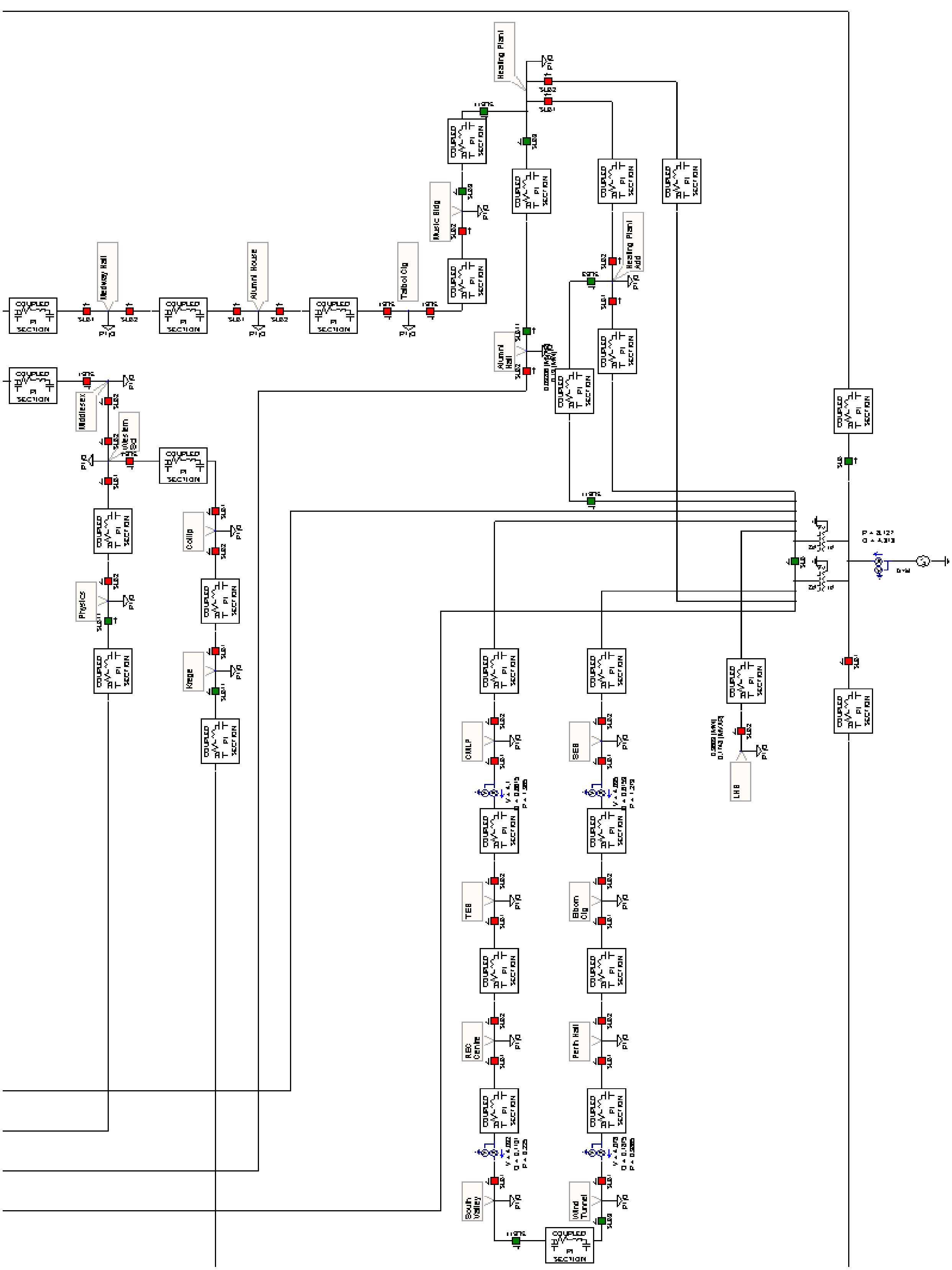

Figure 5.1: EMTDC/PSCAD model for south substation of Western campus

5.2.2 PSS-Sincal Model

To simulate the behaviour of a distribution/transmission network and perform load flow calculations, a power network simulator owned by Siemens, called PSS Sincal was integrated into the Simulators Layer at ENEA Italy. The electrical model made in EMTDC/PSCAD was already validated in the chapter 4. The same validated electrical model is now made in PSS Sincal, which is a load flow software.

PSS Sincal allows user modelling and simulating the behaviour of different power networks. This software is used only to simulate the behaviour of the considered network which models a subset of the power distribution network of Western campus. Figure 5.2 presents the PSS Sincal model for Western campus. The data used for the PSS Sincal model is almost the same as the PSCAD model but with some additions. These additions were combining two buildings loads together in order to reduce the number of buildings in the PSS Sincal model. The data used in the model is presented in Appendix A.

In PSS Sincal, the Western model is used to get the various load flow values at different buses in the network. The next step is to obtain the different values of Quality of Service (QoS) indicator. To get the Quality of Service value, a web application is used, which helps in implementing a web service that allows the performing of operations on a particular power network [50]. An explanation of the operations (methods) that may be invoked on the considered power network and the steps to invoke them are explained below.

The calculation formulas for the QoS are explained in Section 2.6.3. A specific java programming code and procedure was followed to obtain different values of QoS for different load conditions. The value for QoS under normal conditions in PSS Sincal is 0.85, but as the lines are disconnected, the value of QoS decreases. The value of QoS should lie between 0 and 1. The procedure for changing the value of QoS is as follows [48][49]:

i. QoS is approximately 0.85, as the majority of lines are connected.

ii. All the available lines can be checked by calling the subroutine getLines().

iii. The ID of each line can be seen by calling the above function.

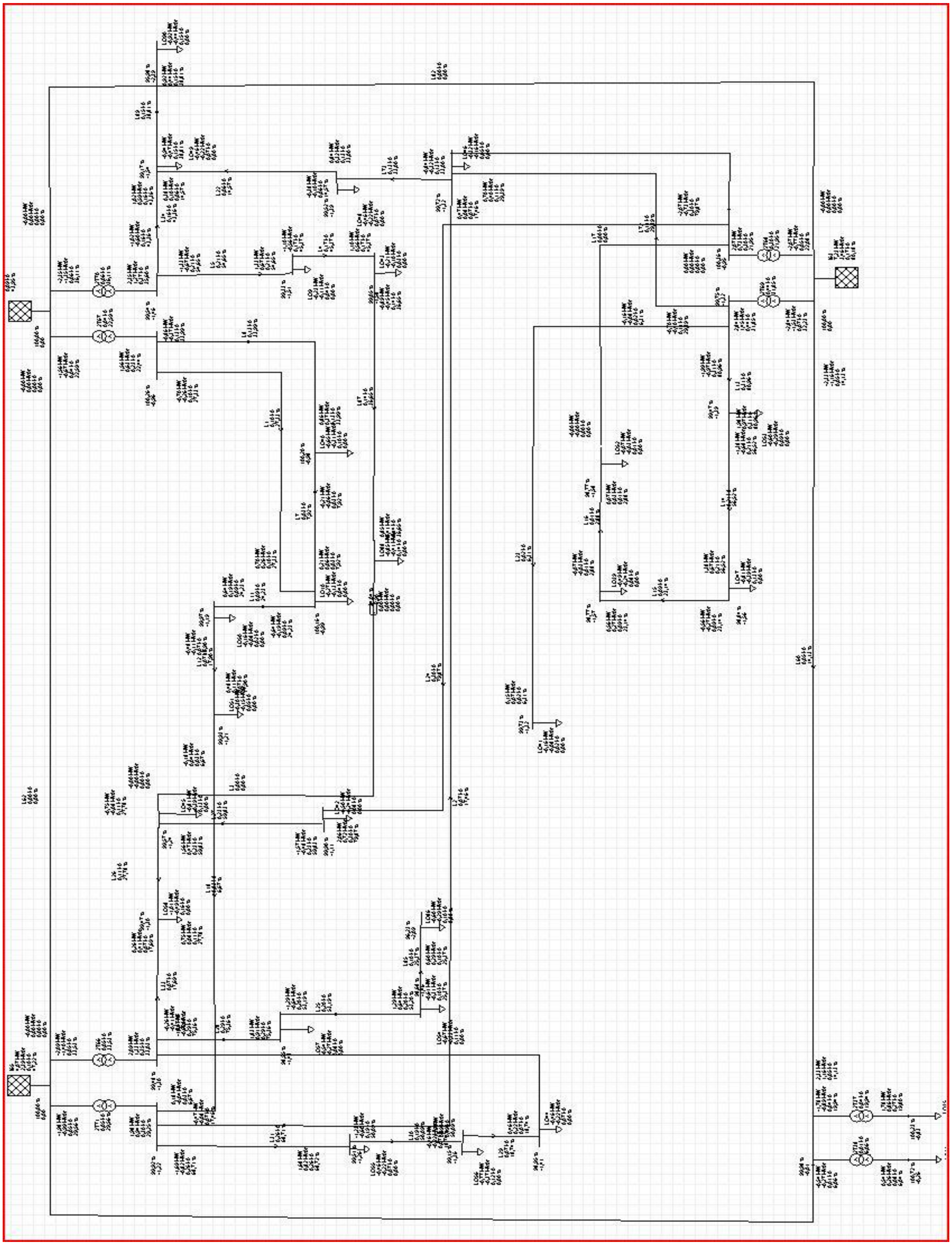

Figure 5.2: PSS-Sincal model for Western campus

iv. Only distribution lines (no other components) can be disconnected by calling the subroutine setLineStatus ("LineID" , 0).

v. To connect a distribution line again, “1”, instead of “0”, has to be written as a second parameter of the method. It is mandatory to call updateLines() after each operation of connection/disconnection.

vi. The more lines that are disconnected, the less QoS value will be obtained.

By using the above procedure, different values of QoS were generated based on the disaster scenario created. The number of distribution lines in PSS Sincal directly impacts the value of QoS. After obtaining the values of quality of service for different fault conditions, the next step was to integrate the results from PSS Sincal into the I2Sim model.

5.3 Integrating Electrical Outputs with I2Sim

In this section, the structure of the electrical power system infrastructure is presented along with its integration methodology with the infrastructure interdependency software I2Sim. As the overall study was based on the effect of infrastructure interdependency during disaster, only electrical power systems will be discussed which lies within the scope of this thesis work. To understand the overall structure of the power system and its integration with I2Sim, it is better to refer to Figure 5.3, which is a reduced block diagram of the Western test case model. Figure 5.3 shows all of the major subsystems used in the Western test case during disaster events. It also presents information about the inputs and outputs of different subsystems.

In the disaster scenarios, different entities were modelled using the I2Sim software. The study case and the objectives of the disaster scenario are explained in section 2.8. To integrate all of the available entities into I2Sim, different domain simulators were chosen. The description of all chosen domain simulators is explained in Section 2.6. The campus was divided into three parts; A1: central campus, A2: UCC and social science, and A3: south campus, which are denoted by three different blocks in Figure 5.3. Different inputs are provided to the buildings in the form of different entities such as water and power.

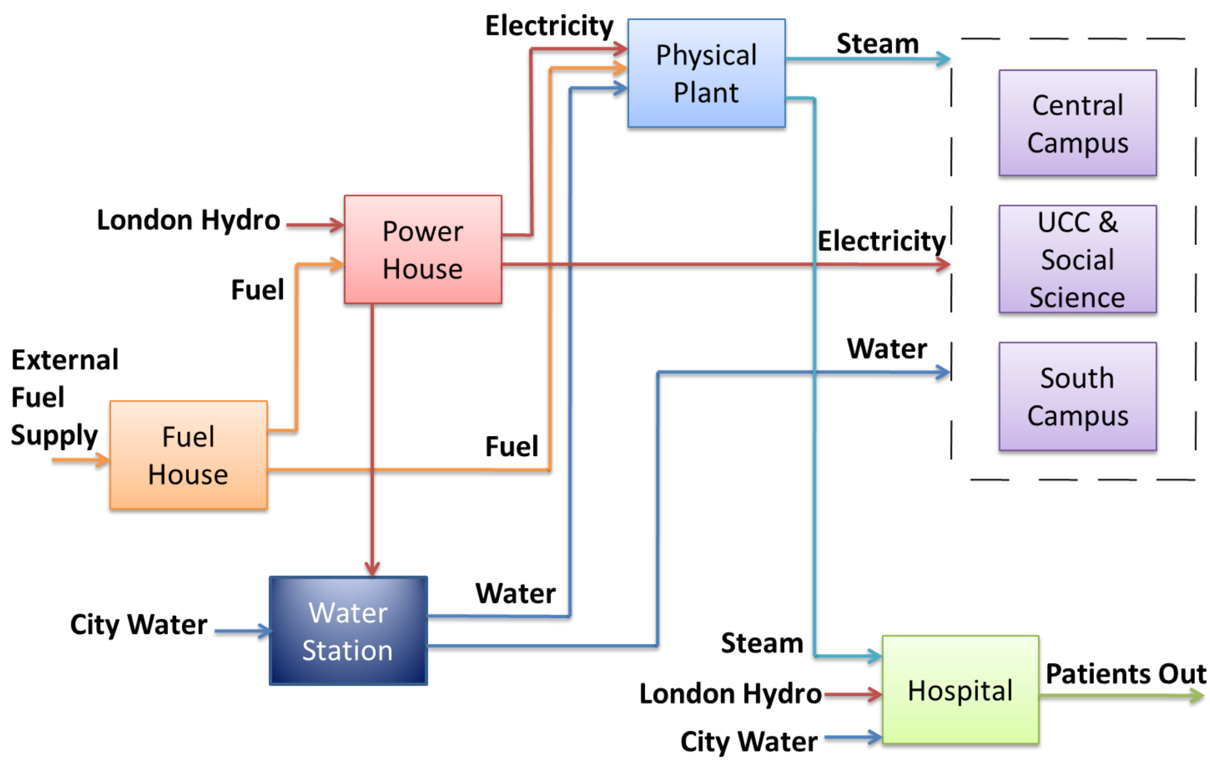

Figure 5.3: Reduced block diagram of Western test case model

The output from the buildings is in the form of condensate return, which again goes to the feed water control and increases the amount of water available for usage. In terms of electrical power, the power house and different channels, or distribution lines, were built using I2Sim.

Figure 5.4 presents the block diagram of power distribution methodology used in the I2Sim model. All of the different blocks represented in Figure 5.4 are explained below, in detail, to provide the complete picture of the electrical power system architecture used in the final I2Sim model.

- **The Power House:** The power house block represents the cell in the I2Sim model which consists of substations and back-up generators. The input to the power house is the city's electricity supply from London Hydro, which is at 27.6 kV. This block represents three different substations that supply power to the physical plant and to the entire Western campus. Physically, the output of the block is fed to all the buildings on campus, including the steam and water stations. Back-up generators are also included in the power house cell model. The responsibility of the back-up generators is to provide power to the water station, steam station, and to some of the critical buildings on campus, in the absence of power input from the utility due to any faults, or during a disaster event. As the back-up generators are diesel generators, it is necessary to maintain a fixed amount of oil in reserve to be used in case of emergency.

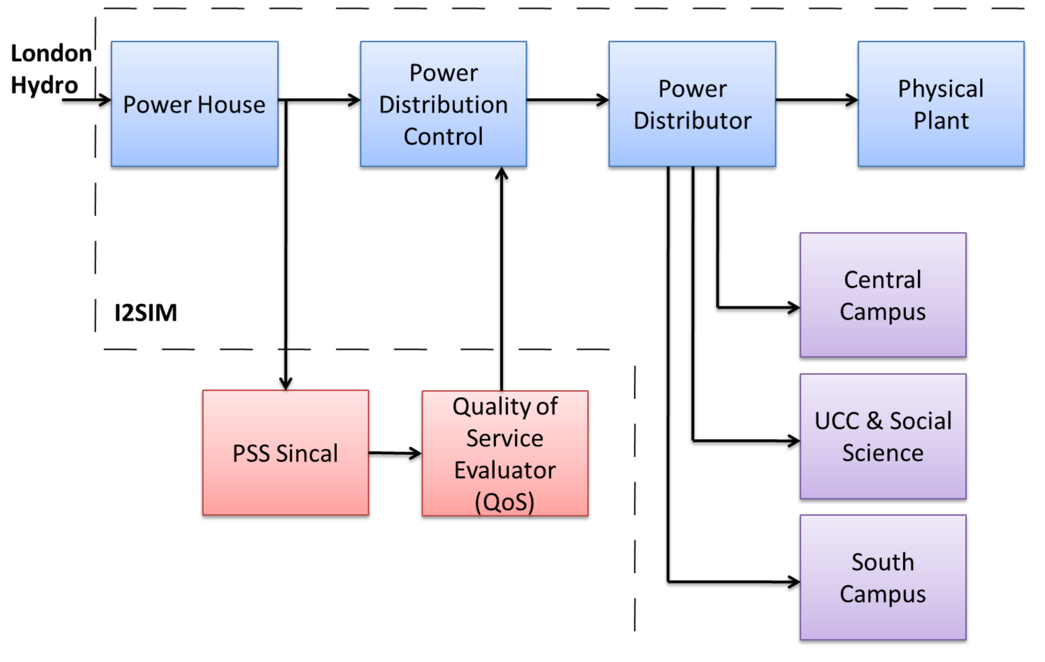

Figure 5.4: Block diagram of power distribution methodology in I2Sim

- **PSS Sincal:** The PSS Sincal block in Figure 5.4 represents the load flow software used to calculate the power flow values at different points in the electrical power network. The PSS Sincal block has been discussed in detail in Section 5.2.2. The input from the power house is fed into the PSS Sincal, and according to the availability of power from the power house, load flow calculations are performed and different points in the network are checked for power flow values for voltage, active, and reactive power availability. In PSS Sincal, different load flow values can be calculated for different events or scenarios and can be used to get valuable information about power availability at different points on the Western campus. The data used for modelling the network using PSS Sincal was the same as used in EMTDC/PSCAD.

- **Quality of Service (QoS):** QoS evaluator is the block that is connected to the output of the PSS Sincal block. The Quality of Service indicator, or evaluator, is used as a tool to indicate how the network is behaving in the event of an emergency. The value of the QoS evaluator is highest when the network is healthy. But when an emergency event is experienced, the lines in the electrical network have to be reduced or disconnected.

  The information from PSS Sincal is passed to the QoS, which calculates using the number of normal lines, overloaded lines, and critical lines (which always need electrical power). Accordingly, the decision maker disconnects the overloaded lines to obtain a new value of QoS, as well as a value of power actually available to be fed to the distributor block. For every load flow value change, a new value of QoS is generated, which gives the actual available power. Reduction of lines leads to the lowering of the value of QoS, which gives exact information about the healthiness of the network.

- **Power Distributor Control:** This block has two inputs and one output which is fed into the power distributor. The inputs are received from the power house and QoS evaluator. The power house provides the information of the amount of power that is available from three substations on campus. The QoS gives an idea about available power after load flow calculations. In power distributor control, both inputs are compared and a final signal is sent to the power distributor with information about actual power distribution. During emergency situations, the final signal sent is based on the following criteria:

  i. The critical infrastructures get the required power on priority basis.

  ii. The power distribution for non-critical infrastructures can be compromised.

- **Power Distributor:** A distributor is a block in the I2Sim model that is used to distribute entities (tokens) such as power, steam, and water through channels to various cells. In Figure 5.4, the distributor is used to distribute power, thus, it is named the power distributor. The power distributor is used to distribute available power to different buildings on campus. As the entire campus is divided into different cells, power is distributed to the physical plant and to the different buildings combined together, as different cells.

In the I2Sim model, the power distribution in the distributor can be done through three different mechanisms: Manual mode, Human Readable Table (HRT), or external mode.

i. **Manual mode:** In this mode, the decision maker defines a single set of output ratios. These apply until changed by the decision maker.
ii. **HRT mode:** In this mode, the output ratios of the distributor block are read from the Human Readable Table (HRT). Each Physical Mode (PM) contains a set of output ratios. By changing the PM, the user can change the output ratios available to the distributor.
iii. **External mode**: In this mode, a number of input ports appear on the block. The decision maker can define the number of output ports using the number of outputs edit box. The number of the distribution factor port will be one less than the number of outputs, as the last factor is calculated internally.

All three above stated distribution methods can be used. In this study for power distribution, the manual mode was used. Special care is taken to ensure that the Physical Plant always receives electrical power to generate the required amount of steam needed to sustain the campus activities. Thus in this work, the Physical Plant is considered to be a life critical system.

- **Physical Plant:** The Physical Plant is the most important building to the Western community, as it has boilers installed for producing steam for the campus and University Hospital. During the winter, heating is the main priority for running any kind of business or educational institution. During the winter season at Western, the Physical Plant produces the required steam. The Physical Plant uses a combination of five of the installed boilers to produce steam. As such, during a disaster situation, it is necessary to keep the Physical Plant working to provide the necessary heating for the campus. The output of the Physical Plant is steam, for which it requires different types of inputs.

In this thesis, the focus is on only one of the inputs to the Physical Plant: the electrical power input. In the I2Sim model, various distribution strategies were employed for electrical power to receive the best decision making scenarios in case of a disaster event. These are presented in Section 5.4.

5.4 Effects of Including Electrical Power as a Critical Entity

Of all entities considered in the campus case study, the electrical power supply is the most important and critical entity. It is the most important as it is required by all of the other infrastructures, as input. This fact has been presented by using three different figures. Figure 5.3 depicts the reduced block diagram of the Western test case model. Figure 5.5 presents the block diagram of the inside of a boiler. Figure 5.6 presents the diagram of a water pump with basic inputs.

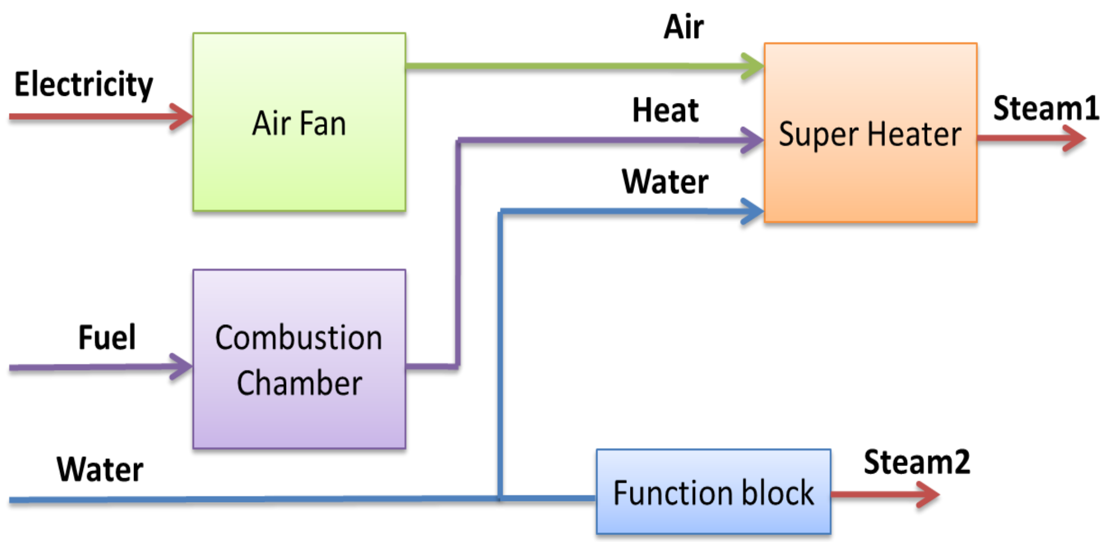

Figure 5.5: Block diagram of inside of a boiler

In this research work, some studies are done that were not a part of the overall DR-NEP project. In the DR-NEP project results, electrical infrastructure was not included. However, electrical infrastructure has been included in this study. In this section, some of the differences are presented between the types of inputs used in this research and those that were not used as part of the DR-NEP project.

Figure 5.5 depicts two different methods of producing steam. The first method gives output as Steam1. This output is based on three entities as input: electricity, fuel, and water. The second method gives output as Steam2. This method only takes water as input. The second method does not consider other critical entities such as electrical power or fuel. In this research work, the results are presented by following the first method of producing steam (taking electricity as a critical input), which has not been studied in the DR-NEP project. The objective of this research work is to provide all of the information on the availability of electrical power during emergency situations.

In Figure 5.6, water can be received as an output by using two different methods. The first method gives W1 as an output of the water pump, which takes two inputs: electricity and water. In the second method, the W2 output is obtained directly without using any other physical entity. In this research work, the first method (W1) of producing water is used, which was not used previously in the DR-NEP studies, as the information on electrical power infrastructure was not available.

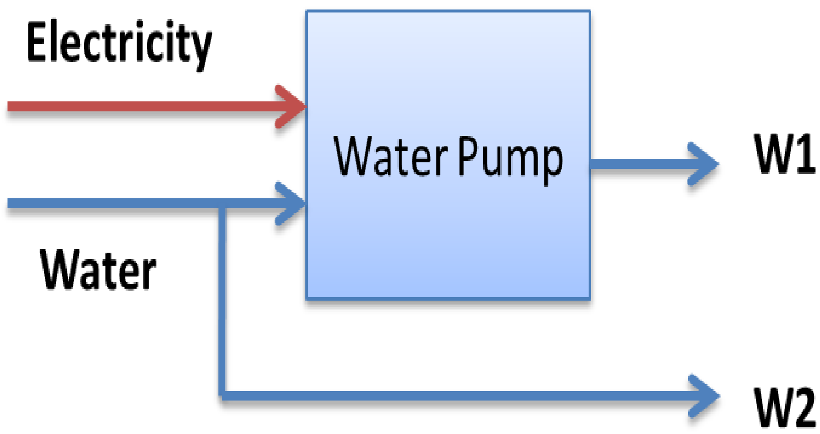

Figure 5.6: Diagram of a water pump with basic inputs

From Figures 5.5 and 5.6, it is clear that the work done in this research study is totally based on a set of criteria that includes electricity as one of the critical inputs to all other subsystems. This work has not been done earlier as part of the DR-NEP project, and in fact, is a contribution of this thesis.

5.5 Operating Scenarios with Collaboration

Operating scenarios with collaboration means that different disaster scenarios will be presented for electrical power systems in collaboration with other entities such as water, steam, and condensate return. While presenting these operating scenarios, the effect of all of the interdependent entities is taken into consideration while searching for an optimal decision making scenario. These operating scenarios are based on multiple infrastructures involved during a disaster event.

To examine the interdependencies of infrastructures, this study has been done using the Western campus model created using the I2Sim software. Different entities such as electrical power, water, and steam were used as infrastructures. To study the interdependency and to determine an optimal operating scenario in case of a disaster, different operating scenarios were created using I2Sim. The overall model used in the study can be divided into two different categories. The first is the I2Sim model that was validated based on a real incident in 2006 on the Western campus. The second is the electrical model that has been developed in Chapter 3 and validated in Chapter 4.

To study the interdependency relationship between different infrastructures, three different operating scenarios were created with collaboration from other entities during the DR-NEP project. These three scenarios are created keeping in mind all of the entities used in the I2Sim model. However, in this section, the results and analysis will be presented from the point of view of one entity – electrical power, which is within the scope of the thesis at all times. The objective in these scenarios is to keep University Hospital operational at all times. Thus in these scenarios, priority is given to the Physical Plant, which produces steam that is supplied to University Hospital. The goal in the simulation study is to keep the electrical input to the physical plant above a certain threshold level and also to continue supply other campus activities. In the following subsections, different operating scenarios will be discussed, and the simulation results will be presented.

The scenarios are selected on the basis of the overall objectives that are mentioned in Chapter 1. The scenarios were created to better analyze and understand different operating conditions in case of the occurrence of a disaster, and to find out which of the operating scenarios gives the most efficient results.

5.5.1 Scenario 1

This section presents Scenario 1, which is simulated and analyzed using I2Sim, to better understand the interdependency approach during critical emergency situations. In this scenario, a fire starts in one of the buildings close to the west substation on the Western campus, followed by the opening of fire hydrants.

- **Scenario description**
    - Month of the event: December
    - At initial stage $t=t_0$; the whole system runs in a normal state.
    - At $t=t_0+120$ minutes; a fire starts in one of the buildings close to electrical substation, which leads to the immediate shutdown of the west substation. Due to the shutdown of the west substation, other substations become overloaded.
    - This is followed by a reduction in water pressure on campus due to the opening of fire hydrants.
    - At $t=t_0+190$ minutes, water pressure returns to normal.
    - At $t=t_0+200$ minutes, electrical power is returned to normal.

In the above scenario, the objective is to determine the available electrical power supply by using both PSS Sincal and the Quality of service (QoS) evaluator, as described in Section 5.3 above. The power output given by the QoS evaluator guarantees that none of the distribution line is overloaded. The second objective is to provide a constant power supply to the Physical Plant and water pumping station. It is vital to supply electrical power to the Physical Plant whose output is steam, which is consumed by University Hospital, and all Western buildings. In this scenario the power to be supplied to the water pumps is combined with the Physical Plant input. Thus, the input to the Physical Plant represents the input of electrical power to both the water pumps and to the boilers in the Physical Plant.

- **Simulation Results**

In this scenario, due to a fire on campus, many variables or entities representing different infrastructures were changed. These variables are electrical power, water system, and other forms of water - steam and condensate return. The whole scenario is modelled for 225 minutes using I2Sim, with a time step of one minute. The fire starts at 120 minutes and the system returns to normal at 200 minutes.

Due to the disaster event, many variables are changed; but in this section, the focus is only on the results related to electrical power change. In this scenario, only the peak loading power model was used, of three different loading conditions models mentioned in Chapter 4. Based on any disaster event or emergency situation, the peak loading condition represents the worst case scenario, as it always represents scarcity of power and requires proper load management.

The results of Scenario 1 are shown in Figures 5.7 to 5.9. Figure 5.7 depicts the electrical power sent to the physical plant and water pumps during Scenario 1, in the disaster study.

Figure 5.7: Scenario 1; Electrical power sent to physical plant and water pumps.

In Figure 5.7, the power sent from the power house to the physical plant and all of the water pumps is shown. Physical plant is the building that contains all of the equipment used to produce steam. To produce steam, electrical power, water, and fuel are three required components. To provide water supply, electrical power is needed for the water pumps, condensate tanks, and condensate pumps. At $t=t_{0,}$ during peak loading conditions, the total power consumed by the physical plant and water pumping equipment is 1.76 MW. At $t=t_0+120$, due to the closure of the west substation, the electrical power sent is decreased to 1.28 MW. At $t=t_0+200$, the system is restored and electrical power increases to a normal output of 1.76MW. The availability of power values during the disaster events are calculated based on results from the PSS Sincal software and Quality of Service Evaluator, which is 0.85 in normal conditions. The amount of available power during the disaster period is enough to carry on the processes of the physical plant.

Figure 5.8 shows the electrical power sent to the different cells on the Western campus: A1, A2, and A3, as described in Section 2.8. According to the size of the cell, the distribution of electrical power has been done with the help of the distributor. In Figure 5.8, at $t=t_0$, the electrical power values represent the peak loading condition of all the three cells, A1, A2, and A3. At $t=t_0+120$, due to the closure of the west substation, the power sent to all buildings drops in proportion to the value of QoS. After the closure of the west substation, the QoS value drops from 0.85 to 0.73. At $t=t_0+200$, the west substation is turned on and the entire campus returns to a normal state. The availability of the electrical power during the disaster event is much more than the threshold values, therefore, the impact during this event can be considered minor.

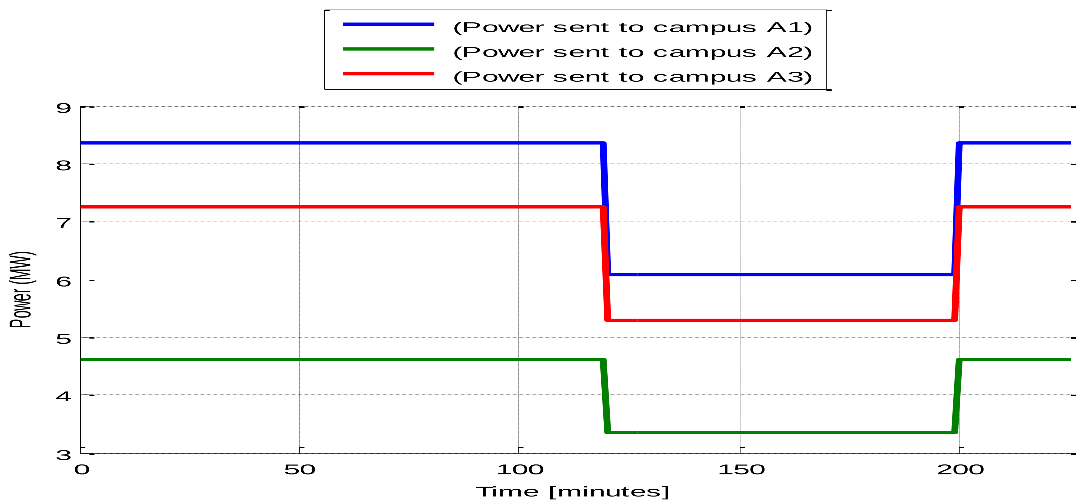

Figure 5.8: Scenario 1; Electrical power sent to different parts of the campus

Figure 5.9 presents the output of the physical plant as steam, measured in m^3. The steam output of the Physical Plant is fed to University Hospital and the campus buildings. The output of the physical plant is directly related to one of its most important inputs: electrical power. Alternatively stated, the electrical input to the physical plant is based on its overall output, which is steam. Figure 5.9 shows the total steam output of the Physical Plant, out of which 15% is sent to University Hospital.

In the I2Sim model, a steam output block was created by the DR-NEP team. Information about electrical power was generated from the Western electrical power model. The results obtained from the power systems model is fed into the I2Sim model to determine the steam output presented in Figure 5.9. Initially, the steam output is normal, but at $t=t_0+120$ minutes, the output of physical plant decreases following the shutdown of the west substation and the drop in water pressure. At $t=t_0+190$, there is a small rise in steam output, as water pressure returns to normal. Finally, the steam output returns to its normal value with the turning on of the west substation.

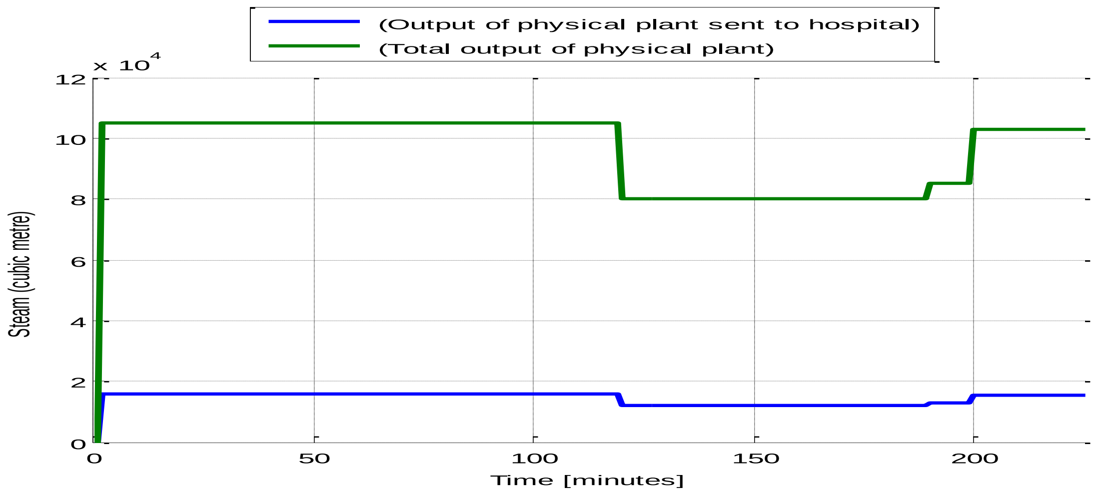

Figure 5.9: Scenario 1; Output of Physical Plant based on different variables

Action Plan: The output of the Physical Plant is considered to be a life critical system. In Scenario 1, the impact of the disaster event is not significant, as it does not have any major impact on the Western campus or hospital activities. All of the entities needed are available above the threshold values. In addition, the situation can be improved with the help of back-up generators, if needed.

5.5.2 Scenario 2

This section presents Scenario 2, which is simulated and analyzed using I2Sim to better understand the interdependency approach during a different disaster event. In Scenario 2, a fire starts in one of the buildings close to the south substation on the Western campus. There is a substantial difference in the west and south substations on campus. The south substation actually gets its power supply from London Hydro, but the west substation does not. Instead, it gets power from either the south or north substation. If the south substation is not operational, it implies that the probability of the west substation getting power during emergencies reduces to half. In Scenario 2, the back-up generator is also used at some point, to compensate for the substation shutdown.

- **Scenario description**
  - Month of the event: December
  - At initial stage $t=t_0$; the whole system runs in a normal state.
  - At $t=t_0+120$ minutes; a fire starts in one of the buildings, which leads to the immediate shutdown of the south substation. Due to the shutdown of the south substation, the other substations become overloaded.
  - This is followed by a reduction in water pressure on campus due to the opening of fire hydrants.
  - At $t=t_0+130$ minutes; back-up generators failed to start. Available power decreases further.
  - At $t=t_0+190$ minutes, water pressure returns to normal.
  - At $t=t_0+200$ minutes, electrical power is returned to normal.

- **Simulation Results**

The results for Scenario 2 are presented in Figures 5.10 to 5.12. Figure 5.10 depicts the amount of electrical power sent to the Physical Plant and water pumps, during the disaster study. The plots for Scenario 2 appear to be the same as in Scenario 1. In both scenarios, the total time of simulation is the same and the peak loading condition power model is used.

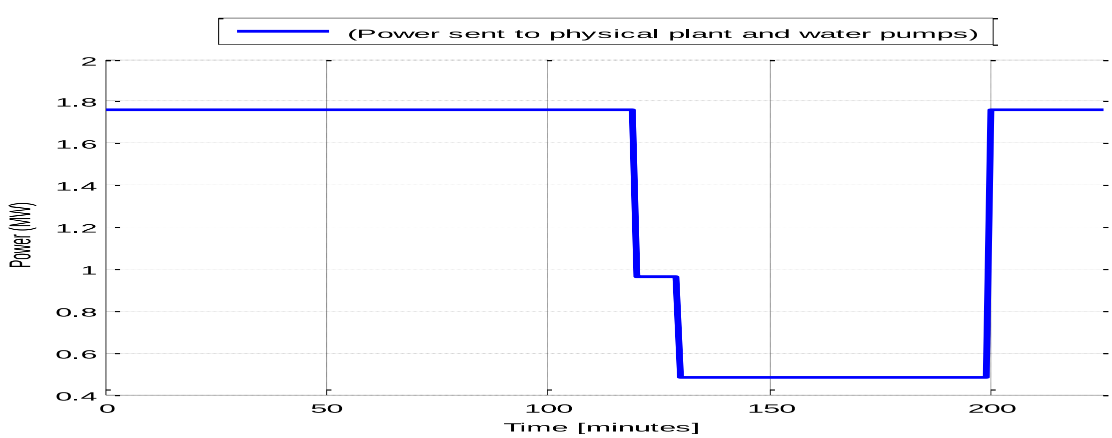

Figure 5.10: Scenario 2; Electrical power sent to Physical Plant and water pumps.

Thus, the initial conditions remain the same as in Scenario 1. In Figure 5.10, power sent to the Physical Plant and water pumps is shown. At $t=t_0+120$, the power drops from its peak value to 0.96 MW due to the shutdown of the south substation. At this point the QoS value drops from 0.85 to 0.66. Such a low value of QoS indicates that there are a large number of overloaded distribution lines. Due to this overload, an attempt to start the back-up generators was initiated at $t=t_0+130$, which was not successful. This led to further overload of the distribution system. Hence, after $t=t_0+130$,the QoS value drops further and the amount of available power drops from 0.96 MW to 0.48 MW, which is below the threshold value for giving minimal output required to sustain activities on campus and the hospital. At $t=t_0+200$ there is a rise in power as the south substation is turned back on.

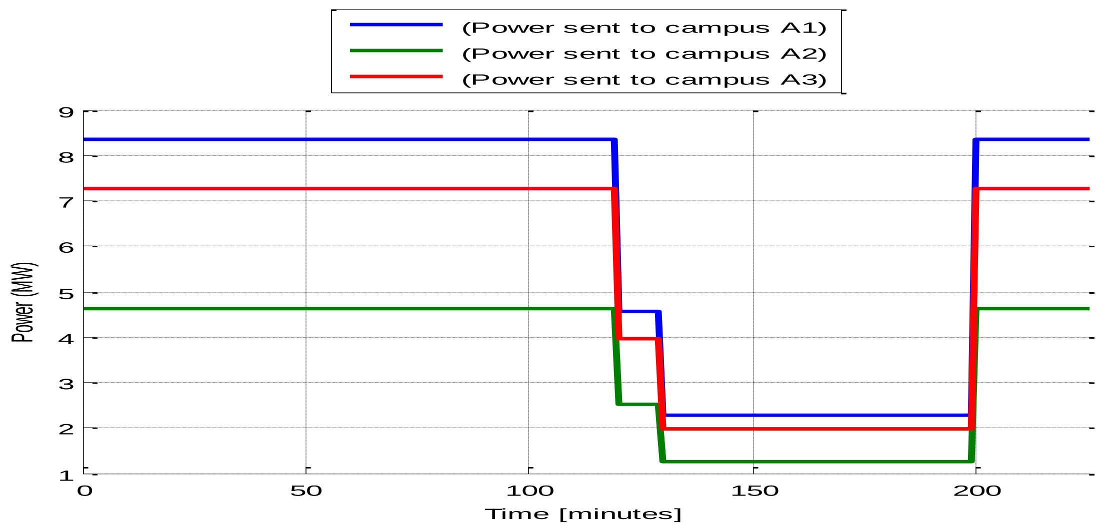

Figure 5.11: Scenario 2; Electrical power sent to different parts of the campus

Figure 5.11 shows the electrical power sent to the different cells on the Western campus: A1, A2, and A3, as described in Section 2.8. All of the conditions in Figure 5.11 remain the same as in Figure 5.10. Initially, all cells get maximum power supply, but during the disaster event, the power supply drops corresponding to the value of QoS, as evaluated in the previous paragraph. The amount of power available during the disaster event is below the threshold values and cannot sustain the campus activities. As the power available is substantially less, it will lead to evacuation of the majority of campus buildings. The remaining available power can then be distributed to the critical loads on the campus such as the Chemistry laboratory, buildings with animal care, etc.

As explained in Section 5.5.1, the output of the Physical Plant is directly related to one of its most important inputs: electrical power. It has been shown in Figures 5.10 and 5.11, that amount of electrical power is less than the threshold value. This has a direct impact on the output of the Physical Plant, as the amount of steam produced is proportional to the power available to the Physical Plant. Figure 5.12 shows the total steam output of the Physical Plant, out of which 15% is sent to University Hospital. During the disaster event, the amount of steam produced is only about 20% of the total steam produced. In Figure 5.12, the amount of steam available for the hospital during the disaster event is 2000 cubic metres, which is substantially lower than threshold value required for supporting hospital and campus activities.

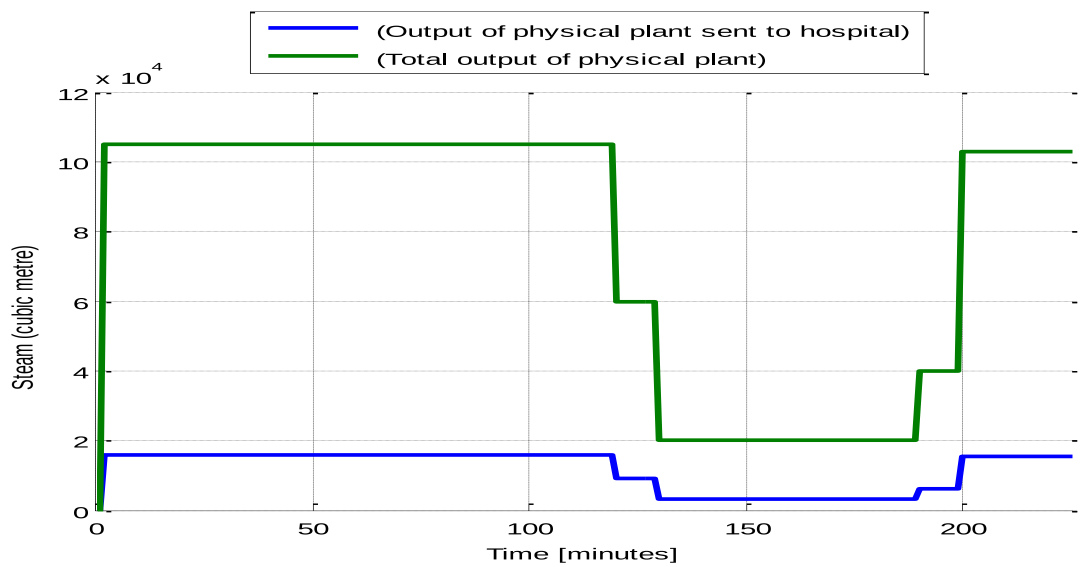

Figure 5.12: Scenario 2; Output of Physical Plant based on different variables.

Action Plan: This scarcity of steam is due to the shortage of both electrical power and water. To cope with this situation, all of the resources should be redirected towards the life critical system, which is University Hospital. Instead of supplying power to the campus buildings, it should be redistributed to the Physical Plant and the campus should be evacuated as soon as possible. The buildings on campus with critical loads have to be supplied a proportion of the available power. This can be done by manually changing the distribution ratios of different distributors used in the I2Sim model. It can be done for all of the entities modelled in the case study to better support the critical cells and subsystems.

5.5.3 Scenario 3

Scenario 3 is similar to Scenario 2, with a minor change. In Scenario 2, due to overload, an attempt to start the back-up generators was initiated to make-up for the shutdown of the south substation, but failed. In Scenario 3, the back-up generators were started successfully, which added some more MW of electrical power during the disaster event. Also, a hit and trial method has been used with the help of the distributor to distribute power to the Western campus to continue the campus activities and to avoid any disturbance to hospital activities.

- **Scenario description**
    - Month of the event: December
    - At initial stage $t=t_0$; the whole system runs in a normal state.
    - At $t=t_0+120$ minutes; a fire starts in one of the buildings, which leads to the immediate shutdown of the south substation. Due to the shutdown of the south substation, the other substations become overloaded.
    - This is followed by a reduction in water pressure on campus due to the opening of fire hydrants.
    - At $t=t_0+130$ minutes, back-up generators are started successfully to meet the overload on electrical power substations. The amount of power available does not decrease further.
    - At $t=t_0+190$ minutes, water pressure returns to normal.
    - At $t=t_0+200$ minutes, electrical power is returned to normal.

- **Simulation Results**

Figure 5.13 depicts the electrical power sent to the Physical Plant and water pumps during the disaster study, in Scenario 3. In Figure 5.13, power reduction due to the shutdown of a substation is demonstrated for the Physical Plant and the water pumps during the period t_0+120 to t_0+200. Power availability decreases to 0.96 MW from 1.76 MW at the time instant of t_0+120 minutes. Due to a reduction in power availability, the distribution system is overloaded, which was evident in the results of the load flow study in PSS Sincal, and the evaluation of the QoS.

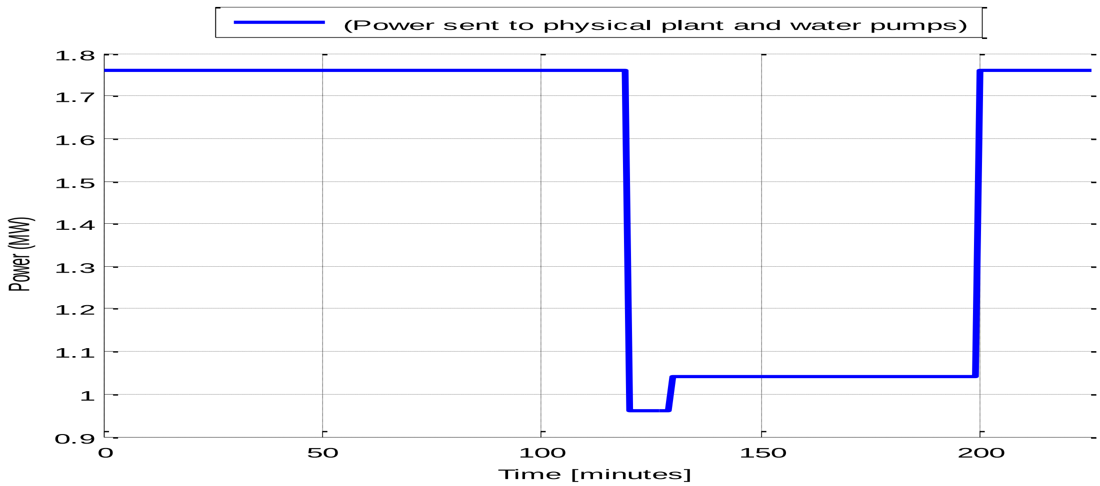

Figure 5.13: Scenario 3; Electrical power sent to Physical Plant and water pumps.

At t_0+130 minutes, back-up generators were started immediately, to save further reduction of available power. Thus, after t_0+130 minutes, the power sent to the Physical Plant and water pumps does not decrease further as seen in Figure 5.13. In contrast, the power sent to the physical plant is increased by a small amount, which was provided by the back-up generators.

Figure 5.14 demonstrates the same processes as shown in Figure 5.13. The only difference is that power is sent towards different buildings of the campus instead of to the physical plant and water pumps. Power sent to all three cells (A1, A2, and A3) is above the threshold value and can sustain campus activities.

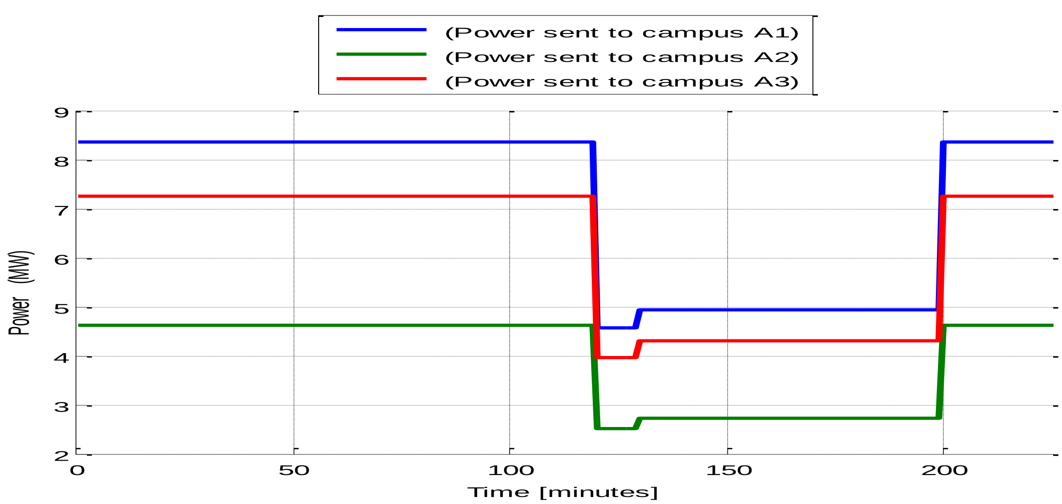

Figure 5.14: Scenario 3; Electrical power sent to different parts of the campus

There may still be a need to shut down some of the unused loads in non-critical and less crowded buildings.

For Scenario 3, Figure 5.15 presents two types of steam outputs from the Physical Plant. The total steam output from the Physical Plant can be divided into the output of the plant sent to the hospital, and the remainder sent to the campus buildings. Initially, the Physical Plant provides a normal steam output until the fire starts in one of the buildings.

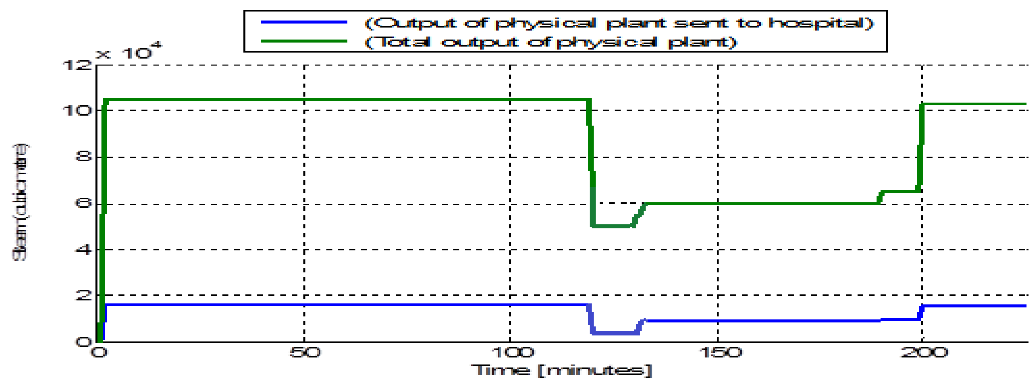

Figure 5.15: Scenario 3, Output of physical plant based on different variables.

At t_0+120, the output of the Physical Plant decreases in the same way it decreased in Scenario 2, shown in Figure 5.12. Scenario 3 is different from Scenario 2 in that at time instant t_0+130, the back-up generator kicked in immediately, thus increasing the available power as shown in Figures 5.13 and 5.14. As a result, the steam output does not decrease further as the electric power and water resources are available to produce enough steam for University Hospital and the campus buildings. When the disaster event is over, the steam output of the plant increases as the water supply becomes normal. The output returns to normal at t_0+200, when the electrical power supply is restored as the south substation is switched on again. In this scenario, there is no need for evacuation. From Figures 5.13 to 5.15, it is shown that all campus and hospital activities can be continued, although at a reduced scale.

Action Plan: Scenario 3 is an intermediate scenario, as compared to Scenarios 1 and 2. The available power supply and other resources are just adequate to carry on the activities of both the Western campus and the hospital. Depending upon the available power, a proper proportion for the allotment of power has to be determined, so that both can be carried out on a reduced scale. A method is needed to determine the allotment of power resources required. In terms of electrical power distribution, the load shedding and load flow techniques can be utilized for this purpose. In addition, a hit and trial method can also be used to determine the proportion of resources needed for different cells or subsystems. Once the proportion is known, it can be manually implemented with the help of distributors and electrical power distribution control systems.

5.6 Operating Scenarios without Collaboration

Operating scenarios without collaboration means that different disaster scenarios will be presented only for electrical power systems without collaboration with other entities like water, steam, and condensate return. While presenting these operating scenarios, the effect of electrical power quantities only is taken into consideration while searching for an optimal decision making scenario. These operating scenarios are based on a single infrastructure: electrical power systems.

In Section 5.5, three operating scenarios were selected and were presented in collaboration with other entities (steam, water) to study the optimal decision-making processes during the disaster scenarios. From the viewpoint of power availability, two of the four substations were selected in the disaster scenarios. The action plan during the disaster event was based on the power availability and the output of the critical infrastructures. In order to do a complete analysis of power availability during a disaster scenario, the remaining two substations are selected for analysis in the section below.

In this section, the north and east substations are selected for two different operating scenarios. These operating scenarios were framed to study the power availability during different disasters or faulty conditions. As the operating scenarios are framed without collaboration from other infrastructures, only the results related to electrical power systems will be presented. The objective is to perform a power availability analysis of the remainder of campus and to differentiate between the earlier disaster scenarios presented in Section 5.5.

5.6.1 Scenario I

This section describes Scenario I, which is based on the results from PSS Sincal and the Quality of Service evaluator. The scenario is selected to analyze the power availability during an emergency event. In Scenario I, the east substation is selected as the main substation. A snowstorm is chosen to occur in London during the peak loading conditions in the campus. Peak loading conditions have been selected for the event as it represents the worst-case scenario.

- **Scenario description**
  - Month of the event: December
  - At initial stage $t=t_0$; the whole system runs in a normal state.
  - At $t=t_0+120$ minutes; a snow storm hits London, which leads to an outage of power on the east substation as the incoming feeder is cut down due to fallen trees. Due to the shutdown of the east substation, the other substations become overloaded.
  - At $t=t_0+130$ minutes; back-up generators started, but did not kick in immediately. Available power decreases further.
  - At $t=t_0+140$ minutes; the back-up generator kicks in.
  - At $t=t_0+200$ minutes, electrical power is returned to normal.

- **Simulation Results**

In this section, the simulated results are presented for scenario I, which has been modelled for peak load conditions with the total load of 22 MW. The emergency event was simulated using PSS Sincal. The QoS value was then calculated by the QoS evaluator, to determine the available power entity. Figure 5.16 depicts the electrical power available for the Physical Plant and water pumps, in Scenario I. The QoS value for a healthy network is 0.85. In Figure 5.16 at $t=t_0+120$, due to the disaster event, the available power decreases from 1.76 MW to 1.11 MW. During the calculation of the QoS it is found that more lines are overloaded and the entire network is under overload. As such, there is a need to get support from the back-up generators. At $t=t_0+130$, the generators do not kick in immediately, leading to a decrease in electrical power from 1.11 MW to 0.8 MW, as shown in Figure 5.16.

After a lapse of 10 more minutes, at $t=t_0+140$, the back-up generators were started successfully, which led to a reduction in load on the substations. This event resulted in the increase in overall power availability.

Of the total power of 22 MW, almost 50% of the power is still available, which should be able to sustain both campus activities and the Physical Plant operations at a reduced level. To improve the situation, some of the less important buildings could be evacuated. Figure 5.17 depicts the electrical power available for the different cells (A1, A2 and A3) on the Western campus.

Figure 5.16: Scenario I; Electrical power available for Physical Plant and water pumps

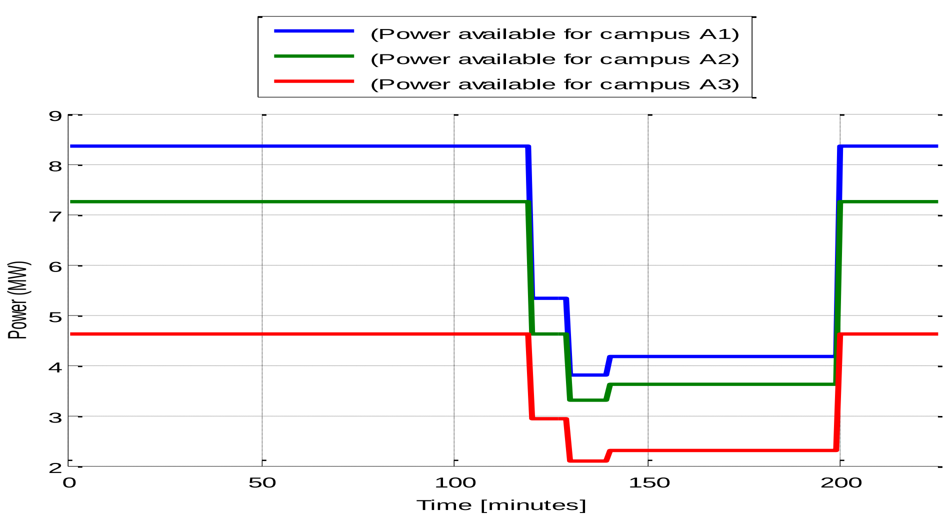

Figure 5.17: Scenario I; Electrical power available for different parts of the campus

Figure 5.17 demonstrates the same processes as shown in Figure 5.16. The only difference is that power is sent towards different buildings of the campus instead of to the Physical Plant and water pumps.

5.6.2 Scenario II

In Scenario II, the basic disaster event remains the same as in the occurrence of a snowstorm. However, instead of affecting the east substation, the incoming feeder to the north substation experiences a power outage. The results are presented based on the simulation in PSS Sincal and available power information is provided by the Quality of Service evaluator. The information provided by the QoS evaluator is fed into the I2Sim model to obtain the simulation results for the availability of power across the entire campus. A description of scenario II is provided below:

- **Scenario description**

  - Month of the event: December
  - At initial stage $t=t_0$; the whole system runs in a normal state.
  - At $t=t_0+120$ minutes; a snowstorm hits London, which leads to the outage of power to the north substation as the incoming feeder is cut down due to fallen trees. Due to the shutdown of the north substation, the other substations become overloaded.
  - The west substation is connected to the south substation and does not have any direct impact from the north substation power outage.
  - At $t=t_0+130$ minutes; back-up generators were started, and kicked in immediately. Available power does not decrease further.
  - At $t=t_0+200$ minutes, electrical power is returned to normal.

- **Simulation Results**

In Scenario II, Figure 5.18 presents the results of the availability of power for the Physical Plant where the incoming power is not available to the north substation. The system runs in a normal state, until the emergency event starts at $t=t_0+120$ minutes, which leads to the immediate shutdown of the north substation and reducing the total power available to around 11.5 MW. To increase the available active power and to better meet the load demand, the back-up generators were started successfully at $t=t_0+130$. Power available from back-up generators resulted in an increase of electrical power for the physical plant, from 0.89 MW to 0.99 MW, shown in Figure 5.18. In Figure 5.18, during the disaster event, the available power for the Physical Plant is close to 1 MW, which is just above the threshold value required to produce the steam for the campus and University Hospital. At $t=t_0+200$, the electrical power is restored back to normal.

Figure 5.18: Scenario II; Electrical power available for Physical Plant and water pumps

Figure 5.19 presents the power availability for the different cells of the campus during the disaster event.

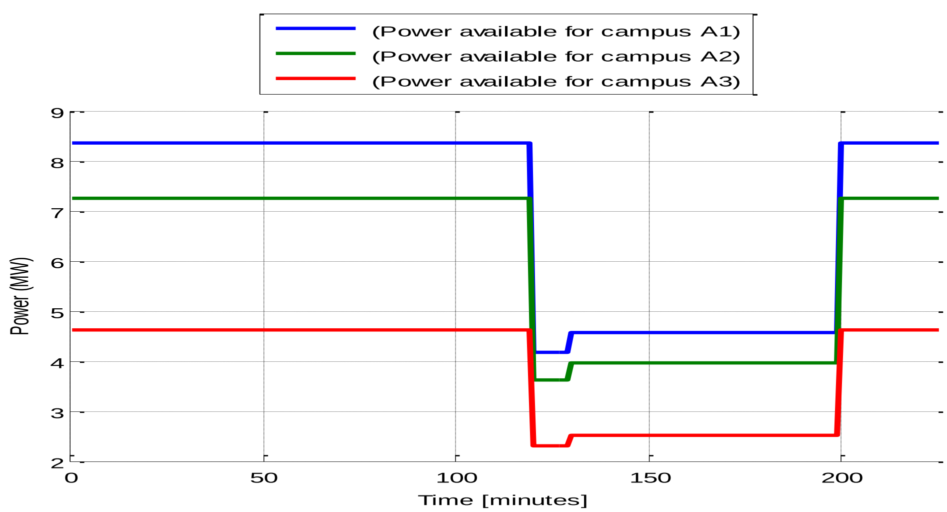

Figure 5.19: Scenario II; Electrical power available for different parts of the campus

The available power can be utilized in an efficient way. Some of the unnecessary loads can be reduced in each building, for example corridor lights and un-used computer labs. Thus, the available power can be utilized and the need for evacuating some of the buildings can be averted.

5.6.3 Scenario III

Scenario III is similar to Scenario II, using the snowstorm which causes the north substation to experience a power outage. The only difference is the connection of the west substation. The west substation is either connected to the north substation or the south substation. However, in this scenario the west substation is connected to the north substation. Thus, with the power outage of the north substation, the west substation is also out of power. There is another difference between Scenarios II and III, which is the kick in time of back-up generators. A detailed scenario description is provided below.

- **Scenario description**
  - Month of the event: December
  - At initial stage $t=t_0$; the whole system runs in a normal state.
  - At $t=t_0+120$ minutes; a snowstorm hits London, which leads to the outage of power to the north substation as the incoming feeder is cut down due to fallen trees. Due to the shutdown of the north substation, the other substations become overloaded.
  - The west substation is connected to the north substation and is not getting incoming power as the north substation is experiencing an outage.
  - At $t=t_0+130$ minutes; back-up generators were started, but did not kick in immediately. Available power decreases further.
  - At $t=t_0+150$ minutes; the back-up generator kicks in.
  - At $t=t_0+200$ minutes, electrical power is returned to normal.

- **Simulation Results**

Scenario III is similar to Scenario II, with a different starting time of the back-up generator. Initially the system runs in a normal state. At $t=t_0+120$ minutes, the north substation shuts down as the incoming power supply is not available. The value of the QoS evaluator decreases from

0.85 to 0.36. Figure 5.20 illustrates the electrical power available for the Physical Plant and water pumps during Scenario III. In Figure 5.20, at $t=t_0+120$ the available power decreases from 1.76 MW to 0.8 MW. There is a total loss of 57% of total power. At $t=t_0+130$, the available power drops further to 0.59 MW from 0.8 MW. At $t=t_0+150$ minutes, the attempt to start the back-up generators was successful and the amount of power available was increased to 0.62 MW, as shown in Figure 5.20. However, since the power available is still very low, it is not possible to sustain both hospital and campus activities together. In order to sustain the hospital operations and maintain a supply to the critical buildings on campus, it is necessary to evacuate the buildings on campus to divert the newly available power to the critical building loads such as the Physical Plant, water pumps, chemistry building, and animal care buildings, etc.

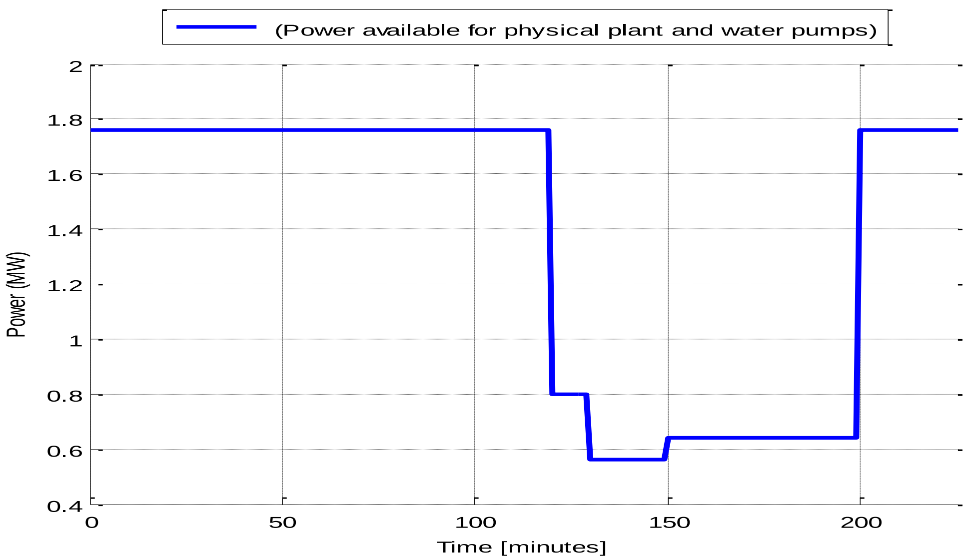

Figure 5.20: Scenario III, electrical power available for physical plant and water pumps

Figure 5.21 shows the electrical power sent to the different cells on the Western campus: A1, A2, and A3, as described in Section 2.8. According to the size of the cell, distribution of electrical power has been done with the help of the distributor. In Figure 5.21, at $t=t_0$, the electrical power values represent the peak loading condition of all three cells, A1, A2, and A3. At $t=t_0+ 120$, due to the closure of the north and west substations, the power sent to all buildings drops in proportion to the value of QoS.

The total power available to campus during the disaster event after the support from back-up generators at $t=t_0+150$ is around 7 MW, which is not sufficient to supply power to all of the campus buildings.

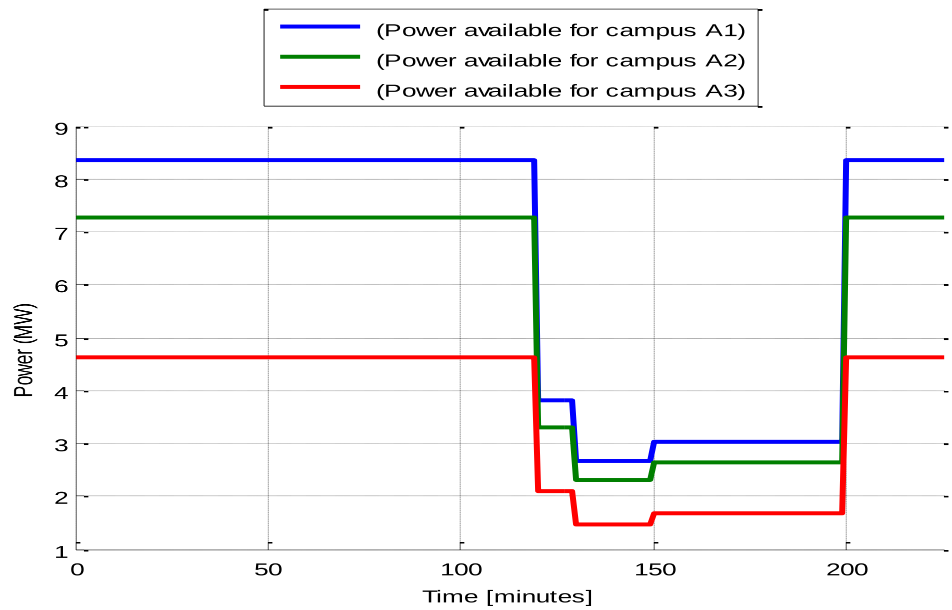

Figure 5.21: Scenario III, electrical power available for different parts of the campus

Therefore, it is better to evacuate the campus as quickly as possible and distribute the newly available power to the critical buildings on campus. At $t=t_0+200$, the substations are turned on and the entire campus returns to a normal state.

5.7 Conclusions

In this chapter, different disaster scenario events were created to formulate a new type of efficient decision making, while simulating multiple infrastructures in I2Sim to study interdependencies. This chapter presented the EMTDC/PSCAD model, the PSS Sincal model, and the integration of all simulators in the I2Sim model, with the major emphasis on electrical power simulation. The results of three different disaster events were presented under different emergency situations in collaboration with other entities (water and steam). The Western campus was divided into smaller cells, so that it is easier to relate different subsystems with one another. Three separate scenarios based on power infrastructure were analyzed and presented without collaboration from the steam and water networks. It has been shown that the availability of one entity or resource has a direct impact on several other related entities. Redundancy of a particular cell, for example back-up generators, increases the overall robustness of the system. A major role is played by the distributor and distributor control block, which helps in the proper allocation of power resources.

The results presented in this chapter are in addition to earlier work done under the DR-NEP project. The earlier work was done on three subsystems: steam, condensate return, and water. This work was restricted to three subsystems because electrical modelling information was not available. It is realized that every infrastructure needs electrical power input for its day-to-day operations, for example electrical water pumps in water networks, modems, routers in communications, and providing signals in transportation. In this chapter, the information on electrical networks is obtained through electrical power models and the results are presented by incorporating the effect of the electrical power, along with that of steam and water networks.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Introduction

This thesis deals mainly with the electrical power system modelling for the purpose of studying the interdependencies between multiple infrastructures. Electrical power, steam, and water systems are the three infrastructures involved in this work, but the predominant emphasis is on electrical power systems. While it is easy to prepare a disaster plan for a single infrastructure, various challenges are encountered in managing all the infrastructures together. The decision-making during any emergency situation becomes quite complex when multiple infrastructures are involved, as all the infrastructures are dependent upon each other.

This thesis presents the development of a detailed model of the electrical power system of Western campus. This is validated with actual measured data provided by the Western Facilities management. The electrical model is validated for different loading conditions and different feeder positions. The thesis further describes three different infrastructures involved in the Western campus case study under the DR-NEP project. The results from the validated electrical model are incorporated into the infrastructural interdependency software (I2Sim). A total of six disaster scenarios are studied; three involving the electrical power systems in collaboration with water and steam systems, and the other three involving only the electrical power system. The study of interdependency during disasters is performed to generate a wiser decision making process that will lead to less economic damage and more human survival. The major conclusions drawn from the different system studies for the aforementioned topics are outlined in the succeeding subsections.

6.2 Infrastructural Interdependencies

In Chapter 2, the definitions, concepts, and understanding of interdependencies are presented. This chapter also provides details about various subsystems in different infrastructures, their interconnection techniques and methods of analysis. It presents a brief description of the interconnecting software that is used to model infrastructure interdependencies. It also gives a detailed description of the DR-NEP disaster case study for the Western campus.

In studying the infrastructural interdependencies, three infrastructures were selected for the Western campus cases under the DR-NEP project. These three infrastructures are electrical power, steam, and water systems. To better understanding the infrastructural interdependencies, these three subsystems are modelled using the infrastructural interdependency software I2Sim. The I2Sim architecture study is presented in detail along with the DR-NEP project architecture. Various studies are presented to illustrate the integration of domain simulators for all the three subsystems using I2Sim.

The major emphasis of this thesis is on the mechanism for integrating the electrical power domain simulator into I2Sim. The results from the electrical domain simulator are used to obtain the Quality of Service (QoS) index. The QoS gives knowledge about power availability during different fault conditions. For a specific disaster condition, the information about the electrical domain simulator is fed into I2Sim in the form of a QoS value. The significance of electrical infrastructure in an overall interdependency study is also presented in this chapter. It is demonstrated that an electrical network study is the most crucial entity in the interdependency studies, as other infrastructures cannot function properly without electrical power supply.

6.3 Electrical Power System Modelling

Chapter 3 presents the basic concepts of the modelling of electrical power distribution systems. It also provides a description of all the major components of the electrical system of Western campus.

This chapter further presents the criteria for choosing the appropriate software for modelling of electrical power systems. Two commercial softwares EMTDC/PSCAD and PSS Sincal are selected to develop the electrical power system model for the Western campus. The Western study system consists of four substations. Each substation comprises transformers, underground feeders, capacitor banks, and circuit breakers. The modelling concept of each and every component of the electrical systems is presented with respect to the EMTDC/PSCAD and PSS Sincal softwares. Finally, an overall electrical model of the actual Western campus is developed for performing load flow studies and fault studies using PSS Sincal and EMTDC/PSCAD software, respectively.

6.4 Electrical Model Validation

Chapter 4 demonstrates a methodology for the validation of the electrical power distribution model for the Western campus developed in Chapter 3. The electrical power distribution model is built using EMTDC/PSCAD software. In EMTDC/PSCAD, a steady state analysis is performed on the electrical distribution model under reasonable assumptions.

The actual data for validation is provided by Western Facilities Management. To validate the electrical power model, three different scenarios are selected for steady state analysis. These three scenarios are peak load conditions, light load conditions, and medium load conditions. For each of these three loading conditions, three different locations are selected for analysis: the start, middle, and end of the feeder. For all of the scenarios, load flow studies are performed. For each scenario, the simulated values for voltage, active power, and reactive power are recorded and compared with the actual measured values obtained from Western Facilities Management. The correlation of all three electrical quantities is done for all three locations of feeders, and for the three different loading conditions. It is shown that the values obtained from simulation studies are within 5% of the actual measured data. This validates the electrical system model of the Western campus.

It is emphasized that this validated model has been developed for the first time at Western and can be of great benefit to Western University to study the campus electrical networks for future projects and expansion of facilities.

6.5 Case Studies of Disaster Scenarios

Chapter 5 presents a detailed disaster scenario analysis based on the simulation studies conducted with the Western electrical system model. This chapter describes different disaster scenarios, performance of the critical subsystem (power system), and the impact of appropriate decision making during these disasters on the overall operation of the Western campus. In these studies, disaster scenarios covering each and every possibility are modelled with a special focus on power systems.

Different disaster scenarios are simulated using PSS Sincal, a load flow software. The results of the load flow studies using PSS Sincal generate different values of the Quality of Service (QoS) index, which are used in decision making during the disaster. The final electrical outputs from PSS Sincal and QoS evaluator are integrated into I2Sim. Different power distribution scenarios are created across the campus with the development of a power distribution methodology in I2Sim. The power distribution methodology is based on the functioning of the power house, PSS Sincal, QoS, power distribution control, and the power distributor.

The results presented in this work are an important addition to the earlier work done under the DR-NEP project. The previous work was done on three infrastructures: steam, condensate return, and water. It was restricted to three subsystems only because electrical modelling information was not available earlier. It is, however, realized that every infrastructure needs electrical power input, for example electrical water pumps in water networks. In this chapter, the performance of the Western electrical power system is obtained through its validated model. Results of different operating scenarios are presented by incorporating the effects of the electrical power along with those of steam and water networks.

On the basis of different operating scenarios, simulation studies are conducted using all of the different substations in the disaster events. These scenarios are simulated for electrical power systems with and without collaboration with other entities (water, steam, and condensate return). Similar results are obtained in all disaster scenarios. The conclusions based on the results of all of the different scenarios are presented below:

- Decisions to reduce power consumption on campus by evacuating selected campus areas is effective in stabilizing steam in the University Hospital, but not in maintaining Western business continuity.

- Decisions to change the power distribution ratio among the campus areas have no major impact on the hospital steam supply. Providing an optimal output from the Physical Plant requires all entities to be above threshold values. However, a change in the power distribution ratio among the campus areas has an effect on the working of buildings across campus.

- A decision to produce steam supply according to the power availability seems to be appropriate as this preserves continuity of both hospital and campus operations.

- More case studies are required to pre-plan an efficient emergency disaster plan before an actual disaster occurs.

6.6 Thesis Contributions

The following are the main contributions of this thesis:

- Development of a detailed electromagnetic transients model for the Western campus, which has been validated for three widely different loading scenarios at three different locations of the feeder. Such a model has been developed for the first time at Western University. This model can be used not just for studying disaster scenarios but also for planning of future electrical projects and expansion of facilities in the Western campus.

- Presenting the concept of a Quality of Service evaluator through web services along with PSS Sincal, which provides knowledge about healthy and non-healthy conditions of a power network based on different disaster scenarios.

- A detailed study is presented on the integration of electrical power networks with other infrastructures for studying interdependencies between multiple infrastructures. An extensive analysis of different decision making options based on six different disaster scenarios is provided. This will help in developing much better survival strategies during any potential future disasters.

6.7 Future Work

Some studies that could be undertaken in the future to further investigate the aforementioned issues, are described below:

- A probabilistic based framework to assess the risk could be developed.

- More physical entities can be added to this study system, such as communication systems and transportation systems, which will be more realistic

- The electrical model could be expanded to include more details, such as, transformers, critical fans, and rooms at the level of individual buildings.

- The results from the QoS evaluator were fed manually into the I2Sim model; attempts could be made to do this automatically, using appropriate programming to save time in future.

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Appendix A: Study System Data for Peak Loading Conditions for Chapter 4

(Extracted from Facilities Management website)

Data for the elements used in study system is shown below:

A. Source Data

System Base MVA =100 MVA

Base Voltage = 27.6 kV

B. Substation and Breaker Data

Transformer at South substation = 10 MVA, Z = 6.3%

Transformer at East substation = 7.5 MVA, Z = 6.3%

Transformer at North substation = 7.5 MVA, Z = 6.3%

C. Cables Data and Capacitor Bank Data

Cables data presented here is in ohms per phase per mile

Resistance = 0.134

Reactance = 0.135

Shunt capacitive reactance = 2410

Capacitor bank at North substation Qc = 750 kVAR

D. Buildings/Load Data

Peak Loading Conditions

Serial Number	Building Name	Building ID	KW rating	KVAR rating	Power Factor
1.	Support Services Building	218	881.3777778	426.8512578	0.9
2.	Clinical Skills	-	53	25.6679	0.9
3.	UCC	-	556.1388889	269.3380639	0.9
4.	Social Science	-	1833.819444	888.1187569	0.9
5.	SLB	050	124.540625	60.31502469	0.9
6.	UC	1	72.76888889	35.24197289	0.9
7.	UC Add	1	116.8425926	56.58686759	0.9
8.	Physics Building	023	423.5416667	205.1212292	0.9
9.	Kresge Building	011	73.63541667	35.66163229	0.9
10.	Medical Sciences Building	010	670.3363636	324.6439009	0.9
11.	Dental Sciences	013	614.1990741	297.4566116	0.9
12.	Dental Sciences Addition	013	59.94791667	29.03277604	0.9
13.	West Valley Building	016	942.2666667	456.3397467	0.9
14.	Health Sciences	015	207.6759259	100.5774509	0.9
15.	Natural Sciences Centre	022	293.8759259	142.3241109	0.9
16.	Taylor Library	027	245.9814815	119.1288315	0.9
17.	Chemistry Building	021	290.8259259	140.8469959	0.9
18.	Chemistry Addition	021	171.6574074	83.13368241	0.9
19.	Material Sciences	020	151.6666667	73.45216667	0.9
20.	B & G	-	395.75	191.661725	0.9
21.	Collip Building	014	37.90740741	18.35855741	0.9
22.	Western Sciences Building	028	417.1990741	202.0495116	0.9
23.	Middlesex College	002	214.0324074	103.6558949	0.9
24.	Biotron	026	572.3240741	277.1765491	0.9
25.	Visual Arts Building	035	216.7407407	104.9675407	0.9
26.	North Campus Building	034	389.9166667	188.8366417	0.9
27.	Staging Building	080	74.36574074	36.01532824	0.9
28.	Talbot College	003	488.75	236.701625	0.9
29.	Music Building	007	150.8240741	73.04409907	0.9
30.	NCMRD	-	234.8002245	113.7137487	0.9
31.	Ivey	-	276.762963	134.036303	0.9

32.	Somerville House	055	246.9259259	119.5862259	0.9
33.	Thames Hall		123.1990741	59.66531157	0.9
34.	Services Building	051	106.9123377	51.77764513	0.9
35.	South Valley	-	237.5324074	115.0369449	0.9
36.	Power Plant	-	288.1298701	139.5412961	0.9
37.	Alumni Hall	060	195.9305556	94.88916806	0.9
38.	SEB	031	654.0648148	316.7635898	0.9
39.	CMLP	074	70	33.901	0.9
40.	TEB	064	474.395	229.7494985	0.9
41.	Recreation Centre	217	722.6388889	349.9740139	0.9
42.	Perth Hall	-	463.1666667	224.3116167	0.9
43.	Elborn College	039	470.9027778	228.0582153	0.9
44.	Law Building	037	148.5925926	71.96339259	0.9
45.	Weldon Library	058	599.1820988	290.1838904	0.9
46.	Student Services	058	117	56.6631	0.9
47.	Lambton Hall	088	233	112.8419	0.9
48.	Bayfield Hall	089	633	306.5619	0.9
49.	Beaver Hall	091	189	91.5327	0.9
50.	Saugeen Maitland Hall	093	755	365.6465	0.9
51.	Sydenham	097	222	107.5146	0.9
52.	Elgin Hall	081	371	179.6753	0.9
53.	Delaware Hall	095	888	430.0584	0.9
54.	Sebandrake	-	1	0.4843	0.9
55.	Graphic & A	220	390	188.877	0.9
56.	LHB	-	377	182.5811	0.9
57.	Wind tunnel	032	410	198.563	0.9

Appendix B: Study System Data for Light Loading Conditions for Chapter 4

Light Loading Conditions

Serial Number	Building Name	Building ID	KW Rating	KVAR rating	Power Factor
1.	Support Services Building	218	528.4673089	255.9367177	0.9
2.	Clinical Skills	-	31.77839069	15.39027461	0.9
3.	UCC	-	333.4565829	161.4930231	0.9
4.	Social Science	-	1099.543977	532.5091479	0.9
5.	SLB	050	74.67359695	36.164423	0.9
6.	UC	1	43.6316638	21.13081478	0.9
7.	UC Add	1	70.05791617	33.9290488	0.9
8.	Physics Building	023	253.9523124	122.9891049	0.9
9.	Kresge Building	011	44.15122717	21.38243932	0.9
10.	Medical Sciences Building	010	401.9285068	194.6539758	0.9
11.	Dental Sciences	013	368.2690215	178.3526871	0.9
12.	Dental Sciences Addition	013	35.94430787	17.4078283	0.9
13.	West Valley Building	016	564.9758164	273.6177879	0.9
14.	Health Sciences	015	124.5208814	60.30546284	0.9
15.	Natural Sciences Centre	022	176.2057357	85.33643778	0.9
16.	Taylor Library	027	147.4885966	71.42872735	0.9
17.	Chemistry Building	021	174.3769792	84.45077103	0.9
18.	Chemistry Addition	021	102.9244558	49.84631395	0.9
19.	Material Sciences	020	90.93816205	44.04135188	0.9
20.	B & G		237.2886437	114.9188902	0.9
21.	Collip Building	014	22.72898873	11.00764924	0.9
22.	Western Sciences Building	028	250.1493429	121.1473268	0.9
23.	Middlesex College	002	128.3321786	62.15127408	0.9
24.	Biotron	026	343.1610949	166.1929183	0.9
25.	Visual Arts Building	035	129.9560743	62.93772679	0.9
26.	North Campus Building	034	233.7910221	113.224992	0.9
27.	Staging Building	080	44.58912384	21.59451268	0.9
28.	Talbot College	003	293.0507255	141.9244664	0.9

29.	Music Building	007	90.43295004	43.7966777	0.9
30.	NCMRD	-	140.7844013	68.18188554	0.9
31.	Ivey	-	165.9449352	80.36713213	0.9
32.	Somerville House	055	148.0548782	71.70297753	0.9
33.	Thames Hall	-	73.86921338	35.77486004	0.9
34.	Services Building	051	64.10381201	31.04547615	0.9
35.	South Valley	-	142.4225971	68.97526377	0.9
36.	Power Plant	-	172.760445	83.6678835	0.9
37.	Alumni Hall	060	117.478448	56.89481236	0.9
38.	SEB	031	41.97145941	189.9290022	0.9
39.	CMLP	074	284.4435784	20.32677779	0.9
40.	TEB	064	433.288697	137.756025	0.9
41.	Recreation Centre	217	277.7111564	209.841716	0.9
42.	Perth Hall	-	282.3496689	134.4955131	0.9
43.	Elborn College	039	89.09497098	136.7419446	0.9
44.	Law Building	037	359.2649591	43.14869444	0.9
45.	Weldon Library	058	70.15229644	173.9920197	0.9
46.	Student Services	058	139.7050006	33.97475717	0.9
47.	Lambton Hall	088	379.5419115	67.65913179	0.9
48.	Bayfield Hall	089	113.3229404	183.8121477	0.9
49.	Beaver Hall	091	452.6921693	54.88230004	0.9
50.	Saugeen Maitland Hall	093	133.1094855	219.2388176	0.9
51.	Sydenham	097	222.4487349	64.46492385	0.9
52.	Elgin Hall	081	532.4379422	107.7319223	0.9
53.	Delaware Hall	095	0.599592277	257.8596954	0.9
54.	Seiban-drake	-	233.8409881	0.29038254	0.9
55.	Graphic & A	220	226.0462885	113.2491906	0.9
56.	LHB	-	245.8328337	109.4742175	0.9
57.	Wind tunnel	032	528.4673089	119.0568413	0.9

Appendix C: Study System Data for Medium Loading Conditions for Chapter 4

Medium Loading Conditions

Serial Number	Building Name	Building ID	KW Rating	KVAR rating	Power Factor
1.	Support Services Building	218	704.8378089	341.3529508	0.9
2.	Clinical Skills	-	42.3841	20.52661963	0.9
3.	UCC	-	444.7442694	215.3896497	0.9
4.	Social Science	-	1466.50541	710.2285699	0.9
5.	SLB	050	99.59513781	48.23392524	0.9
6.	UC	1	58.19328044	28.18300572	0.9
7.	UC Add	1	93.4390213	45.25251801	0.9
8.	Physics Building	023	338.7062708	164.035447	0.9
9.	Kresge Building	011	58.88624271	28.51860734	0.9
10.	Medical Sciences Building	010	536.06799	259.6177276	0.9
11.	Dental Sciences	013	491.1749995	237.8760523	0.9
12.	Dental Sciences Addition	013	47.94034896	23.217511	0.9
13.	West Valley Building	016	753.5306533	364.9348954	0.9
14.	Health Sciences	015	166.078438	80.43178751	0.9
15.	Natural Sciences Centre	022	235.012578	113.8165915	0.9
16.	Taylor Library	027	196.7113907	95.26732654	0.9
17.	Chemistry Building	021	232.573493	112.6353426	0.9
18.	Chemistry Addition	021	137.2744287	66.48200582	0.9
19.	Material Sciences	020	121.2878333	58.73969768	0.9
20.	B & G	-	316.481275	153.2718815	0.9
21.	Collip Building	014	30.3145537	14.68133836	0.9
22.	Western Sciences Building	028	333.6340995	161.5789944	0.9
23.	Middlesex College	002	171.1617162	82.89361916	0.9
24.	Biotron	026	457.687562	221.6580863	0.9
25.	Visual Arts Building	035	173.3275704	83.94254233	0.9
26.	North Campus Building	034	311.8163583	151.0126623	0.9
27.	Staging Building	080	59.47028287	28.80145799	0.9
28.	Talbot College	003	390.853375	189.2902895	0.9

29.	Music Building	007	120.614012	58.41336603	0.9
30.	NCMRD	-	187.7697395	90.93688484	0.9
31.	Ivey	-	221.3273415	107.1888315	0.9
32.	Somerville House	055	197.466663	95.63310487	0.9
33.	Thames Hall	-	98.52229954	47.71434967	0.9
34.	Services Building	051	85.49779643	41.40658281	0.9
35.	South Valley	-	189.9546662	91.99504484	0.9
36.	Power Plant	-	230.4174571	111.5911745	0.9
37.	Alumni Hall	060	156.6856653	75.88286769	0.9
38.	SEB	031	523.0556324	253.3158428	0.9
39.	CMLP	074	55.979	27.1106297	0.9
40.	TEB	064	379.3736815	183.730674	0.9
41.	Recreation Centre	217	577.8943194	279.8742189	0.9
42.	Perth Hall	-	370.3943833	179.3819998	0.9
43.	Elborn College	039	376.5809514	182.3781548	0.9
44.	Law Building	037	118.8294963	57.54912506	0.9
45.	Weldon Library	058	479.1659244	232.0600572	0.9
46.	Student Services	058	93.5649	45.31348107	0.9
47.	Lambton Hall	088	186.3301	90.23966743	0.9
48.	Bayfield Hall	089	506.2101	245.1575514	0.9
49.	Beaver Hall	091	151.1433	73.19870019	0.9
50.	Saugeen Maitland Hall	093	603.7735	292.4075061	0.9
51.	Sydenham	097	177.5334	85.97942562	0.9
52.	Elgin Hall	081	296.6887	143.6863374	0.9
53.	Delaware Hall	095	710.1336	343.9177025	0.9
54.	Seiban-drake	-	0.7997	0.38729471	0.9
55.	Graphic & A	220	311.883	151.0449369	0.9
56.	LHB	-	301.4869	146.0101057	0.9
57.	Wind tunnel	032	327.877	158.7908311	0.9

Appendix D: Length of Cables used in Chapter 4

(Calculated using AutoCAD map from Physical Plant website)

Serial Number	Building 1	Building 2	Distance (meters)
1.	ESS	Natural Science	208
2.	ESS	Natural Science	208
3.	ESS	Visual Arts	206
4.	ESS	Delaware	445
5.	ESS	Biotron	100
6.	ESS	Science Lib 2	206
7.	Delaware	Elgin	326
8.	Sydenham	Elgin	104
9.	Sydenham	Medway	122
10.	Staging	Middlesex	156
11.	Staging	North Campus	96
12.	Visual Arts	North Campus	74
13.	Material science	Biotron	74
14.	Material science	Chemistry	79
15.	Natural Science	Chemistry	137
16.	Natural Science	Natural Science Add	25
17.	Science Lib 2	Natural Science Add	45
18.	Natural Science Chiller	Natural Science Add	25
19.	Chemistry Add	Natural Science Add	20
20.	Chemistry Add	Science lib 1	68
21.	NSS	Science lib 2	262
22.	NSS	West valley	50
23.	NSS	Medical Science	244
24.	NSS	SLB	374
25.	NSS	Alumni Hall	730
26.	NSS	Saugeen	162
27.	NSS	Lambton	200
28.	NSS	ESS	500
29.	NSS	WSS	300
30.	West Valley	Dental ADD	70
31.	Dental	Dental ADD	38
32.	Dental	Health Add	55
33.	Medical Science	Health Add	93
34.	Law	SLB	313
35.	Law	SSS	164
36.	SLB	Somerville	58
37.	Ivey	Somerville	72
38.	Ivey	UC	76
39.	SLB	UC	92

40.	Medical Science	Weldon	322
41.	Medical Science	Kresge	76
42.	Weldon	Student Service	55
43.	Weldon	SSS	320
44.	LHB	SSS	90
45.	CMLP	SSS	122
46.	SEB	SSS	185
47.	Heating ADD	SSS	40
48.	Heating	SSS	40
49.	Heating	Heating ADD	20
50.	Heating	Music	250
51.	Heating	Alumni hall	30
52.	SSS	ESS	850
53.	Music	Talbot	90
54.	Alumni house	Talbot	740
55.	Alumni house	Medway	136
56.	Western Science	Middlesex	85
57.	Western Science	Collip	40
58.	Western Science	Physics	130
59.	SLB	Physics	145
60.	Collip	Kresge	190
61.	Elborn college	Wind tunnel	185
62	Elborn college	SEB	270
63.	Rec centre	Wind tunnel	142
64.	Rec centre	TEB	155
65.	CMLP	TEB	58
66.	Lambton	Support Service	382
67.	Bayfield	Support Service	371
68.	Bayfield	Beaver	88
69.	Saugeen	Beaver	93
70.	WSS	SSC	84
71.	WSS	UCC	50
72.	WSS	SSS	565
73.	WSS	NSS	500

Appendix E: MATLAB code used in Chapter 4

i. Code for generating graph for actual data

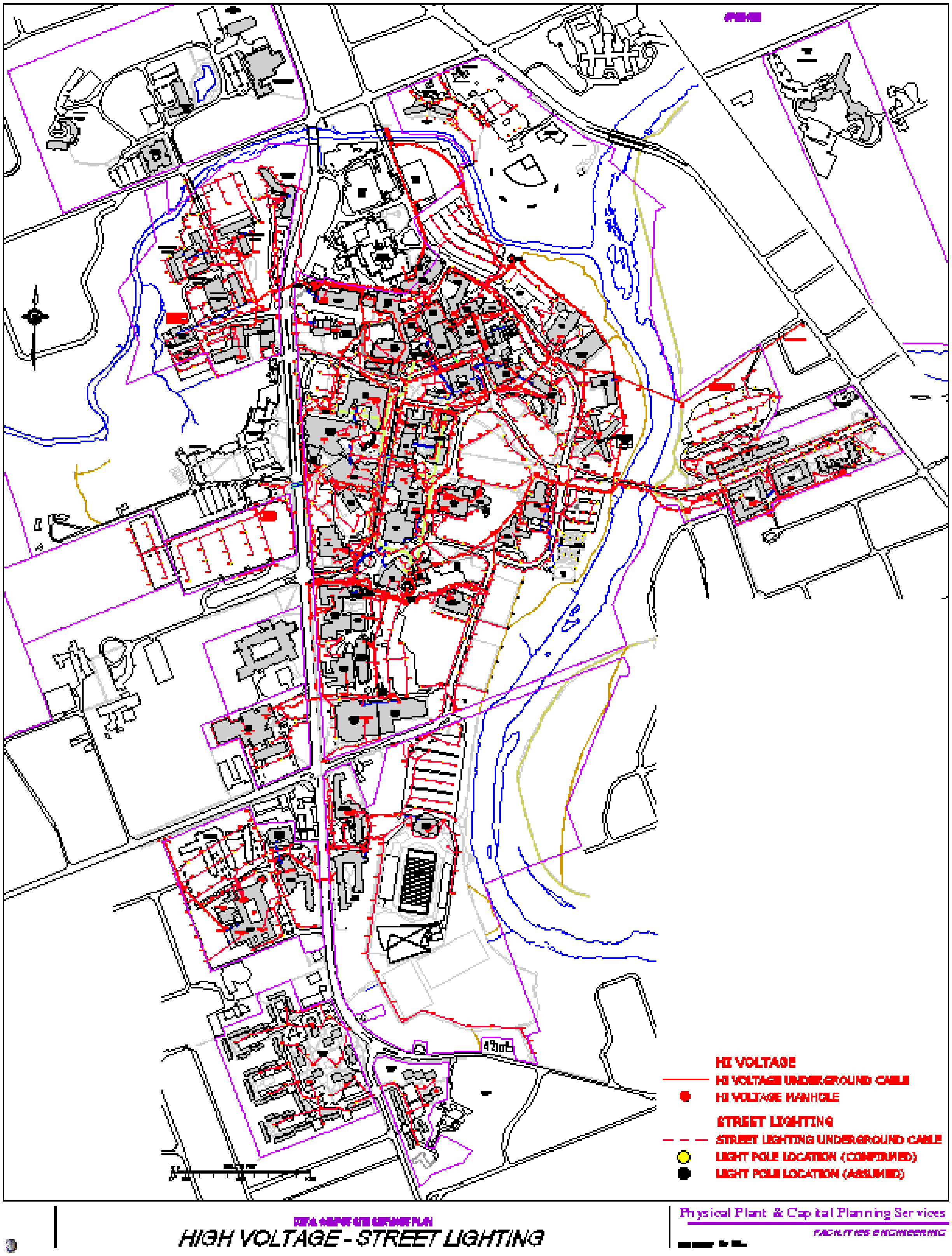
```
clc
clearall
closeall
x1=xlsread('SS_data.xlsx');
y=x1(:,1);
Ess=x1(:,2)/1e3;
Nth=x1(:,3)/1e3;
Sth=x1(:,4)/1e3;
t=y/288;

t1=3;
t2=10;
figure(1)
plot(t(288*t1:288*t2),Ess(288*t1:288*t2),'r'), hold on
plot(t(288*t1:288*t2),Sth(288*t1:288*t2),'b'), hold on
plot(t(288*t1:288*t2),Nth(288*t1:288*t2),'k'), legend('East
Substation','SouthSubstation','North Substation')
Ys=Ess(288*t1:288*t2)+Sth(288*t1:288*t2)+Nth(288*t1:288*t2);
gridon
title('Actual Measured Individual Active Power')
xlabel('Days')
ylabel('Power (MW)')
figure(2)
plot(t(288*t1:288*t2), Ys)
gridon
title('Actual Measured Total Active Power')
xlabel('Days')
ylabel('Power (MW)')

% plot(t(288*t1:288*t2),smooth(Ess(288*t1:288*t2)),'r'),
```

ii. Code for transferring data from PSCAD to MATLAB and generating graphs for simulated data

```
clc
clearall
closeall
% x1=xlsread('SS_data.xlsx');
T1=importdata('load_01.out'); % Calling of the variables assigend to T1...
% y=x1(:,1);
% Ess=x1(:,2)/1e3;
% Nth=x1(:,3)/1e3;
% Sth=x1(:,4)/1e3;
% t=y/288;
%
% t1=10;
% t2=17;
% figure(1)
% plot(t(288*t1:288*t2),Ess(288*t1:288*t2),'r'), hold on
```

```
% plot(t(288*t1:288*t2),Sth(288*t1:288*t2),'b'), hold on
% plot(t(288*t1:288*t2),Nth(288*t1:288*t2),'k'),
legend('East','North','South')
% Ys=Ess(288*t1:288*t2)+Sth(288*t1:288*t2)+Nth(288*t1:288*t2);

figure(2)
% plot(Ys), hold on
plot(T1(:,7),'r')
title('Total Active Power consumption during Peak Loading')
xlabel('Time')
ylabel('Active Power (MW)')

% E1=Ess(288*t1:288*t2);
figure(3)
% plot(E1), hold on
plot(T1(:,4),'r')
title('East Substation Active Power consumption during Peak Loading')
xlabel('Time')
ylabel('Active Power (MW)')

% S1=Sth(288*t1:288*t2);
figure(4)
% plot(S1), hold on
plot(T1(:,9),'r')
title('South Substation Active Power consumption during Peak Loading')
xlabel('Time')
ylabel('Active Power (MW)')

% N1=Nth(288*t1:288*t2);
figure(5)
% plot(N1), hold on
plot(T1(:,2),'r')
title('North Substation Active Power consumption during Peak Loading')
xlabel('Time')
ylabel('Active Power (MW)')
```

Appendix F: Western Campus map in AutoCAD



Curriculum Vitae

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