Next Generation Information Communication Infrastructure and Case Studies for Future Power Systems

By

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ABSTRACT

As power industry enters the new century, powerful driving forces, uncertainties and new functions are compelling electric utilities to make dramatic changes in their information communication infrastructure. Expanding network services such as real time measurement and monitoring are also driving the need for more bandwidth in the communication network. These needs will grow further as new remote real-time protection and control applications become more feasible and pervasive. This dissertation addresses two main issues for the future power system information infrastructure: communication network infrastructure and associated power system applications.

Optical networks no doubt will become the predominant data transmission media for next generation power system communication. The rapid development of fiber optic network technology poses new challenges in the areas of topology design, network management and real time applications. Based on advanced fiber optic technologies, an all-fiber network is investigated and proposed. The study will cover the system architecture and data exchange protocol aspects.

High bandwidth, robust optical networks could provide great opportunities to the power system for better service and efficient operation. In the dissertation, different applications are investigated. One of the typical applications is the SCADA information accessing system. An Internet-based application for the substation automation system will be presented. VLSI (Very Large Scale Integration) technology is also used for one-line diagrams auto-generation. High transition rate and low latency optical network is especially suitable for power system real time control. In the dissertation, a new local area network based Load Shedding Controller (LSC) for isolated power system will be presented. By using PMU (Phasor Measurement Unit) and fiber optic network, an AGE (Area Generation Error) based accurate wide area load shedding scheme will also be proposed. The objective is to shed the load in the limited area with minimum disturbance.

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To My Parents and Wife Ying

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List of Acronym and Symbols

ACE: Area Control Error
AGC: Automatic Generation Control
AGE: Area Generation Error
ATM: The Asynchronous Transfer Mode
API: Application Program Interface
CB: Circuit Breaker
CSMA/CD: Carrier Sense Multiple Access / Collision Detection
DC: Digital Certificate
DMS: Distributed Management System
DoD: Department of Defense
DOM: Document Object Model
DTD: Document Type Definition
DWM: Dense Wavelength Multiplexy
EDFA: Erbium Doped Fiber Amplifier
EJB: Enterprise Java Beans
EMS: Energy Management System
EPRI: Electric Power Research Institute
ETMSP: Extended Transient Midterm Stability Program
FACTS: Flexible AC Transmission System
FDDI: Fiber Distributed Data Interface
FFT: Fast Fourier Transforms
FRU: Frequency Record Unit
GPS: Global Position System
GTG: Gas Turbine Generator
GUI: Graphical User Interface
HTML: Hyper Text Markup Language
IED: Intelligent Electronic Device
IP: Internet Protocol
IPP: Independent Power Producer
ISO: International Standard Organization
IT: Information Technology
J2EE: Java 2 Enterprise Edition
JDBC: Java Database Connectivity
JSP: Java Server Pages
LAN: Local Area Network
LSC: Load Shedding Controller
MMI: Man Machine Interface
MPLS: Multiprotocol Label Switching
$MP\lambda S$ Multiprotocol Lambda Switching
OADM: Optical Add-Drop Multiplexer
OASIS: Open Access Same Time Information Systems
ODBC: Open Database Connectivity
OLE DB: Object-Linking and Embedding Database

QoS: Quality of Service
OpenGL: Open Graphics Library
OSI: Open Systems Interconnection
OXC: Optical Crossconnects
PD: Partial Discharge
PKI: Public Key Infrastructure
PLC: Power Line Carrier
PLC: Programmable Logic Controller
PMU: Phasor Measurement Unit
PQ: Power Quality
RMI: Remote Method Invocation
RTU: Remote Terminal Unit
SDH: Synchronous Digital Hierarchy
SNMP: Simple Network Management Protocol
SOA: Semiconductor Optical Amplifier
SONET: Synchronous Optical Network
SPID: Strategy Power Infrastructure Defense
SQL: Structured Query Language
SCADA: Supervisory Control and Data Acquisition
TCP: Transport Control Protocol
TDM: Time Division Multiplexing
UCA: Utility Communications Architecture
UDP: User Datagram Protocol
UFLS: Under Frequency Load Shedding
UHF: Ultra High Frequency
VHF: Very High Frequency
VLSI: Very Large Scale Integration
WAN: Wide Area Network
WDM: Multi-channel Wavelength Division Multiplexed
WSCC: Western System Coordinating Council
XML: eXtensible Markup Language

Chapter 1 Introduction

1.1 Introduction

Power supply is one of the most important resources to the human society development. The cost of power outage is on the order of millions of dollars [1][2]. However, power system can become vulnerable [2] in the face of possible system abnormalities such as control, protection or communication system failures, disturbances and human operation errors. Therefore, to keep power supply stable and reliable is a very critical issue for future power systems design.

Computer networks and data communication play important roles [3] in power systems. Applications from SCADA (Supervisory Control and Data Acquisition System) [4] system, remote measurement [5][6], to monitoring [7], and control, protection [8], are critical to the proper operation of power system in order to maintain system reliability and stability.

In the summer of 1996, two massive breakups [1] of the WSCC (Western System Coordinating Council) system cost up to 2 – 5 billion dollars direct and indirect loss. The two incidents demonstrated the importance of real time information coordination for the control system strategy design. In nearly every case, the power system controller did what it designed to do [1]. However, the control strategy did not include a control law that was adaptive to the changing circumstances. To achieve sufficient effectiveness of the control law, it must develop strategies in association with real time information from other wide range data sources. Currently, most communication technologies employed in the power system only allow local, narrowly focuses, control actions [9] at the substation or line level due to lack of efficient, high speed, high bandwidth, reliable communication media.

As the electric power industry enters the new century, powerful driving forces, uncertainties and new services are compelling electric utilities to make dramatic changes in the power system information infrastructure design [9][11]. The increasing incorporation of digital devices throughout the enterprise [12] as well as the forces of deregulation is driving utility communications into new realms. Expanding network services such as real time monitoring are also compelling the need for more increasing bandwidth in the communication network backbone. These needs will grow further as new remote real-time protection and control applications [13][14] become more feasible and pervasive.

1.2 Placing Value on the Real Time Information

Real time date can be highly valuable information source for automatic control to maintain system stability; it can also be used as a guide to immediate operating decisions in support of system recovery and for extensive analysis [15][16]. According to the research [1], the widespread power outage in the western United States on 10 August 1996 could have been avoided if 0.4% of the wide area loads had been shed for 30 minutes. The 1996 breakups as well as other outages demonstrate that wide area, comprehensive and real time information exchange is becoming a critical factor for the future power system reliability and stability.

Figure 1.1 illustrates the relationship between measurement, information, and decision-making. The real time data applications [1] range from very rapid control function to the very slow functions such as expansion planning. With high-speed real time measurement, proper protection and control actions could be taken to ensure the reliability of power system when event occurs.

Fast, real time and comprehensive information acquisition and transmission are the key to wide area power system operation optimization and control [17][18][19]. To support such data communication requirements, the candidate communication architecture and technologies must be able to deliver operational data and dynamic real time information to those who need it, when they need it. In short, the communication infrastructure must have the following features:

- It should have high bandwidth to support large volume power system monitoring and measurement information transmission.
- It should have low latency to support local area and wide area real time control and protection.

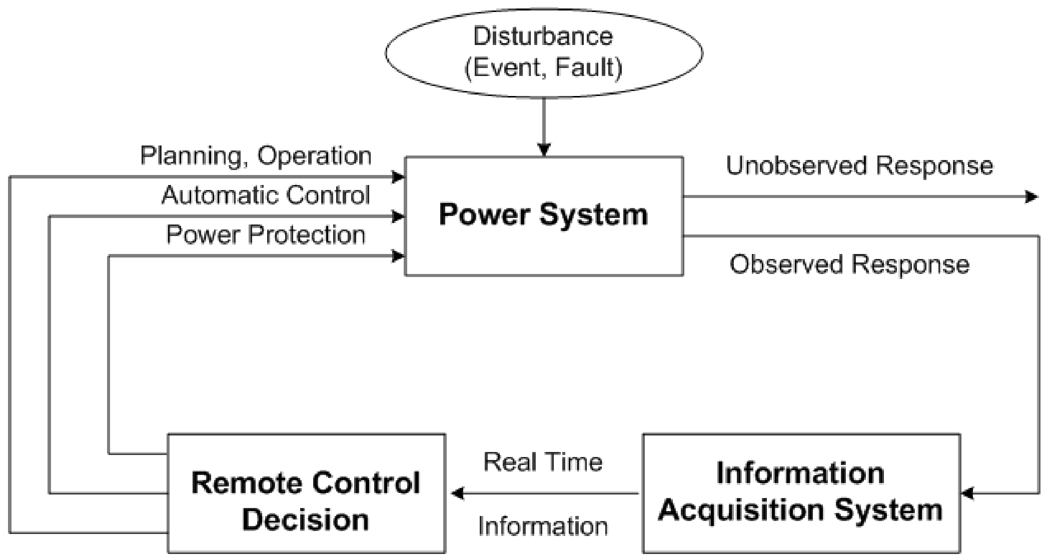

Figure 1.1 The Circle of Measurement, Information, Decision Making

Today, different communication media [4][20] are employed in power system, such as power line carrier, radio frequency system and microwave. However, their performance cannot meet the future power system information exchange needs. To provide feature-rich services for power systems, a new paradigm is needed. Fiber optic network no doubt will be the best choice to meet future power system real time control, protection and monitoring application requirements due to its high-bandwidth, low latency and QoS (Quality of Service) features.

Power system deregulation [3] results in information consolidation and open access, and pushes for more extensive internal and external utility information exchange, integration, and dissemination. Inter-company communication and integration of data from various control centers, power plants, and substations, have become necessary. SCADA (Supervisory Control and Data Acquisition) systems are essential parts of the DMS

(Distributed Management System) and EMS (Energy Management System) that employ a wide range of computer and communication technologies. A SCADA system gathers incoming power system data for further processing by a number of distributed processes. However, existing SCADA information management systems [20][21] cannot satisfy the new challenges as more and faster information has now become desirable by many users and players. Technological advances in networking have made it possible to develop a low cost communication system for accessing real time power system information over digital network.

High performance fiber optic network brings great opportunities for the power system real time applications. Power system frequency [22][23] is one of the most critical parameters for understanding and controlling power system dynamics. However, frequency instability scenario can be initiated by a large mismatch between generation and load [24][25]. Such a scenario can result in a cascaded loss of generation through under-or over-frequency related operation that would eventually lead to a blackout. Under frequency load-shedding scheme [26] is commonly implemented in isolated and large interconnected system as an emergency measure in case of falling frequency conditions or loss of power generation. Traditionally, the load-shedding scheme was evaluated and set using simulation [27] based on the assumption of constant deceleration, constant voltage, constant load and constant generator power. The scheme was adequate for simple and special cases. However, when system operation status is changed, the load-shedding scheme cannot be easily modified to adapt to new system conditions. The results of the early efforts point to the need of fast and accurate load shedding strategy. In recent years, technology advances in networking and communication as well as in power system design have opened the door for fast and accurate load shedding system design.

1.3 Objective of the Dissertation

This dissertation addresses two main issues for future power system information infrastructure: communication network investigation and associated power system real time applications. The major objectives of the study are to systematically analyze the fiber optic network for future power system communication; develop models and algorithms for advanced system applications based on the all fiber optic networks and advanced power system technologies. The main research topics are summarized as follows:

- **Systematic analysis of fiber optic networks for next generation power system communication infrastructure**

  A few fiber optic networks were installed in power systems for long distance or local area communication. The technologies for these fiber optic networks are still based on the multi-tier architecture (IP/ATM/SONET/WDM), which has longer time latency and low bandwidth. We proposed an all-fiber network for the future power system communication infrastructure. The proposed all-fiber network could make use of the latest IP over DWM technology to simplify the network structure while improving the network performance. The proposed all-fiber network contains three major components: wide area data communication network; local area substation communication network; and data transmission protocol.

- **Development of Internet based SCADA system**

  In the previous work [21], we have first presented and set up an Internet based SCADA display system prototype. However, how to integrate the advanced IT technology with existing SCADA system becomes a practical problem. In this thesis, an Internet based SCADA information accessing system integrating with existing SCADA package will be designed and implemented. In addition, an important topic of one line diagram auto-generation using VLSI technology will also be addressed and implemented.

- **Local Area Network based Load Shedding Scheme Design**

  Fiber optic network brings great opportunities to the power system real time applications. In this dissertation, we will design and present a new fiber optic local area network based load shedding controller for isolated power system. The LAN-based load shedding scheme makes use of real time load and generation information via a local area network to determine the load shedding strategy and therefore fast, accurate and flexible load shedding scheme can be achieved. Actual on site implementation of LAN-based load shedding controller will also be introduced.

- **Area Generation Error based Wide Area Load Shedding Scheme Design**
  Another application of the fiber optic network is for wide area LSC design. In this part of the work, we will propose a wide area load shedding scheme based on real time phasor measurement frequency and tie line information inputs. The proposed load shedding scheme can accurately predict the generation deficiency at the initial instant of the contingency and therefore, be able to concentrate the load shedding in the incident area with minimum system disturbance. Different case studies in various generation loss contingencies will also be introduced to test the efficiency of the proposed scheme.

1.4 Arrangement of the Dissertation

There are six chapters in this dissertation. Chapter 1 is the introduction of the research project. Chapter 2 is a systematic study of all-fiber optic network and XML application for the future power system. Chapter 3 discusses the Internet based SCADA display system design. LAN-based load shedding controller is introduced in Chapter 4. In Chapter 5, an AGE (Area Generation Error) and PMU (Phasor Measurement Unit) based fast and accurate load shedding scheme is proposed. As a conclusion, Chapter 6 will summarize the work. It will also suggest ideas for additional research in this field.

Chapter 2 Fiber Optic Network Infrastructure for Future Power System Communication

From high-speed substation control and protection data communication [14][28] to wide area power system monitoring [29][30] and measurement data transmission, the increasing incorporation of computer network throughout the utility as well as the forces of deregulation are compelling power system communications into new realms with new requirements and challenges. Expanding network services such as real time wide area control [31][32] and FACTS (Flexible AC Transmission System) device coordination [33][34] are also driving the need for evermore bandwidth in the network backbone. These needs will grow further as new real-time service, protection and control applications become more feasible and pervasive. Electric utilities often employ several types of communication media [4][6] for different functions. With more and more bandwidth required by the power system data communication, the current transmission media cannot meet all the high capacity and quality of service requirement. Fiber optic provides the ideal alternative for the future power system communication infrastructure design.

Although fast response is always desirable, different functions could have different time latency requirements. Clearance of a transmission line grounded fault requires millisecond of time delay, while several hours are reasonable for power system restoring. In the power system, various applications response time could range from few cycles to hours or even years. The large span of time scale for various power grid control and operation tasks greatly complicates modeling, analysis, simulation, control, and operation.

This chapter will systematically analyze the new optical networking architectures and protocols enabled by recent advances in network and IT technologies such as WDM (Multi-channel Wavelength Division Multiplexed connection) and XML (eXtensible Markup Language). Based on IP over WDM, an all-fiber network design for future power system communication infrastructure is also proposed. Rather than specifying the detailed network design, this section provides an overview of the architecture issues.

2.1 Introduction

As illustrated in Figure 2.1, fast, real time and comprehensive information acquisition and transmission are the keys to the power system operation. The real time information can be used for power system control, protection, monitoring or even for the system maintenance. This section highlights some typical applications which can be greatly improved by using real time information.

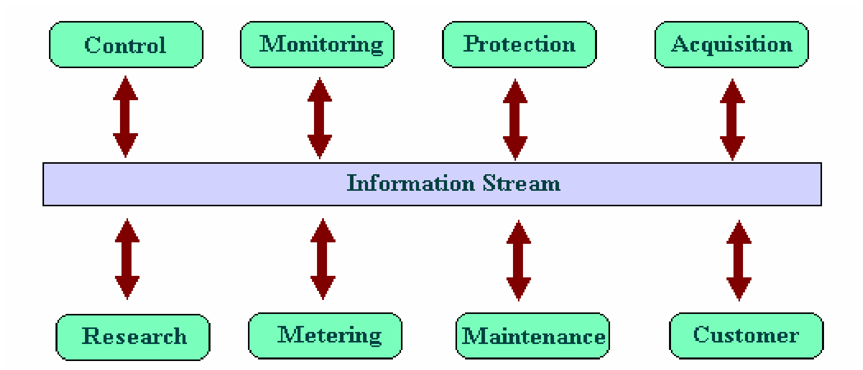

Figure 2.1 Future Power System Information Needs

- **Substation protection and control**

  Power system substation [35][36] tends to be more complex due to the growth of new service requirements. Information sampled by IED (Intelligent Electronic Device) units must be transmitted under few milliseconds for the proper protection and control operations. Table 2.1 [37] illustrates the data-sampling rate and time latency requirement of some typical protection functions. All these functions demand reliable, high-speed, real time communication links between field units and station unit. Therefore, the type of communication systems becomes one of the important considerations in the design of the future substation system.

- **Power Quality**

Power quality can be used for device diagnoses, event analysis or even settlement of legal arguments. In recent years, power quality's functionality has been changed from simple system monitoring to real time trouble shooting, diagnosis and restoration. High bandwidth and low latency data transmission is needed for power quality to play an even more important role.

Table 2.1 Data-Sampling Rate and Time Latency Requirement for Protection

Type of relay	Data Volume (kbps)		Latency (sec.)	
	Present	Future	Primary	Secondary
Over current protection	160	2500	4-8 ms	0.3-1
Differential protection	70	1100	4-8 ms	0.3-1
Distance protection	140	2200	4-8 ms	0.3-1
Load shedding	370	4400	0.06-0.1	
Adaptive multi terminal	200	3300	4-8 ms	0.3-1
Adaptive out of step	1100	13000	4-8 ms	0.3-1

- **Wide area stability and voltage control**

  Wide area control [20] provides a flexible platform for rapid implementation of generator tripping and reactive power compensation for voltage support and stability. Currently, wide area stability controls [5] are based on offline simulations, which operate only for well-studied outage cases. By using real time on line security assessment, more sophisticated wide area stability control are possible, and the uncertainty of the control environment could be reduced. Wide area control can be categorized into fast control and slow control. Fast control needs tens to hundreds millisecond (typical response time will be 4-6 cycles delay for data receiving; 4-6 cycles delay for control logic; and 6 cycle delay for output transfer trip signals and circuit breaker operation) to ensure transient stability following major disturbances. Slower control normally needs tens of seconds for application such as voltage stability control. Data communication speed and reliability are critical for fast speed control.

- **Voltage security assessment**

Voltage security is very critical to maintain power system stability. The conventional offline studies cannot meet the system dynamic requirements, due to the infinite number of possible running conditions. For instance, power transfer must be reduces if unstudied conditions occur. The delays for off line simulation of proposed operation can be costly. Highly automated, real time on line assessment is rapidly becoming a necessity. Therefore, on line voltage security assessment can be greatly improved by making use of high speed, high efficient data transmission network.

Table 2.2 [37] summarizes some typical applications of using real time information in the power system.

Table 2.2 Real Time Information Applications in Power Industry

Special fields	Real Time Information Applications	References
Utility Information Management	AM/FM/GIS	[37][39][40]
	Data warehouse/database	[41][42]
Operation	Substation/Distribution automation (SCADA/ EMS/MIS)	[35][36]
Maintenance	Remote monitoring and diagnosis	[29][36]
	Power quality	[30]
Power Market	Open Access Same-time Information System	[43][44][45]
Education and Training	Distance learning courses; laboratories; operator training; Inter-university, inter-utility education program sharing	[46][47]

Future power system poses new challenges and requirements to the next generation information infrastructure and communication network. Such kind of infrastructure and network must be able to:

- Support high-speed, real time communication link demanded by new power system protection and control applications.
- Support high bandwidth and the highest data rate required by the new power system service and functions.
- Access all the locations to support real time monitoring and control functions.
- Continue to operate even if part of the network were damaged.

The operational and commercial needs of the power industry require broad bandwidth, high-speed communication infrastructure to fit requirements for the future [36]. To build the optimal network, power system engineers may decide to integrate existing communication systems using fiber optic network. This section systematically analyzes the communication issues for the future power system including:

- Long distance date communication such as wide area information exchange.
- Local area communication such as substation automation and operation.

2.2 Current Power System Data Communication Media

Expanding network services like real time monitoring are driving the need for ever-wider bandwidth in the network backbone. These needs will grow further as new remote real-time protection and control applications become more feasible and pervasive. Electric utilities often use several types of communication media [3][4][6] for different functions. With more and more bandwidth required by the power system data communication, fiber optic will be the ideal choice for the future power system communication infrastructure. The following sections highlight some commonly used communication media in the power system.

2.2.1 Power Line Carrier

PLC [4][9] is the most commonly used communication media in the United State for protection function. This medium does not offer a reliable solution for wide area data transmission. Communication with remote sites cannot be maintained during a disturbance. Therefore, its effectiveness for wide area data transmission is limited.

2.2.2 Dedicated Links

Dedicated links [4][5][6] are employed by many SCADA systems to communicate between control center and substation RTUs. The main advantage of dedicated link is its capability to provide high data rate. Dedicated links are impractical for controlling medium voltage grids due to lack of connectivity in remote areas. Installation of private lines on electric poles is expensive. Public networks are dependent on third party providers and are subject to service charges.

2.2.3 Radio Systems

Different radio systems, such as conventional radio, trunked radio or spread spectrum are suitable for wide area data transmission [4][6][12]. They are based either on licensed channels or over non-licensed frequencies. However, many countries suffer from a shortage of available frequencies in the VHF/UHF (Very High Frequency / Ultra High Frequency) bands. Besides, due to over-utilization of these unlicensed frequencies by mass consumer applications, their reliability for commercial and industrial uses are questionable. It is important to note that using line protocols over radio results in unreliable communication and poor utilization of airtime.

2.2.4 Microwave

Microwave [4][6][12] is the radio signal operating in the 150 MHz to 20 GHz frequency range. The disadvantage of the microwave is that the transmission length is limited to a line of sight path between antennas. Microwave is subject to atmospheric attenuation and distortion. The combined latency using modem plus analog microwave is around 100 milliseconds between two adjacent antennas.

Table 2.3 [59] shows some commonly used communication medium in the power system. From the table, we can see, none of the above existing wide area transmission media can meet the real time measurement requirement. Besides bandwidth, time latency is another important issue. For the wide area oscillation, damping and load shedding, 100-200 milliseconds or better is required. The above technologies do not have QoS (Quality of Service) function to guarantee the time latency requirements by fast control and protection functions.

Table 2.3 Currently Used Transmission Media in the Power system

Transmission Media	Data Rate
T1	1Mbps. Effective bandwidth considering network traffic, data collision etc is 125kbps.
Frame Relay	280 kbps
ISDN	140 kbps
T1 Fractional	62.5 kbps
56k leased line	56 kbps (Effective bandwidth lower than this)
Internet	Effective rate 40 kbps depends on network traffic
Radio Frequency	9.6 kbps
Power Line Carrier	1.2 kbps

2.3 Networks and Information Technology

The problems mentioned in the previous sections pose the challenge of making use of more advanced technology for future power system communication infrastructure design.

2.3.1 Fiber Optic and its Enabling Technologies

Fiber optic system [50] is the most suitable data transmission medium for power system control, protection and monitoring functions. The particular characteristics [51][52] of the optical fibers that make them so useful are: low attenuation; high bandwidth; electromagnetic interface immunity; and security.

- **Low Attenuation**: The attenuation of an optical fiber is dependent on the wavelength of the light signal in use. Representative attenuations at 1300 nm and 1550 nm wavelengths are 0.35 and 0.2 dB/km, respectively. With an easily achievable net loss of 20 dB, the latter attenuation value allows 100 km between repeaters or amplifiers.
- **High Bandwidth**: A single optical fiber operating at 1300 or 1550 nm of wavelength has a potential bandwidth of 20 Tbps (Tera Hz bits per second), which is enough for 312 million voice channels (64kbps). Bandwidth limits of fiber optic transmission

systems are mostly determined by the electro-optic drivers and receivers or the electronic interface to these devices.

- **Small Physical Cross Section**: Fiber optic system provides the advantage of small physical cross section. Furthermore, it can also be upgraded for more capability by merely installing higher speed electronics or wavelength division multiplexing (WDM).
- **Electromagnetic Interface Immunity**: The immunity of fiber to external interference such as noise and crosstalk implies there is no crosstalk-induced limit from high-powered transmitter or more sensitive receivers.
- **Security**: Optical fibers radiate no energy, noninvasive eavesdropping of the signal impossible.

The rise of the optical networking such as WDM can be attributed to the advancements in key component technologies [50] - [55], such as fiber, amplifiers, lasers, filters, and switching devices. The fiber optic network components can be classified into two types: switching components and optical linking components. Switching components include tunable transmitter/receivers, OADMs (All Optical Add-drop Multiplexer) / OXCs (All Optical Crossconnects). The optical linking components include WDM multiplexier/demultiplexers, WDM passive star coupler etc. Multiplexers aggregate multiple wavelengths onto a single fiber, and demultiplexers perform the reverse function. OADMs are programmable devices configured to add or drop different wavelengths. OXC cross-connects acts as wavelength routers or wavelength cross-connects. Transmitters which send the optical signal to the fiber are of two types: tunable or fixed. Advances in amplifier technology have increased the distances between the signal re-generators. Two basic optical amplifiers have been proposed. Semiconductor Optical Amplifier (SOA) can be integrated with other silicon components for improved packaging. Meanwhile, Erbium Doped Fiber amplifier (EDFA) design can typically achieve high gain. Finally, optical packet switches are nodes that have optical buffering capability and perform the packet header processing functions required of packet switches.

2.3.2 IP over Optic Network Topology

At present, most WDM deployments [54] are point-to-point and uses SONET/SDH (Synchronous Optical Network / Synchronous Digital Hierarchy) as the standard layer for interfacing to the higher layer of the protocol stacks. These different protocol stacks provide different functionality, in terms of bandwidth overhead, rate scalability, traffic management, and QoS (Quality of Service). The Asynchronous Transfer Mode (ATM) layer mainly performs segmentation and reassembly of data, with class of service and sets up connections from source to destination. The SONET/SDH layer mainly interfaces with the electrical to optical layers, delivers highly reliable ring-based topologies, performs mapping of Time-Division Multiplexing (TDM) time slots from digital hierarchical levels; The Wave Division Multiplexing layer multiplexes electrical signals onto specific wavelengths in a point-to-point topology and constructs the power system communication backbone.

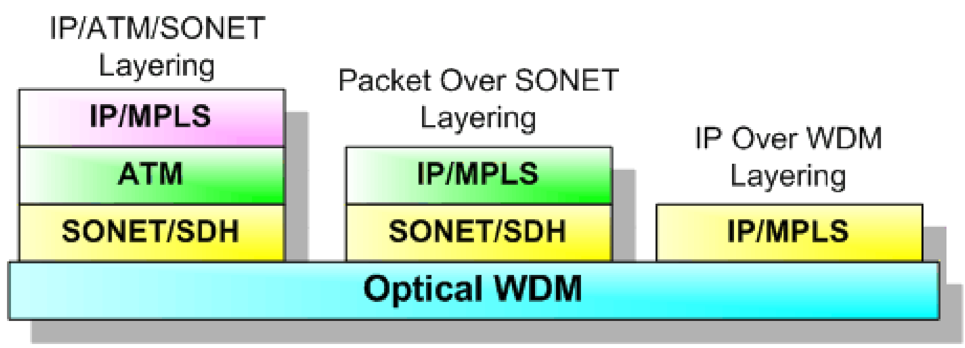

Figure 2.2 IP over Optic Network Topology

Current fiber optic networks are based on the multi-layer topology as shown in Figure 2.2. However, the multi-layer topology does have some problems, such as time delay and function-overlap. Facing these problems, the research community has devoted increasing efforts to the study and development of prototypes for transmitting IP packets in the optical domain. The studies show that the better combination will be IP over WDM [55], because of the absence of many layers. IP over WDM architecture brings in the property of virtual fibers where each wavelength can be considered as a dedicated connection. The signals do not need to be converted onto an electrical domain for performing control operations. Hence, the latency in the IP/WDM system is smaller compared to that encountered in the SONET system. The absence of a vendor specific component makes the system service transparent. However, IP over WDM can become a reality only when all the end-to-end services are offered optically.

By using IP over WDM, the ATM function of traffic engineering (QoS) is being absorbed into IP, and the transport capabilities of SONET/SDH (e.g. protection and accommodation of VBR (Various Bit Rates) through tributaries) are being absorbed by the optical layer. Therefore, the multi-layer architecture converges to two-layer. MPLS (Multiprotocol Label Switching) [52] or a slightly modified version, *MPλS* (Multiprotocol Lambda Switching) for the optical layer can be chosen to control both layers.

2.3.3 The Need of Information Management Methodology

The great needs of the information exchange in the power system are pushing IT to play an increasingly important role. Utilities begin to re-consider their information needs, and redesign the system for information exchange, integration. A methodology for efficient information consolation, exchange and sharing is required. This need will become increasingly more critical as the volume of information holding increases [56].

IT technology has been employed in power systems in different applications such as information accessing and sharing [57][58]. However, issues like multiple data formats compatibility problem and lack of metadata standardization complicate the exchange of data among different users. Many standards have already been developed for information management, but they tend to be overlap, and even worse, are often incompatible with one another. For example, some SCADA systems use UCA (Utility Communications Architecture) [59] for data management while Modbus™ [60] is used as the common data language in EMS/DMS. The data exchange among them is difficult. To resolve this problem, one possibility is to interface different types of systems and applications using the same standards to facilitate power system data exchange, but it can be very difficult, time-consuming and costly. The lack of standards among the disparate systems has resulted in great waste of resources. Isolation between power system applications also hinders the development of a universal information infrastructure in power system utilities. Future power industry may benefit from the use of universal information architectures, such as a standard data exchange model and communication network that can support the different data requirements, transfer rates and qualities of data flow among various systems.

Thus, to facilitate a successful universal information access/exchange infrastructure in the current power system, it is clear that the standardization of data models and communication protocols is inevitable [13]. Incidentally, applications that provide power system data exchange must be constructed using technologies that can provide both program and data portability.

The more recent XML technology can be used to address the critical need of a universal data interchange problem. XML technology enables easy information exchange between disparate power systems and applications. Using XML, information exchange can be accomplished with minimum modifications necessary on existing applications. Utilities can continue to use their respective proprietary data formats internally, while still be able to exchange power system data with other applications.

The use of XML will ensure the portability of the data. This advantage will be greatly enhanced if the applications that use it are also portable across multiple platforms. Java with its "Write once, Run anywhere" portability is the perfect partner to the XML in this quest for a flexible data interchange systems. In addition, the new J2EE spells out the specification to ease the development, deployment and management of Java-based applications in a widely accepted Internet environment. Hence, the XML data exchange prototype was created using J2EE to demonstrate the benefits of having portable applications in addition to portable data.

XML [61] has been widely used in networking [62], e-commerce [63], earth science [64], simulation [65] for data exchange. With the development of power industry deregulation, XML has also been introduced and discussed in power systems for power market and information exchange [58]. In this paper, we discussed some potential uses of XML for data exchange in the power system. These applications include data exchange among utility databases, power market on-line trading and others. In addition, a Java based XML data exchange prototype using JSP/Servlet/XML was setup to demonstrate the potential utilization of XML for data exchange in power systems.

2.3.4 XML Technology

The extraordinary growth of the Internet has been fueled by the ability that it greatly facilitates information access, distribution and exchange. However, information exchange has begun to experience the limitation that does not provide the extensibility, structure, and data checking needed for multi-platform, large-scale data exchange. To address these issues and facilitate the greater use of Web technology into new domains of distributed information exchange and processing, XML was created by the World Wide Web consortium [61]. XML is structured and hierarchical, which means it can be represented as a tree structure or data model appropriate to applications. It also uses plain text for data representation, which makes it easy for both humans and machines to read or understand.

XML specifies a rigorous, text-based way to represent the structure inherent in data so that it can be authored, searched, and interpreted unambiguously. Its simple tag-based approach provides a flexible extensible mechanism that can handle the range of digital data from highly structured database records to unstructured. A typical example will be the XML-based metadata exchange and search engine system.

XML also provides a human-readable format for defining data object names, attributes and methods. It provides a means for an application to find additional information about the date objects, embed in the DOM (Document Object Model) and send to the server for data access. Due to its platform, vendor and language-neutral properties, XML is ideal to act as the common format among the numerous of proprietary standards that currently exist, so as to facilitate seamless data sharing and exchange between different utility systems and applications. These features are quite suitable for power system information exchange, since power applications are normally based on various platforms and protocols from different vendors. XML standard and its tools provide excellent opportunity for the information exchange among different systems without changing much of the existing system.

XML-based inquiries is based on the terms being defined as specific data elements or tags conforming to the DTD (Document Type Definition)/XML schema. DTD schema is a definitive listing of the data "names" which will be used in the particular document/data type at hand. Another feature of XML is that all the organizations can set their enterprise agendas to cooperate in the construction of an open standard, driven entirely by user needs. These include:

- Extensibility – Users can freely define their own information tags.
- Structure - Data structure can be modeled to any level of complexity.
- Validation - Data can be checked for structural correctness.
- Platform independence - Data content can be published in multiple platforms.

Currently, the CSV (Comma Separated Variable) format is also used in power system for information exchange like OASIS [44][45]. However, the CSV format is redundant due to its data encapsulation method. It also lacks the flexibility since users have to read in all the information in the CSV format in fixed sequence. The XML technology provides a hierarchical data structure to prevent the data redundancy and makes the data exchange to be much more focused, efficient and flexible. Different applications only need to retrieve the interested information from the tagged XML stream data.

XML has gained vast amount of attention, popularity and support from users, software vendors and Internet standards regulating consortiums in many industries. There has been a tremendous emergence of XML supporting standards and tools after XML was first introduced. Developers are provided tools to use XML-enabled databases, data conversion utilities, authoring and development tools, and data management applications to assist in the delivery of XML data across the Web. These many XML related standards and supporting tools include DOM, SAX (Simple API for XML), XSL (Extensible Stylesheet Language), XQL (XML Query Language), XLL (XML Linking Language), XLink and others. Generally, XML-enabled systems and supports can now be found virtually everywhere.

2.3.5 XML Applications in the Future Power System

The applications that will drive the acceptance of XML in the area of power system are those that cannot be accomplished within the limitations of data exchange formats, protocol and platform. Such applications can be classified into several categories.

2.3.5.1 Transparent Metadata Exchange

Typical examples of metadata exchange will be applications that mediate between two or more heterogeneous databases. One such application could be to provide the control center access to power system/SCADA data stored inside multiple utilities' databases, with transparency to the many different internal data formats and system platforms available. A technically feasible way to implement this seamless exchange is to adopt a single data interchange format, which will serve as the single output format for all data exporting systems and the single input format for all importing systems. This can be realized with the XML technology. Thus within each utility or substation, proprietary formats and platforms can remain to be utilized, while XML equipped applications or mediators perform the job of any necessary translations.

2.3.5.2 Distributed Calculation and Processing

Distributed processing is used when applications attempt to process the data stored in the distributed environment. Such applications could be computation-intensive post-fault data analysis or events statistics calculation. These applications need to retrieve the data/metadata from distributed database source. Each utility or substation maintains large amount of technical data on event reports or recorders. To enable data interchange, a flexible protocol is needed. The data representation must be platform and vendor independent, so that data from variety of sources can be used to drive a variety of distributed applications. Via XML, a significant portion of the processing loads can be shifted from the server to the web clients. The computation-intensive process that would entail an enormous, extended resource on the server would be transformed into a brief interaction with the server followed by an extended interaction with user's Web client.

2.3.5.3 On-Line Transactions

A typical example of on-line trading/transaction would be the OASIS system – an electricity market on-line trading system. Customer buys the electricity according to the seller's price. The client transaction data can be represented as XML-tagged data directed to the OASIS server. The OASIS server then performs the required real-time authentication and sends the results as XML-tagged documents back to the customer.

2.3.5.4 Data Presentation

A typical example would be power system applications that present different views of the same data to cope with the different needs of multiple users. One such application will be viewing of dynamic substation information contents, where users are presented with substation information like transformer parameters, running status, generator information and etc. Using the same XML-tagged data available in the object-oriented database, users can have the choice of multiple presentations. Different forms of substation graphic displays, multiple degrees of details, collapsing or expansion of substation view, all easily achieved through the used of XSL style sheets.

2.4 Wide Area Communication Infrastructure

Through the above discussion, an IP over WDM network design for future power system is proposed. One of the key advantages of WDM is that it offers multi-protocol support, allowing multiple independent network protocols to coexist on the same filter network. It is extremely important to cooperate with the existing multi-protocol network in power systems.

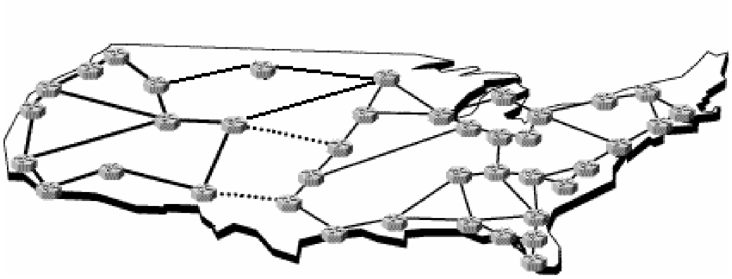

Figure 2.3 IP over WDM Fiber Optic Network

With physical topologies requires increasing operational costs to deploy fiber rings, there is a great desire to deploy WDM technology and further optimize this with wavelength routing. The overall fiber optic network will be mesh architecture [66][68] as shown in Figure 2.3. The key nodes will be the big utilities or control centers. Together they set up the core optical network. Data transmission will set up on this network over IP protocol.

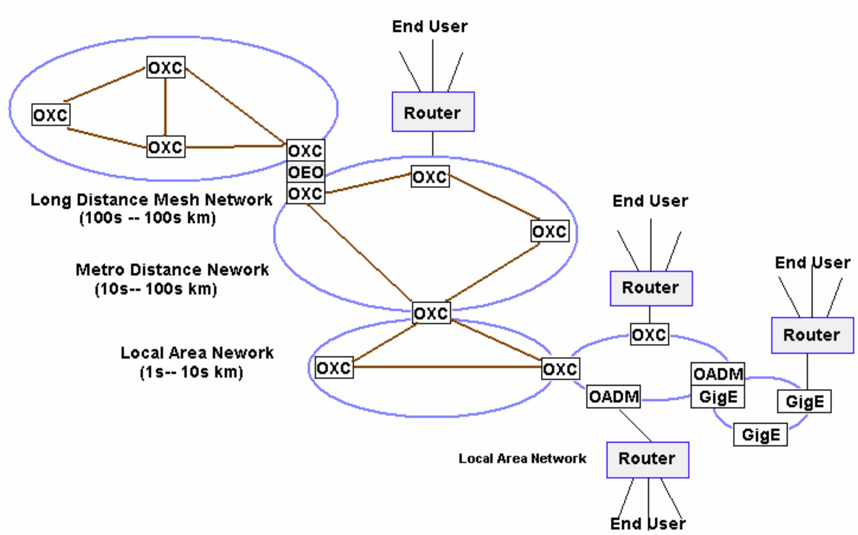

Figure 2.4 Detailed Fiber Optic Network Architecture

Rapid development of fiber optic technologies such as all-optical cross-connects and all-optical add-drop multiplexers enable the evolution from simple point-to-point WDM links to full networks. Detailed fiber optic network architecture is shown in Figure 2.4. An OXC is a large photonic switch having N-full duplex ports, each of which can connect to any other device. The OADM is a 2x2 degenerate form of the $N \times N$ OXC that extracts and reinserts certain light-paths for local use and routes the others through.

Physical Layer

The physical layer is the layer at which signals are exchanged. In the proposed system, the physical layer is based on fiber optic along the distribution feeders, or single mode fiber installed in the substation. Transmitting optics are based on Laser, the bit rates can be OC-48 (2.5Gbps) / OC-192 (10Gbps) or higher.

Data Link Layer

The data link layer, above the network layer, is responsible for delimiting data fields, acknowledgement of receipt of data, and error control. In most of the communication systems, receipt of information that passes the error check is acknowledged to the sending station. In addition to this kind of functions, the data link layer may contain a flow control mechanism, to prevent problems when two devices of different speeds try to communicate. By using flow control mechanism, messages first-time transmission can be ensured to all traffic in the fiber optic network. In combination with the antibody algorithm, they can help guarantee the minimum network congestion.

Application Layer

Power system applications will be allocated to the application layer. The wide area fiber optic network can be used for information exchange between utilities and substations. This information can be used for power system control, protection, monitoring and scheduling etc. The power system information such as rate schedules, operating constraints, available transmission capacity can be shared among different utilities.

2.5 Local Area Substation Network Design

Today, substation automation tends to be more complicated due to implementation of advanced computer and network technologies. Real time information acquired by IED must be transmitted under few milliseconds for the proper protection and control operations. High-speed, real time communication links between field units and station unit is demanded. This type of substation system requires a large number of power equipment supported by an efficient communication system. Optical fibers as transmission medium guarantee the robustness against the EMI (Electrical Magnetic Interference).

2.5.1 Substation Communication Network Requirement

The major needs for the automation system are:

- Data acquisition: The data includes analog and digital information from the equipment in the substation. This facilitates local operations by providing consolidated metering, alarm and status information.
- Control and monitoring: A substation level control and monitoring system is needed. The control hierarchy can be implemented between the control center, local substation and IEDs.
- High availability and redundancy: The system must guarantee the “no single point of failure” communication criterion.
- Capability for future expansion: The system should allow easy future communication expansion.

2.5.2 Substation Communication Network Architecture

The proposed all-fiber substation communication network architecture can be divided into three levels as shown in Figure 2.5. Level-1 involves IEDs or PLCs (Programmable Logic Controllers) connected to substation equipment. These IEDs and PLCs are classified as either control or protection IEDs. Protection IEDs are used to report the equipment status information and implement the protection algorithms. Control IEDs are used as gateway between the Substation server and protection IED. Level 2 consists of substation server. All monitoring and control operations can be performed at any time. Substation server also communicates with the control center server for the information exchange. Level 3 is the utility control server. Its function is to monitor and control the whole substation system. Different LAN topologies such as Giga byte Ethernet or FDDI (Fiber Distributed Data Interface) can be used for substation automation system design.

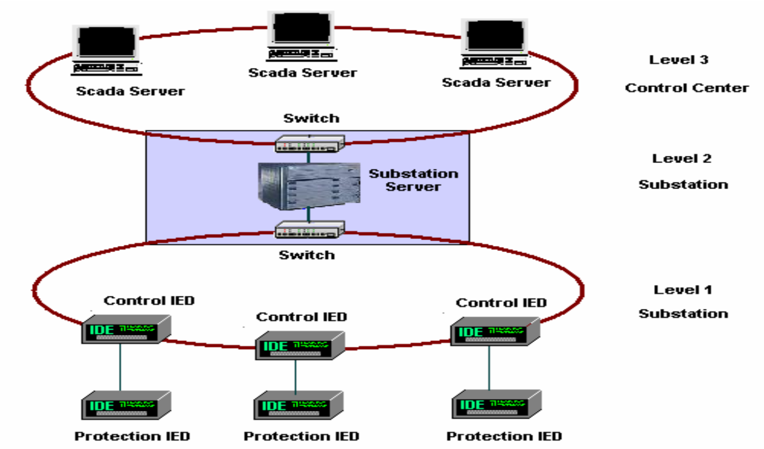

Figure 2.5 Substation Communication Network

2.6 Real Time Data Communication and Exchange

Currently the largest segment of traffic come from applications based on the suite of transmission control protocol/user datagram protocol/real time protocol/Internet protocol/HTTP (TCP/UDP/RTP/IP/HTTP) protocols [67][69][70], or commonly referred to as IP protocol. Therefore, IP protocol is clearly the convergence layer in today's data communication network, and it is no doubt that it will expand this role to multi-service network in the near future. IP based data can be transported over a broad variety of data link layer protocols and underlying networking infrastructures. IP based protocol such as TCP/UDP can be used for real time information transmission through network. IP protocol has been introduced in many books and document, we just briefly introduce the most commonly used two protocols based on IP: TCP and UDP.

2.6.1 ISO-OSI Network Architecture

In order to set up a common way to connect computers, ISO (International Standard Organization) formally defined well-know 7-layer network architecture called Open Systems Interconnection (OSI) architecture. The 7 layers [67][69] are: Physical Layers; Data Link Layer; Network Layer; Transport Layer; Session Layer; Presentation Layer; Application Layer. However, as illustrated in Figure 2.6, four-layer Internet architecture is commonly used instead.

- Network layer performs raw data transmission. This layer is implemented by a combination of hardware (NIC-Network Interface Card) and software (NIC driver). Commonly used networks such as FDDI and Ethernet are defined in this layer.
- IP layer consists of Internet Protocol to support multiple interconnected networks into one logical network.
- TCP/UDP layer contains two most commonly used IP based protocol TCP and UDP to provide logical channels to application program.
- Application layer supports user-defined applications.

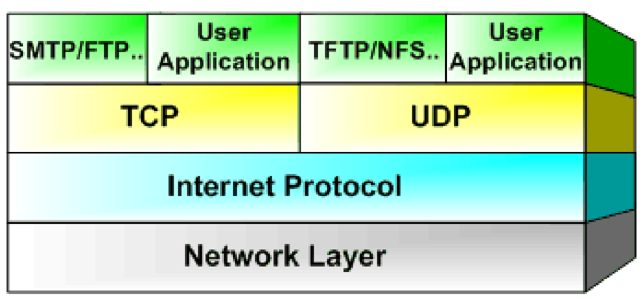

Figure 2.6 Internet Architecture

2.6.2 IP, TCP and UDP

IP [67][69][70] or Internet protocol operates as a network layer protocol responsible for routing, addressing, and package delivery. Like most network layer protocols, IP does not handle assured delivery, package division and sequencing, or error correction.

UDP [67][69][70] does not add much service to the underlying IP protocol. It simply provides a method for sending packets of data called datagrams. The order and arrival of data are neither important nor guaranteed, and each datagram is independent of any other datagrams. UDP is normally used for non-critical and large volume data transmission like stream audio and video.

TCP [67][69][70] adds reliability facilities to the to IP protocol such as error detection and correction; flow control; re-sequencing; duplicate segments management; TCP offers connection-oriented, byte-stream service to the data transmission. These features are very important for power system data transmission, since when data sent to the control center or a command is issued through the network, each bit in a datagram will be very critical for the correct information interpretation.

2.7 Metadata Exchange Using XML

2.7.1 XML Implementation for Metadata Exchange

Power industry becomes more and more complex, variety of data transmission platforms and formats makes information exchange between user to vendor and vendor to vendor a difficult task. XML helps to establish a common standard format for data exchange. Figure 2.7 shows XML-based client/server architecture for future power system data exchange. The system contains the client sites and XML server site.

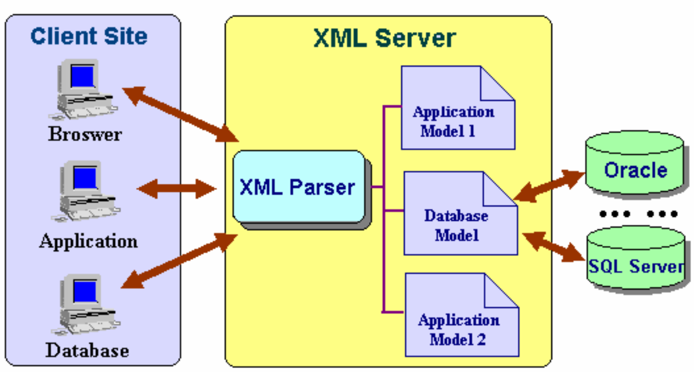

Figure 2.7 XML Server Structure

XML server acts as the mediator between different power utility databases or data source. Server receives XML-tagged requests from the client site browser, and processes this request with other applications within the server using its own data format. Then the database queried results are converted as DOM structure by server before it is returned to the clients/users. Generally, the primary capabilities of this simple prototype include supporting on-line power market transactions; seamless data exchanges between power utility databases or clients/users as well as distributed processing.

From the perspective of data exchange, the process of utilizing the prototype system for performing statistical analyses on the transaction data or information exchange between databases are similar to each other. The difference lies mainly among the associated client/user and definitions of DTD/XML schema and XML tags.

Different utilities usually have different protocols for the data exchange. Thus, their DTD/XML schema definitions and employed XML tags will be different. The following codes illustrate a distributed processing application. Application A needs to query the historical data stored in several utility databases for the post-fault analysis. It can send the following XML file to each utility database.

```
<?xml version =”1.0” ?>
  <XMLServer>
    <Login>
      <ParamName = “userlogin” />
        <LoginURL =”http://www.powerit.vt.edu/login”
          UserID=”Userid”
          Password=”password”
       </Login>
      <Query Database=”Fault Record Database”
        sql=”select Time, Path, duration, VoltageLevel, FaultType, FaultLocation from
FaultRecordTable where Date=06/18/00” />
</XMLServer>
```

This XML document, marked up with the XMLServer tag, consists of two sub-elements:

- Login: Defines user login information.
- Query Information: Gives the SQL (Structured Query Language) statements needed to execute in the remote database. This statement tries to receive the fault recorder information.

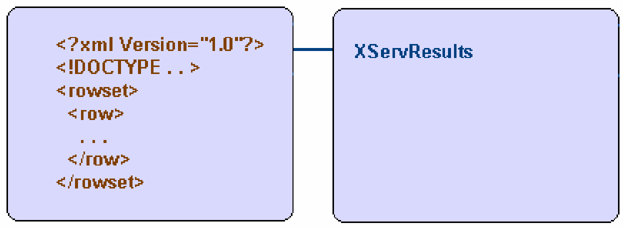

Figure 2.8 Query Result XML Document

Utility server gets this request, after the user status authentication, it will convert the XML tagged information into SQL statement, run the query and get the results. The query result is also represented as an XML document. The following document shows the query result that is obtained by applying the query in the XML-tag file. The result is represented by the results element that contains multiple row elements, each of which corresponds to a record. Figure 2.8 shows the XMLServer searching results and its XML-tagged document.

```
<?xml version =”1.0” ?>
  <!DOCTYPE rowset>
   <!ELEMENT row (Time, Path, Duration, VoltageLevel, FaultType,
FaultLocation)>
   <rowset>
     <row>
       <Time Value=”8:01AM” />
       <Path Value=”BPR A--B” />
       <Duration Value=”12 seconds” />
       <VoltageLevel Value=”66kV” />
       <FaultType Value=”Phase A Ground” />
       <FaultLocation Value=”15 miles A East” />
   </row>
   <row>
```

<Time Value==”11:06PM” />
<Path Value==”DTA South Line” />
<Duration Value==”1 hour” />
<VoltageLevel Value==”220kV” />
<FaultType Value==”AB Ground” />
<FaultLocation Value==”3.5 miles DTA South” />
</row>
<XServ>

In this case, post-fault analysis application does not need to know the data format of utility database. After post-fault analysis application gets the transaction information, it can parse the data in the XML-tag and do the analysis.

2.7.2 Security Issues

XML is implemented in text form, and it is ideal for serving the dual roles of both man-to-machine and machine-to-machine interface. However, security is a problem in this case. Therefore, several security requirements needed to be implemented.

Firewall: Firewall [71] needs to be employed for the server to minimize the possibility that unauthorized users to access or modify any critical or sensitive information. Interfaces through public data network or the Internet will be permitted as long as these security requirements are met.

Data Encryption: Sophisticated data encryption techniques [71] such as 128-bit encryption algorithm can be used to transfer sensitive data across the Internet.

2.8 Summary

Progress in data communication and network technologies have always benefited the field of power system engineering. New protection and control technologies being implemented in power systems provide improved defense against system disturbances.

Future power systems require wide-area monitoring, protection and control systems. This section describes different information technology applications in power system information communication network design. IT technologies will have significant positive effects on the power system information exchange and lead to enhanced data cataloging and archiving. Reliable and secure access to wide area system data is a key to the implementation of many newer protection and control strategies being developed at this time.

Chapter 3 Web-based SCADA Display System

SCADA systems are essential parts of the DMS and EMS. A SCADA system gathers real time power system data for further processing by a number of distributed applications. The control commands for operating a power system can also be issued through the SCADA system. Power system deregulation brings numerous changes in the SCADA/DMS/EMS system. One of the changes requires that the EMS exchange information with external organizations such as utilities and power market brokers. Some information are time critical and needed on a dedicated basis, while others are not. However, they all require quick access and data security. The rapid development of IT technologies such as Internet, distributed computing support the solution for anytime, anywhere, any type SCADA information exchange. This section describes and demonstrates an Internet-based application in the substation automation system, which is implemented based on the existing SCADA system, VLSI and Information Technologies. The user can access the real-time information superimposed on one-line diagrams generated automatically using the VLSI's placement and routing techniques through the Internet. In addition, the user can also control the operation of the substation at the server site through Intranet. The choice of the Java technologies like JNI, RMI, EJB offers unique and powerful features such as zero client installation, on-demand access, platform independence and transaction management to the design of the on line SCADA display system.

This chapter consists of two sections: first section demonstrates an implementation of advanced IT technologies into existing SCADA system; an advanced application – one line diagram auto-generation using VLSI design technologies will be introduced in the second section.

3.1 Introduction

Information technology (IT) plays an increasingly important role in all fronts. In the deregulated environment, information has become the key component to secure power system operation, profitability; satisfy customer requirements; keep market advantage and power industry growth.

SCADA systems [4][14] are essential parts of the DMS and EMS [73] for incoming data acquisition and control commands execution for proper power system operation. The major components of a SCADA system are:

- Substation remote data acquisition, metering, control unit such as RTU (Remote Terminal Unit).
- Data processing unit such as IED or substation server.
- MMI (Man Machine Interface) and center data processing unit installed in the control enter.

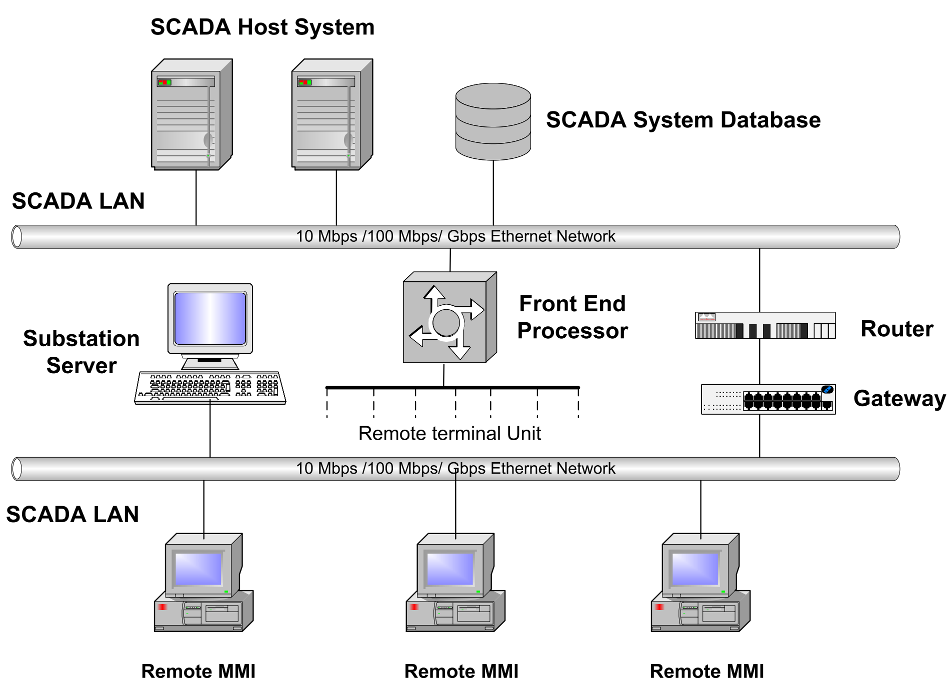

Figure 3.1 Typical SCADA System Architecture

A possible SCADA system architecture is shown in Figure 3.1. Traditionally, SCADA communication systems are established mainly for internal utility information exchange, especially for monitoring and control. Low communication bandwidth, multiple operating systems, incompatible data formats and standards isolated and hampered the large-scale information exchange and interoperation. Information sharing among different utilities or even individual divisions of the same utility is difficult, complex, and sometimes impossible.

Deregulation results in open access and consolidation, pushing for extensive internal and external utility information exchange, integration and dissemination. External company data communication and integration from various information sources such as control centers, power plants, and substations, have become necessity. With more and more real time information has now become desirable by many customers and vendors, existing information management systems cannot satisfy the new challenges. Distributed SCADA/EMS has already become the trend of the future power system development.

Internet/Intranet has been successfully employed in many areas for real-time applications such as audio stream, videoconference. Internet-based SCADA system was also introduced [21] into power system. Several prototype and products have been introduced for on line SCADA application [74] [75]. However, most of the existing SCADAs were set up based on the conventional computer technologies. An important challenge is how to integrate new services and network elements to the existing system. In this section, we will describe an Internet-based information accessing system based on an existing SCADA system.

3.2 SpecNET – Integrate SCADA with Internet

Siemens Spectrum [76] is a distributed network based SCADA/EMS/DMS software package. It is used as the major monitoring and control system that supports real time information acquisition and advanced EMS applications. Spectrum was developed in C/C++/Pascal and was designed to run on UNIX operating system, Integrating Spectrum software with the advanced network technologies means a redesign of the whole system – a process which is difficult and inefficient.

Facing this challenge, a system prototype named SpecNET is developed. SpecNET is an implementation of multiple client/server architecture that models, coordinates, and integrates some of the SCADA functions such as one-line diagram generation and real-time data display. Figure 3.2 describes the three layers SpecNET architecture.

- Internet/Intranet users can access the SCADA system data through the SpecNET server.
- JavaCON, which stands for Java connectivity to SCADA, is used as a data communication bridge between the existing SCADA system and the SpecNET server.
- The SpecNET server receives messages from the existing SCADA system through JavaCON and provides the necessary support for Internet users. Useful information will be saved to the database through the connection between SpecNET server and database server.

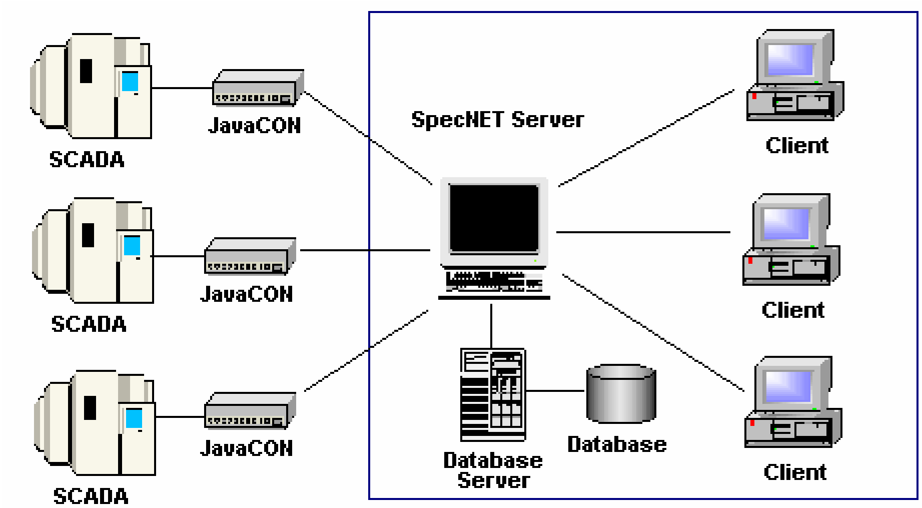

Figure 3.2 Main Configuration of SpecNET

3.2.1 SpecNET Server

As the global Internet continues to grow, Java [77][78][79] is uniquely suited to build the next generation of network applications. SpecNET server is developed in Java to fit for the multiple platform requirements. The functions of the SpecNET are to manage recourses needed to support online services of the SCADA system. As shown in Figure 3.3, the server supports: JavaCON function, Client function, MMI function and Database operation.

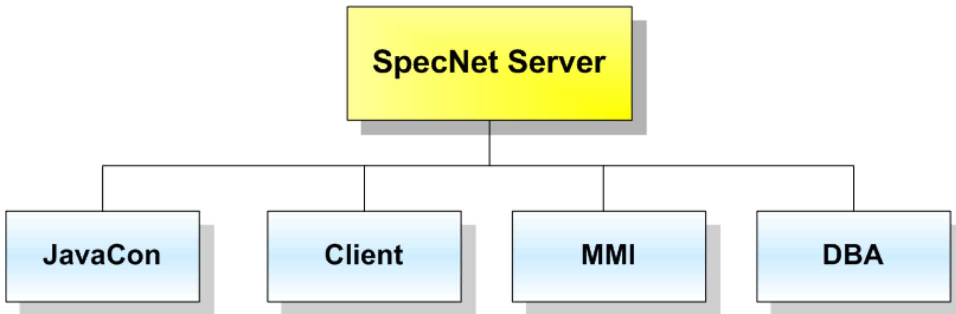

Figure 3.3 SpecNET Server Function

3.2.2 JavaCON - Interface to SCADA Server

Currently, existing SCADA systems are developed based on different platforms using different languages. Spectrum was coded in C/C++. JavaCon acts as a bridge between the existing SCADA system and SpecNET server through JNI (Java Native Interface) connection. JNI [80] provides Java code that runs within a Java Virtual Machine (VM) to operate with applications and libraries written in C, C++, and assembly languages. JNI is used when the SpecNET server wants to talk to the SCADA server. Figure 3.4 shows how the JNI ties the SpecNET server site applications to the SCADA server [80].

JavaCON consists of both C code and Java code at the SpecNET site. SpecNET C code site contains Function and Library modules. The Function modules are coded using SCADA Server API (Application Program Interface). Therefore, they can talk to the SCADA Server kernel program like native components to get the raw data; talk to database to retrieve real-time information. The Library modules are used to define the corresponding methods. The SpecNET Java site contains Virtual Machine (VM), classes and Exception modules. VM can locate and invoke native methods on the SpecNET C code site and acts as a bridge communicating directly with the Spectrum. Classes define the actual methods. The Exception module is used to handle the exception case during the communication.

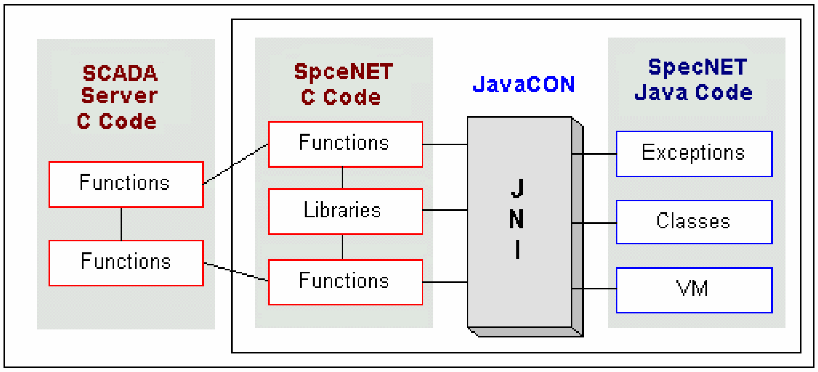

Figure 3.4 JavaCON JNI Structure

3.2.3 Java and Network Programming

Java is a programming language designed to fit for the next generation of network applications requirements. The level of safety with Java applets (programs which adhere to a set of conventions that allow them to run within a Java-compatible browser) for network programming is far greater than what can be obtained from other software. Java makes writing networking programs easier [83]. It is relatively straightforward for Java applications and applet to exchange data across the Internet, limited only by security restrains.

Java is portable and platform-independent. Traditionally, software developers had to work with a specific native instruction set which locked them into a specific hardware and operating environment. Different from other programming languages, Java executes in a run time environment called a virtual machine. The Java virtual machine executes bytecode (platform independent code) that a Java compiler generates and it can be incorporated or embedded in Web browsers (such as Internet Explorer or Netscape), or the kernel of the operating system. Java virtual machines and Java APIs insulate the Java program from hardware dependencies. Therefore, Java's bytecode can run on a wide range of platforms, much larger than other languages would allow. The Java bytecode helps make the "write once, run anywhere" possible.

3.2.4 Client/Server Communication

The evolution of distributed computer architecture results in the birth of the client/server architecture [83]. The client/server structure provides the scalability and robustness required to support mission-critical applications throughout the enterprise. In the SpecNET system, communications between the SpecNET server, SCADA server and customers are setup based on the client/server architecture. Two methods are used for the communication: Java Remote Method Invocation (RMI) and socket communication.

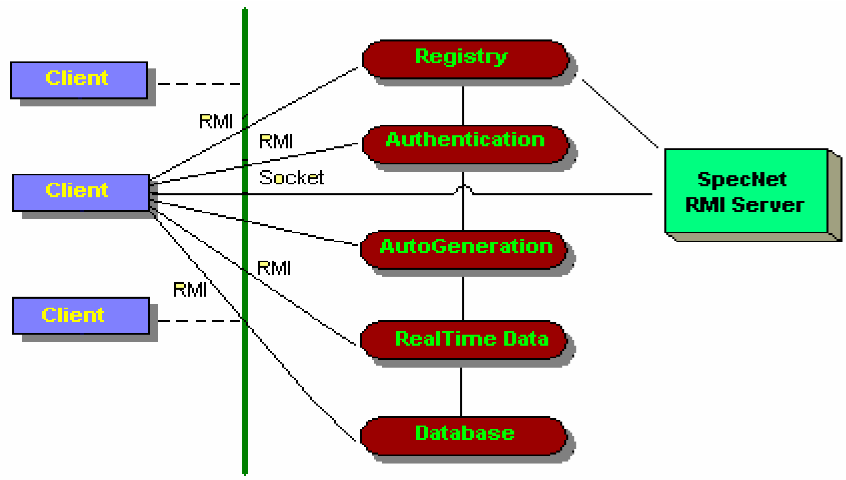

Figure 3.5 Java RMI Architecture

The RMI [84] system allows an object running in one Java Virtual Machine to invoke services or functions on objects running in another Java Virtual Machine. RMI provides the mechanism for free and easy server and the client communicate and information exchange. SpecNET RMI implementation comprises two separate programs: RMI server and RMI client. RMI server creates remote service objects, makes references accessible, and waits for clients to invoke methods on these remote objects. RMI client gets a remote reference to one or more remote objects in the server and then invokes methods on them. Figure 3.5 illustrates the SpecNET RMI distributed applications that make use of the registry to obtain a reference to a remote object. SpecNET RMI server calls the registry to associate (or bind) a name with a remote object. The client looks up the remote object by searching its name in the server's registry and then invokes a method on it. SpecNET RMI server objects include user authentication, database operation, one-line diagram auto-generation etc. The SpecNET server will take requests from clients, runs them, and returns any results.

When a remote client connects to the SpecNET server, it can access the public information immediately. For the confidential information, the SpecNET server redirects the client requests to the user authentication object asking for user name and password, and then allocates user to the different objects according to the user access level. When the user wants to see the substation auto-generation one-line diagram, the SpecNET server will run the JNI communicating with the SCADA server; gathers the one-line diagram raw connection information from the SCADA server and generates the one line diagram. Final layout will be sent to the client for display. After that a socket connection will be set up between the SpecNET server and client site. The real-time analogue data, breaker status information, transformer taps will be transmitted from the SCADA system to the client site. Multi-Threading is used to process multiple client requests. A thread will be set up to process the data transmission when a client activates a connection to the SpecNET server.

3.2.5 Main Machine Interface (MMI)

MMI provides a means for utility operators, planners and higher management to access the SCADA system real time data. When the user accesses the SpecNET server, a security mechanism is triggered to allow only the authorized user to view the SCADA information. The functionality of the MMI, for most of the time, is only limited to viewing the overall picture of the system being monitored. People accessing MMI do not take active part in controlling the system. The MMI at the client site has the same graphical user interface as that of the server site. This design enables the user to view the details of the substation conveniently.

SpecNET server also supports full graphical editor functions. Within a substation, components can be manipulated and edited via the mouse and keyboard. The applicable manipulations are select, drag and double-click. Multiple objects may be selected and the object's attributes may be altered via pop-up dialogs. Users can choose the component symbols from the library or design their own. Component properties may be edited by double clicking the mouse on the respective component, which in turn calls up a dialog box. Panning and zooming are also supported when viewing the details of a network or a substation.

At the server site or within the Intranet, control may be issued to open or close breakers through the one-line display. After the SCADA receives the command, the display will reflect the updated status of the breaker.

3.3 Database Operation

The SpecNET database stores the static and dynamic data of the SCADA system. Most of the databases can be used for storing historical data with JDBC/ODBC [85] driver. It provides a convenient data accessing mechanism on the server. The historical data consists of logged data, events and dynamic data of one-line diagrams. The system status and the real-time data are stored in the database at a periodicity specified by the user. Access to the database is provided through a series of interface modules that read and write data to the database tables.

The database operation on the server site is through RMI and JDBC. JDBC is a Java API for executing SQL statements. It lets the Java program send SQL statements to the appropriate database. Four steps are executed before using the JDBC API to access the database:

- Import the JDBC classes;
- Register JDBC driver;
- Open a connectivity to the database
- Query the database.

3.4 EJB-based System Design

SpecNET as a service provider provides services sent to the on line SCADA server. Due to the rapid increase of software programs in size and complexity, it is very important to reduce the high software cost and complexity while increasing reliability and reusability and extensibility. With the advances of Internet technologies, more distributed systems are built to meet diverse application needs. EJB [86][87] provides low-level services such as support for transactions, concurrency, persistence, security and life cycle management for each service. Therefore, the EJB technology is a good choice for SpecNET system design to achieve better performance. Figure 3.6 illustrates the EJB-based SpecNET architecture.

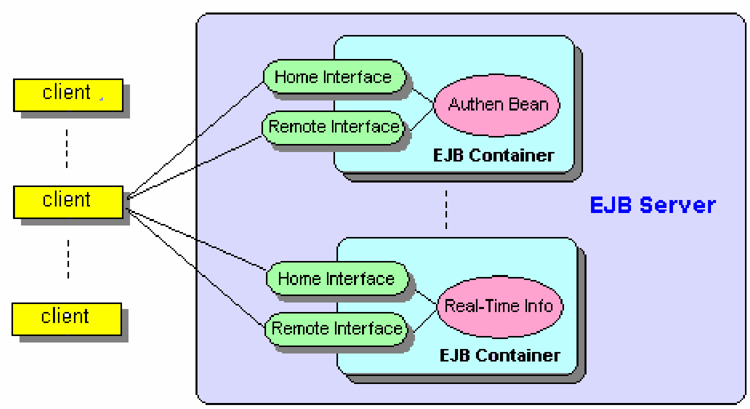

Figure 3.6 EJB-Based SpecNET Architecture

The EJB-based SpecNET server is used to management resources needed to support EJB container. An EJB container runs within the EJB server and provides a scalable, secure and transactional environment in which EJB beans operate. Enterprise beans are server-side Java objects that talk to the SCADA server or database.

A client obtains a reference to a bean by looking up the bean's registered names in the JNDI (Java Name Directory Interface) naming service. Then client talks to beans through home and remote interfaces. The EJB framework offers two types of enterprise beans: session and entity beans.

A session bean [87] is a non-persistent object that operates exclusively on behalf of the client session that creates it. The session bean does not share among multiple clients. Client authentication is a typical example of the session bean. An entity bean typically represents specific data or collections of data in persistent storage, such as shared information. Real time information display can be designed as an entity bean.

3.5 System Security

Some of the most potentially valuable developments in the high-speed technology resolution are Internet, Intranet and Extranet that connect electric utility companies via applications directly to external organizations such as their customers, distributors, brokers and strategic partners. Information exchange and manipulation have different performance and security requirements. Together they will determine the type of networks used for communication and how to set authority. Three access levels will be used for the SCADA system:

- Intranet level.
- Extranet level.
- Internet level.

Intranet Level: Security is [71][71] typically less of a concern for the Intranet level because Intranet applications are deployed within the company firewall. Performance of the Intranet is limited only by the speed of the enterprise local area network. Currently, the scalability of Ethernet is well defined at 10/100 Mbps with the 1/10 Gbps Ethernet on its way. High performance Ethernet technologies can fully meet the Intranet data transmission and time latency performance requirements.

Extranet Level: Extranet applications extend the Intranet architecture beyond the firewall by allowing the information access over public network. Data security at this level could be protected by firewall, cryptography, DC (Digital Certificate), and PKI (Public Key Infrastructure) [71]. Performance of Extranet is more of a concern since inter-network data transmission delays must be considered. However, Extranet is almost always connected via high-speed leased lines and is therefore less susceptible to the bandwidth limitations.

Internet Level: At the Internet level, the requirements for information exchange should be less critical in terms of performance and security. Transaction security can be ensured by using secure hypertext transfer protocol (HTTPS) [71] for web information exchange, the technology already supported by many web browsers. Data security technologies of Extranet such as DC or PKI can also be used at the Internet level.

3.6 One-Line Diagram Auto-Generation

With the power system becomes more and more complex. One-line diagram layout [86] is becoming increasingly complex and in turn is placing even higher demands on one-line diagram auto-generation tools. This section will introduce a new one line diagram automatic layout algorithm. VLSI placement and routing algorithms are used for the substation one-line diagram auto-generation. As shown in Figure 3.7, the auto-generation of the one-line diagram contains four steps: stream input Data, placement, routing and dynamic data linkage.

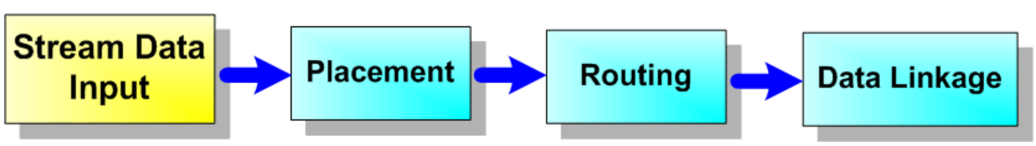

Figure 3.7 Process Involved in One-Line Diagram Generation

3.6.1 Stream Input Data

The stream input data contains the connectivity information of the substation network. The data items include the component's names, start and end nodes, component ratings and modeling parameters. When the data is read in by the auto-generation module, a substation topology will be created according to the connectivity of the components. The topology is then ready to be accessed by the placement and routing modules.

3.6.2 Placement

Component placement determines the location of the component within the one-line diagram. It distributes the nodes of components evenly in the frame. Better placement will have the minimum length of interconnection with minimum line crossovers. Placement is crucial in the overall design cycle as its output must be routable. The overall quality of the layout is determined in this stage.

In this thesis, the Force-Directed [89][91][92] method is used for the placement of power components. The method models the graph as a physical system of rings and springs. In this context, rings represent the vertices in a graph and springs represent the edges of a graph. Repulsive forces are calculated between every pair of vertices, while attractive forces are calculated only between neighbor vertices. Force-Directed method treats the placement problem as a process of reducing the total energy for a system of steel rings interconnected by springs. By minimizing the summary of compression or tension on all the springs, the rings would be most likely at their ideal distances from one another. The energy of the system state is:

$$\sum_{1\le i<j\le n} k_{ij}\left(\left|V_{pos,i}-V_{pos,j}\right|-l_{ij}\right)^2 \qquad 3.1$$

where i and j are vertex numbers; n is the total number of vertices; $V_{Pos,i}$ and $V_{Pos,j}$ is the position of the ring corresponding to vertex V_i and V_j; K_{ij} is the spring constant for the spring between $V_{Pos,i}$ and $V_{Pos,j}$; l_{ij} is the optimum distance between vertices V_i and V_i. In a fixed frame of width W and length L, the area of the frame is

$$area = W\,x\,L \qquad 3.2$$

And the optimal distance between the two vertices is:

$$l_{ij} = \sqrt{\frac{area}{n}} \qquad 3.3$$

Equation 3.3 provides the ideal distance between vertices since the two forces would exactly cancel each other. We define F_a and F_b to be the attractive and repulsive forces respectively and d is the distance between the two vertices, then, we can get:

$$f_a(d) = d^2 / k \qquad 3.4$$

$$f_r(d) = -k^2 / d \qquad 3.5$$

In a graph, for each vertex V_i, it has two position vectors: $V_{Pos,i}$ and $V_{Disp,i}$, where $V_{Pos,i}$ is V_i's position and $V_{Disp,i}$ is V_i's displacement departing from its initial position. When the placement algorithm starts, the vertices are assigned in random initial positions. The locations of vertices are constantly updated according to the attractive and repulsive forces among the vertices.

To finalize the vertex layout in a graph, iteration is used to optimize the vertex position in each step. There are four steps in each iteration.

1. Calculate the effect of attractive forces on each vertex. In this step, the attractive force will be calculated between two vertices V_i and V_i with a direct connectivity line.

$$V_{Disp,i} = V_{Disp,i} - (\Delta / |\Delta|) * f_a(|\Delta|) \qquad 3.6$$

$$V_{Disp,j} = V_{Disp,j} + (\Delta / |\Delta|) * f_a(|\Delta|) \qquad 3.7$$

Where $|\Delta|$ is the distance between two vertices in a connectivity line.

$$|\Delta| = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \qquad 3.8$$

$$\Delta = V_{Pos,i} - V_{Pos,j} \qquad 3.9$$

2. Calculate the effect of repulsive forces on each vertex. The repulsive force will be calculated between any two vertices V_i and V_i.

$$V_{Disp,i} = V_{Disp,i} + (\Delta / |\Delta|) * f_r(|\Delta|) \qquad 3.10$$

3. According to the effects of attractive and repulsive force calculated in step 1 and 2, modify the position of a vertex.

$$V_{Pos,i} = V_{Pos,i} + V_{Pos,i} / |V_{Disp,i}| \qquad 3.11$$

4. The energy of the system state will then be calculated using equation 3.1. The iteration will continue by returning to step 1 and until the energy falls below a preset threshold. At that time, the position of each vertex will be determined.

The optimal positions of vertices determine the vertex placement of the one-line diagram. Figure 3.8 shows the layout result of how the vertices of a sample system are placed using the Force-Directed method from scratch.

After placement, the layout also need to satisfy some general accepted aesthetic criteria, some adjustments are still needed to make it more fitful for the requirements of the substation one-line diagram. For example, the transformer and its related breakers should be at the same x- or y- coordinate. Different sections of a main bus in a substation should be at the same x-or y-coordinate. If needed, the operator can also use the mouse to manually modify the final layout according to each individual taste.

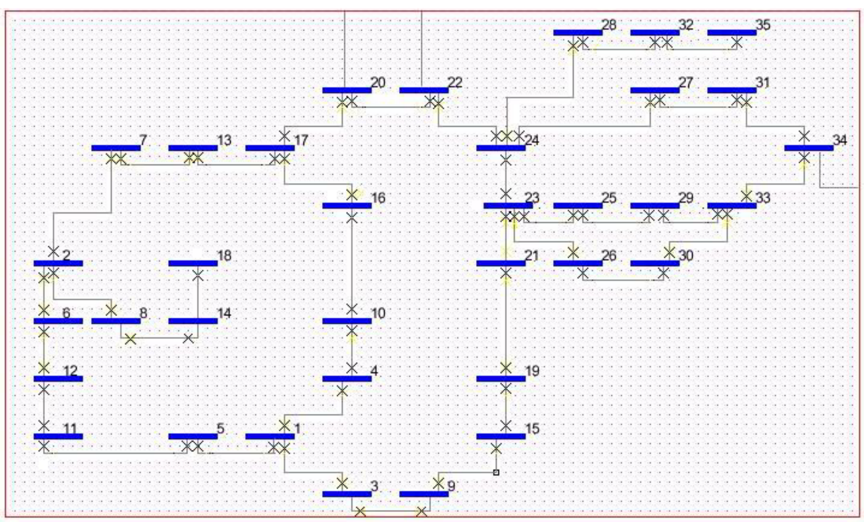

Figure 3.8 Diagram of Force-Directed Placement of a Sample System

3.6.3 Routing

After placement, the diagram is ready for the routing. In this section, the Hightower algorithm is chosen. Hightower method does not store the entire grid in its memory. Instead it only stores lines. So it executes faster and has a lower memory requirement than that of Lee and Maze algorithms [92][93]. To fit for the power system requirements, some modifications were added to the Hightower algorithm to make it more efficient in route searching.

Figure 3.9 [93] shows a diagram routed using the modified Hightower algorithm. The dashed lines represent projected horizontal and vertical lines while the solid lines represent existing blockades in the routing area. A blockade is defined as the cover of a point on the routing surface if any horizontal or vertical lines projected from the point intersect the cover. An escape line is a horizontal or vertical line passing through the point. An escape point is a point on the escape line which has at least one side not obstructed by any blockade or borders. Otherwise the new escape line from this escape point cannot be projected. Points B and C are the source and target respectively. Lines V, W, X, Y and Z are blockades. Points A, D and E are escape points. Lines e, f, g, h, i, j, and m are escape lines. Point F is the intersection where two escape lines meet.

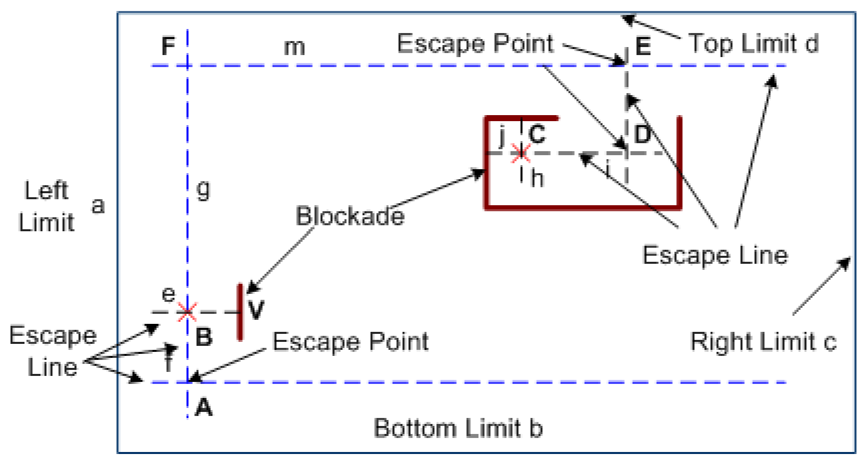

Figure 3.9 Hightower Routing Method

In Figure 3.9, escape lines e and g are projected from source point B. Escape lines h and j are also projected from target point C. Escape lines e, h, and j encounter boundaries or obstacles. Only escape line g has escape point F, which can connect to the target point. D is a escape point along escape line j from target point C. Escape point D connects to E, a escape point along escape line i. From escape point E, escape line m meets escape point F. Thus the source and target connect with each other.

The basis of line routers is to project horizontal and vertical lines from both the source and target points on the routing surface. These lines are projected as far as possible. If during the line projection process, two lines from the two different points intersect, then a connection is found. On the other hand, if an obstacle is encountered or the edge of the routing area is reached, a new escape point is chosen along the current line. New horizontal and vertical lines are projected from the escape point. This process continues until a connection is made.

The original Hightower algorithm stores every occupied point in the cell array. The cells with fixed vertices are called occupied cells. When the search line expands from the source or target point, it must compare to each occupied cell stored in the array. If the grid is large, this comparison is very time-consuming. In the modified algorithm, a block of occupied cells are stored as a line. When the search line expands itself, it only compares with the start and end points of a line to decide whether it hits the obstacle or not. The main algorithm expands the horizontal and vertical lines from both the source and target points to find the connectivity. When the connection is found, the Retrace module is used to find the lines composing horizon and vertical connections. It then stores the lines into the occupied cell array and draws the lines on the screen.

One of the disadvantages mentioned using Hightower line routing is that an earlier connection tends to block those that are to be routed later. This problem could be mitigated by routing the paths according to some order priorities [93]. In this method, the algorithm modifies the connections according to the area of rectangle formed by the line. As illustrated in Figure 3.10, S1 to S4 are four source points, and T1 to T4 are four target points. A pair of source and target points forms a rectangle area. The priority of the connectivity is weighted according to the number of points included in the rectangle area. The more the points included in the rectangle area, the lower the priority is. In Figure 3.10, the S1-T1, S2-T2, S3-T3, S4-T4 pairs contain 5,3,1,0 point(s) respectively and thus their weights are 5,3,1,0 respectively. So the S4-T4 pair will be routed first, followed by S3-T3 and S2-T2 pairs and finally the S1-T1 pair.

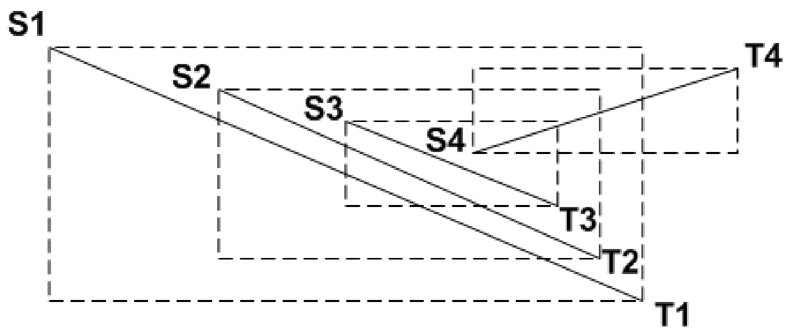

Figure 3.10 How Priority of Connectivity is Determined

The sample system in Figure 3.8 is processed using the Hightower routing method discussed above. After routing, the final layout can be obtained.

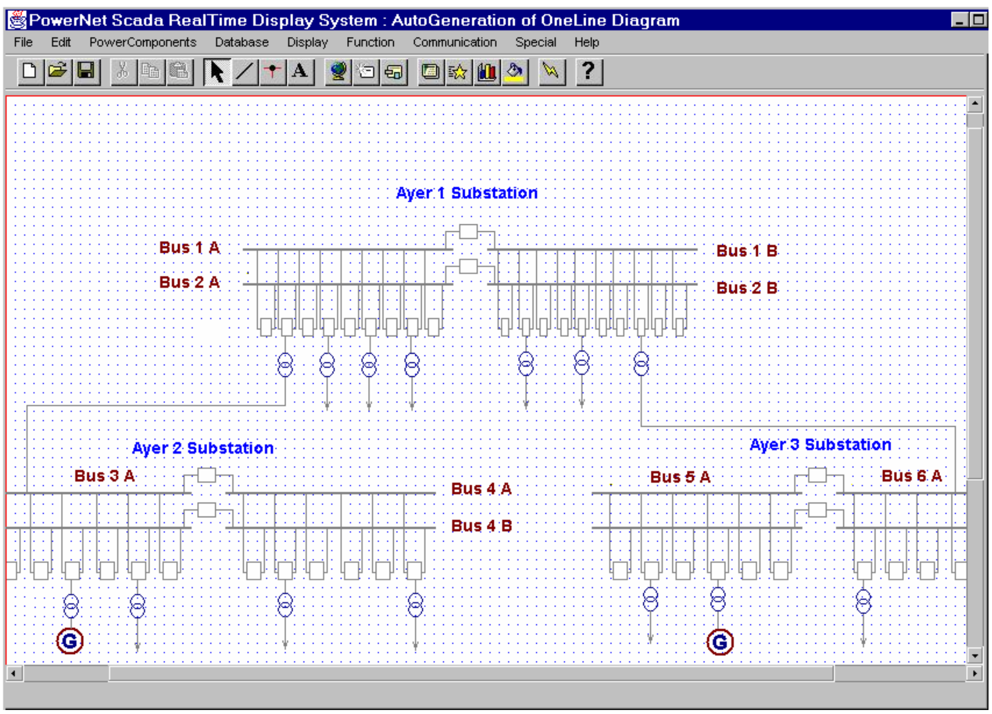

Figure 3.11 Final Layout of One-Line Diagram After Routing

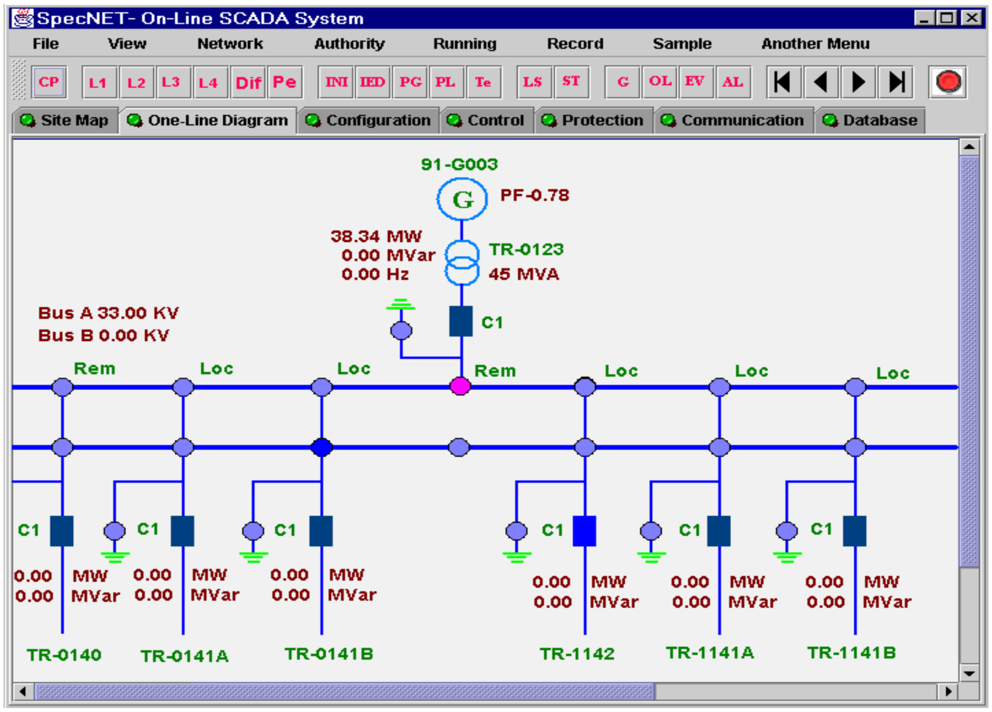

Figure 3.12 Detail Substation Layouts

3.6.4 Dynamic Data Linkage

The SCADA system data will be dynamically linked to the static one-line diagram after routing. The real time information such as real and reactive power (MW/MVar) and/or voltage/current measurements, running status of the power system components will be linked to the SCADA server and displayed at the position close to each individual component. After each time interval, real time data will be retrieved automatically from the SCADA server and updated on the one-line diagram.

3.7 Summary

SCADA systems are essential parts of the DMS and EMS. Power system deregulation brings challenges and numerous changes to the SCADA/DMS/EMS system. One of the changes requires the integration of the existing SCADA system with advanced IT technologies. This chapter described a Web-based SCADA accessing system designed for the Internet. The implementation of the advanced IT technologies such as object-oriented design, client/server module, Java language brings great flexibility to dynamically interact with the SCADA system.

Currently, the generation of one-line diagrams for SCADA/EMS/DMS applications is done manually. The process is tedious, time-consuming and error-prone. This chapter also presents a method to auto-generate the one-line diagrams based on the placement and routing algorithms proposed for the VLSI design. The method can read in the power system network data and automatically generate the one line diagram. The system has been partially implemented into SCADA software package.

Chapter 4 Local Area Network based Load Shedding Controller

Power systems in running conditions could suffer from different kinds of contingencies. Such emergency conditions could be loss of generation, under frequency, low voltage or oscillations. Due to the system complexity and corresponding static and dynamic problems involved, they are difficult to operate and control. When power system experiences big generation loss, such as loss of a tie line or a major generation unit trip, the whole system frequency may decay and even collapse if the total spinning reserve can not compensate for the generation loss sufficiently [94][95].

To serve as emergency frequency drop protection, load shedding scheme is designed and activated at different frequency levels to shed pre-selected and fixed amount of loads. However, due to the power system complexity, different system running conditions and dynamic performance variation, the load shedding amount is difficult to predict and may not match the generation unbalance. The frequency could continue to drop due to under load shedding, or the frequency would jump up due to over load shedding.

Isolated power system and large interconnected power system have different system structure and also have different frequency response characteristics (FRC) to the generation loss. Therefore, they have different requirements for the load shedding design. In Chapter 4, we will analyze isolated system frequency response characteristics and different load shedding schemes. Based on the analysis, we will present a local area network based load shedding controller. Its actual site implementation will also be described. In Chapter 5, we will concentrate on wide area frequency response characteristics for large generation unit loss and corresponding load shedding approaches. A load shedding scheme for large interconnected system using PMU and real time tie line power flow information will also be proposed.

4.1 Introduction

An isolated power system is a relatively independent power system. It normally has limited spinning reserves and also has few or weak link with other power systems to exchange power. It must be self-sufficient to ensure system security and reliability [95][96]. Major generation unit outage in the isolated power system will easily cause the system frequency collapse or even blackout. Therefore, load shedding becomes extremely important strategy to restore system frequency and maintain system stability. More careful design of load shedding scheme is required than a large interconnection system to response to the emergency situations and act as quickly as possible in order to achieve fast system recovery with minimum system disturbance.

Load shedding happens when generation deficiency occurs. The frequency response characteristics of an isolated system can be modeled using Figure 4.1 [96].

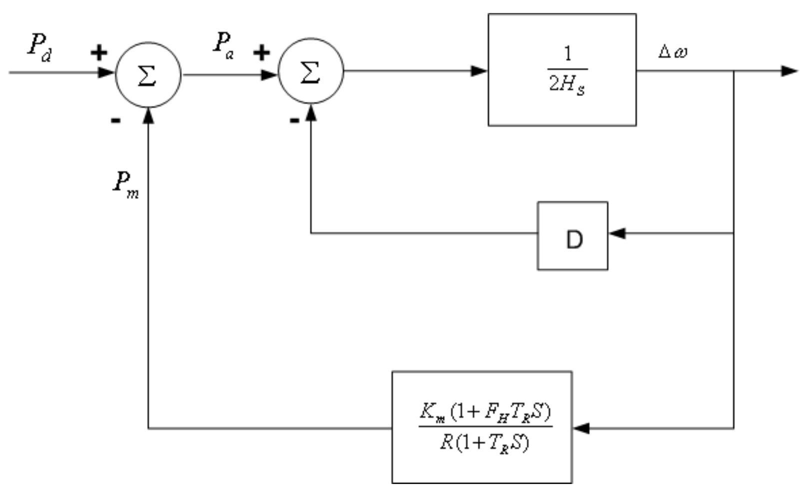

Figure 4.1 Isolated Power System Frequency Response Characteristics

In the figure, P_m is the system mechanical power; P_a is the system acceleration power; D is the system damping factor, H is the inertia constant of the island system; T_R is the average reheat time constant; and F_H is the high pressure power fraction of the reheat turbines. All the system parameters are estimated based on the system design. We can calculate the system frequency response by using

$$\Delta\omega = (\frac{R\omega_n^2}{DR + K_m})(\frac{(1+T_R s)P_d}{s^2 + 2\varsigma\omega_n s + \omega_n^2}) \qquad 4\text{-}1$$

Where

$$\omega_n^2 = \frac{DR + K_m}{2HRT_R} \qquad 4\text{-}2$$

$$\varsigma = (\frac{2HR + (DR + K_m F_H)T_R}{2(DR + K_m)})\omega_n \qquad 4\text{-}3$$

From the analysis, we can see isolated power system frequency response is complex and has different dynamic characteristics involved. For large interconnected system, spinning reserve is intended to compensate for generation loss within tens of seconds to several minutes. However, isolated system does not have much spinning reserve to compensate the generation loss. Therefore, load shedding schemes must accommodate a much wider band of frequency deviations. At the meantime, more actions need to be taken to avoid unacceptable frequency excursions. Therefore, load shedding controller needs more careful design in the isolated power system.

4.2 Literature Review

Different algorithms are used in the isolated power system to restore the system operating frequency after serious disturbances. Such frequency protection strategies can be under-frequency load shedding scheme or change of rate of frequency scheme [97][98]. Following sections list several commonly used load shedding approaches.

- Under frequency load shedding Scheme

  Large power system disturbance will cause frequency decline. Under-frequency load shedding scheme is set to activate based on the preset frequency value to shed the load. When the system frequency drops to the threshold, load shedding relay will start to shed the load according to the pre-selected amount. Table 4.1 gives a frequency setting example of a four-step plan [97]

- Load shedding scheme based on rate of change of frequency (df/dt)

  As the over load or generator trip occurs, the load-generation unbalance will lead to a steep drop in frequency. The rate of change frequency can be analytically estimated by conducting transient stability studies for different operating conditions. Some efforts to improve UFLS use the rate of change frequency df/dt, as a control variable [96]. These methods shed the loads when df/dt is greater than pre-set value.

- Adaptive Load Shedding

  Adaptive scheme [26][96] is proposed to determine the amount of load to be shed by under-frequency relays based on the observed initial slope of the frequency deviation following the system load disturbance.

- Neural Network based Load Shedding

  Neural network based model was proposed to determine the load shedding operation during generation deficiency situation [99]. The method makes use of system running information like actual real power generation, spinning reserve information, active load generation level, and amount of active load being shed etc. information as the input to train the neural network for the load shedding scheme design.

Table 4.1 Frequency Settings of A Four Steps Plan

Relay	**Frequency**	**Load Trip**	**Delay**
F1	59.5 Hz	0.0625 per unit	0.1 s
F2	59.2 Hz	0.0625 per unit	0.1 s
F3	58.9 Hz	0.0625 per unit	0.1 s
F4	58.6 Hz	0.0625 per unit	0.1 s

Choosing the proper load shedding scheme is not an easy job because it depends on several factors such as: system dynamic performance ; the magnitude of the overload which is not predictable; system generation characteristics and running status; load frequency characteristics etc.

The most important items to consider while setting a load shedding scheme are the following:

- Relay pickup frequency setting (frequency or rate of change of frequency).
  Normally, several steps of pickup value are set. Table 4.1 illustrates a typical four-step load shedding relay setting [96]. First step of load shedding is the most important step since the initial frequency slop contains all the information for accurate load shedding estimation. Different system has the different pick up setting. Some utilities use 59.2 Hz while 59.0 Hz is used by other utilities. The main concern for the load shedding setting is the turbine generator operation [100].

- Number of steps for load shedding
  Utilities experience different load shedding steps from 4 to 6 or even more. More steps lead to better system operation performance and less load disturbance. However, more relays are needed and it becomes more difficult and tedious for each step's relay setting.

- Amount of load to be shed in each step
  After number of steps for load shedding is determined. Dynamic simulation based on different model needs be done to determine the amount for each step.

- Load shedding delay time
  Time delay [101][102] is generally used for generation units to avoid malfunction due to surge transient. However, the timer setting can not be set too long in order to shed the load as soon as possible.

Traditionally, the load shedding scheme was evaluated using simulation based on the assumption of constant decelerate, constant voltage, constant load and constant generator power. The scheme was generally adequate for simple and special case. However, it lacked the scalability. When system status was changed, the load shedding scheme could not be adapted to the new situation.

The most commonly used scheme is under frequency load shedding. It is simple and cheap. However, the coordination performance is poor due to tedious step. The under frequency load shedding also depends on assumed load distribution to shed the load. Since it is difficult to predict the actual power deficit and load running status, the exact amount of load may not be shed. To increase the number of load shedding steps without limit is not practical. All these factors could cause over or under load shedding. Neural network sometimes is good in predicting the generation deficiency. However, the computation is time consuming. Neural network also needs to be trained again should the scheme applied to other system and situation. In addition, the load shedding time relays are generally used for generation units to avoid surge or switching transient. This delay time may result in fast frequency drop under larger overload and cause under-frequency relay tripping in generation unit. The blackout in Sweden in 1983 [101] led to the conclusion that under frequency load shedding must operate without significant delay. Therefore, the faster the load shedding starts during generation loss contingency, the better to keep the power system reliability.

Another disadvantage of under frequency load shedding is that it can not accurately consider the spinning reserve. If the shed load is greater than required, the frequency drop is quickly stopped but a frequency overshoot over upper limit (like 61 Hz) is possible. Frequency excursion over 61 Hz may also cause thermal generating units drop. Because the extreme pressure increase in the boiler could be caused by the fast closing of boiler valves in order to reduce the power system generation.

During the generation lose, df/dt is another indicator of power deficiency and can enable incipient recognition of the WM imbalance. However, the change in machine speeds is oscillatory in nature. The oscillation will cause side effect on df/dt [103]. It is also very difficult to set them properly.

The results of the early efforts point to the need of an adaptive, convenient and fast load shedding strategy.

4.3 Local Area Network based Load Shedding Scheme

Technology advances in the computer network and communication have opened the door for fast, accurate load shedding scheme design due to its low cost, convenience, scalability and remote access capability [69]. Network-based systems of various designs have been implemented for monitoring and controlling the power system. Their experiences [9][36] have indicated that network technology can be successfully employed in the real-time power system design.

This section describes a load shedding scheme that makes use of the advanced computer and network technologies in the isolated power plant. The LSC keeps monitoring the real time generation/load information through the local area network and dynamically compares the generation and demand. When the available generation is greater than the demands, the system is running normally; if the generation is less than the loads due to generator trip or overload, LSC will shed the loads according to the mismatch. LSC consists of a center management unit which performs trigger signal processing, load shedding sequences determination and load shedding commands issuing to the loads through RTU in real time. The evaluation processes within the LSC however is kept to a minimum to speed up the load shedding actions since most of the system calculations are performed in the substation main server. Only the required load shedding calculation and decision making are done locally. All the load shedding information acquisition, transmission and commands are via fast fiber Ethernet. More over, the operator is taking an active role to share the control of the load shedding policy. When a new load is added in or any parameter needs to be changed, the operator only needs to change at the SCADA server site, LSC will automatically download the latest setting and update its database. This is very flexible for the load shedding strategy design.

4.3.1 Load Shedding Scheme Logic

During power plant operation, various conditions exist. LAN-based load shedding logic is designed to cover all possible emergency conditions. The actual generation outputs are determined by on-line monitoring of GTG (Gas Turbine Generator) CB (Circuit Breaker) status, output power and ambient air temperature. Loads information is fed back by remotely reading power meter data. Emergency case recognition is activated through trigger signals. An emergency case applies if trigger signals are received.

4.3.2 Assessment of System Status

The load shedding decision making is determined based on the real time generation and loads status.

- **Generator Running Information**

  Generator circuit breaker statue change is the instant trigger of the load shedding. CB statuses can be reported through hardwired DIB (Digital Interface Board) directly connected to them. Generator ambient air temperatures as well as output power are gathered by IED. Data Interface Unit (DIU) acts as an information gateway to send the real time data from IED to the load shedding controller through local area network.

- **Load Information**

  LSC also keeps reading the loads status from digital meters through the local area network. Periodically, load shedding controller will issue a command asking data from all IEDs to check the load status, if there is no reply received from one IED, LSC will keep polling this IED to test its living status. Load shedding priority list will change accordingly if the IED assured to be no longer alive. By using fast local area network, real time system load information can be accurately measured.

- **Power Reserves Determination**

  Total available power generation can be calculated by the GTG ambient air temperature versus output power curve. At any time, the GTG temperature can be acquired and the maximum output power can be determined by looking-up in the above curve. One such curve is illustrated in Figure 4.2. During load shedding operation, only the excessive loads that exceed the GTG maximum output power will be shed.

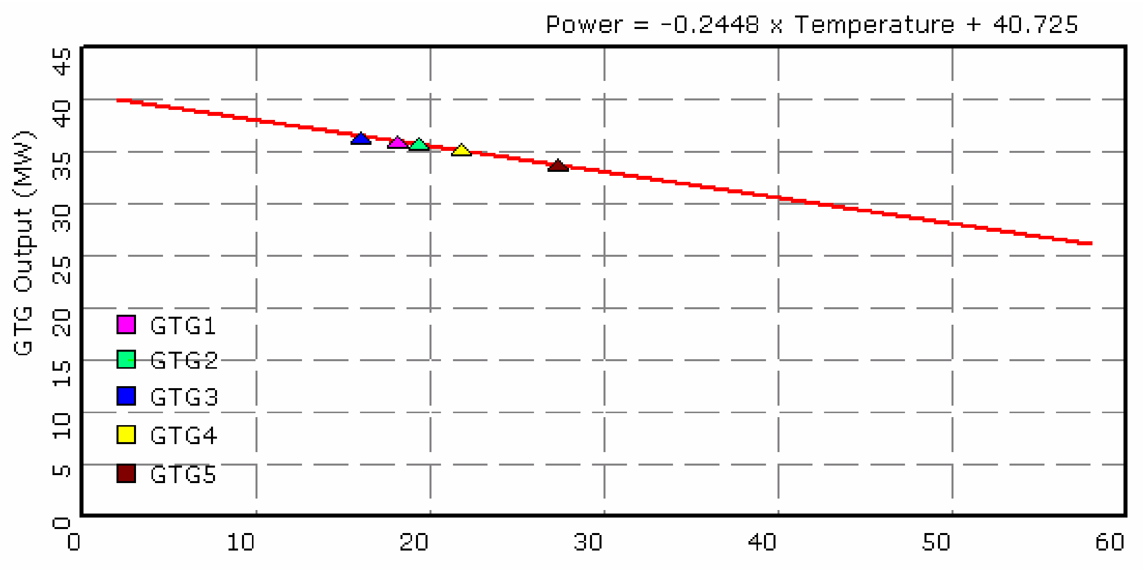

Figure 4.2 GTG Power Versus Temperature Curve

4.3.3 Load Shedding Priority List Administration

Load shedding priority list can be set up according to customer and system requests. Following are some basic criteria for the load shedding priority list management.

- Loads that are essential to the plants operation will not be shed or shed last. Such kind of equipment could be generator cooler, system cathodic protection.
- Loads that are without disruption of process operations will be shed first; such loads could be the power supply for the training building.
- Loads that are easier to restore to normal operation will be shed before those that are difficult to restart.

When an event triggers the LSC, LSC will shed the loads according to the load priority list, lowest priority loads will be shed first. A predetermined load shedding list contains of all loads in rising order of priority. Load shedding sequences can be modified via the

MMI (Man Machine Interface) by selecting one of the predetermined load shedding lists in the load shedding list database. Operator can change the load shedding priority list dynamically, shed, block or reconnect single or multiple loads at the control center. Special strategy is used to keep the priority list consistent at control center and LSC. When the LSC starts or the priority lists are modified by the operator, whole set of priority lists will be downloaded from substation server to LSC.

4.3.4 Load Shedding Scenario

LSC will be activated under two situations: GTG overload or GTG trip.

- **Generator Trip**

  When one or two GTG trip(s) or GTG CB status changes, signal will be sent to LSC immediately through DIB. LSC then captures the system snapshot of generation/demand information. Generation deficiency will be calculated. If total generation with spinning reserve is greater than loads, a GTG tripping warning signal will be reported to SCADA server, no load shedding will occur. If the generation is less than the loads, loads will be shed according to the preset priority list. Figure 4.1 shows the GTG trip load shedding logic used by LSC.

- **Generator Overload**

  When GTG runs normally, and one or two generators are overload due to sudden load increase, warning signal will be generated; a timer will also be initiated at the same time. Loading condition is checked at a pre-defined time interval. If overload condition rectified, the timer will be reset and no loads will be shed. If overload condition persists for the preset amount of time or another GTG also trips, the loads will be shed according to the priority list. Figure 4.4 shows the system overload load shedding logic used by LSC.

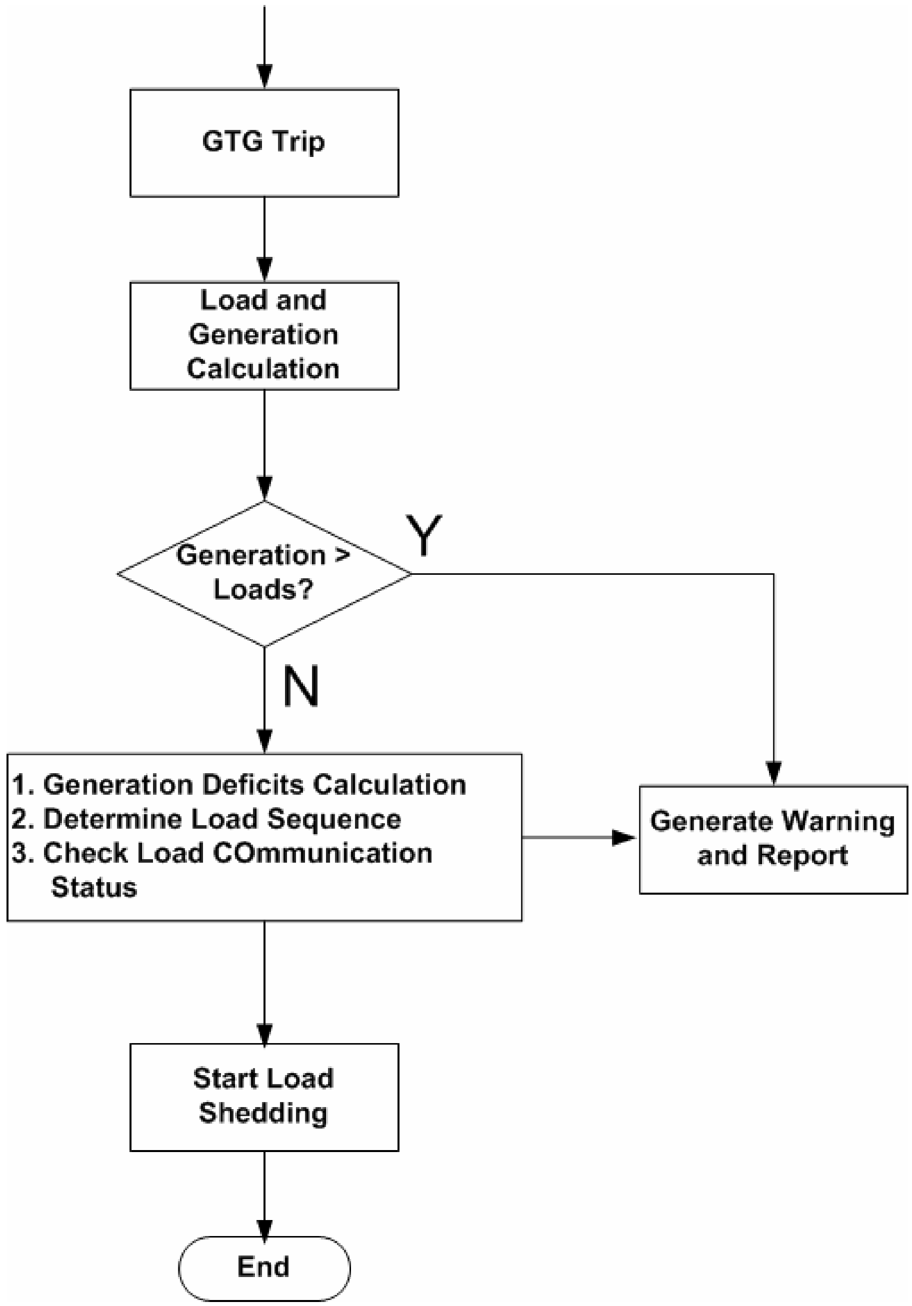

Figure 4.3 LSC GTG Trips Logic Chart

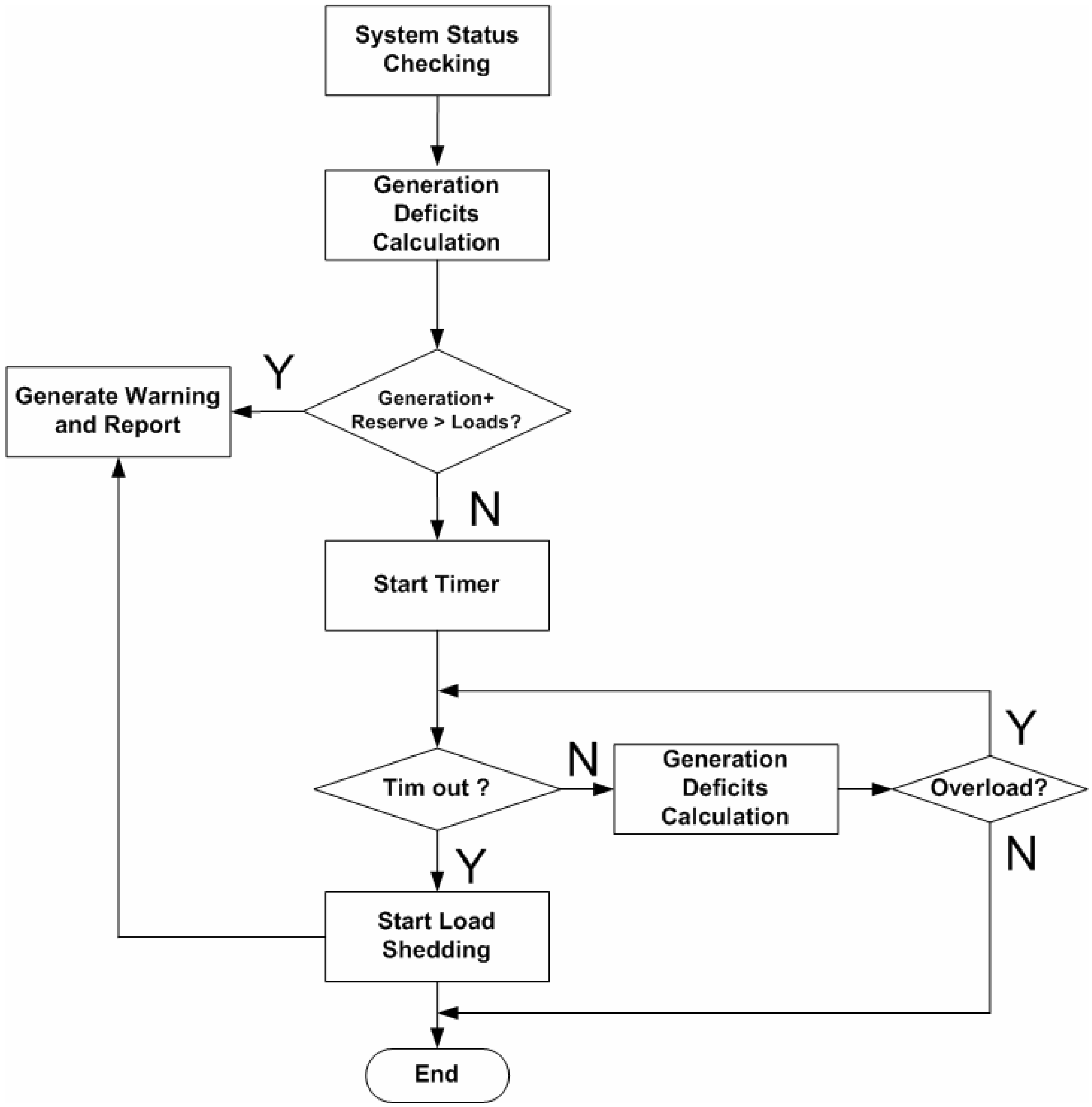

Figure 4.4 LSC System Overload Logic Chart

4.3.5 Load Shedding Strategy

When load shedding is stared, LSC will calculate total GTG power with reserve using equation 4.4

$$P_G = \sum_{i=0}^{n} f_i(Ti) \quad 4.4$$

Where $f_i(Ti) = -a_i T_i + C_i$ is the generator available power including spinning reserve; a_i is the system constant; T_i is the generator temperature and C_i is the maximum generator capacity.

Load will be read in from power meters though IED and calculated by using equation 4.5.

$$P_L = \sum_{i=0}^{n} P_i \qquad 4.5$$

Total load is deducted from the total available power. The difference will be the loads to shed.

$$\sum_{i=1}^{n} P_{Li} \geq P_L - P_G \qquad 4.6$$

LSC counts the loads in the load shedding priority list by sequence, until the summary of the counted loads is greater than the amount needs to shed. Load shedding commands then will be issued to every load in the counting list through PLC. With high Ethernet network performance, from event trigger till all the loads are shed, the response time is less than 200ms in the worst situation. The time latency can meet the requirement of the isolated power system load shedding specification.

4.4 LSC System Architecture

Load area network based data acquisition and control system provides centralized information management with multiple-protocol support for the efficient data communication and exchange between generating plant, substation and control center.

LSC can be a part of the whole SCADA/EMS system that makes use of the SCADA local area network for the load shedding information transmission. Figure 4.5 shows the conception communication network architecture of the SCADA data transmission network.

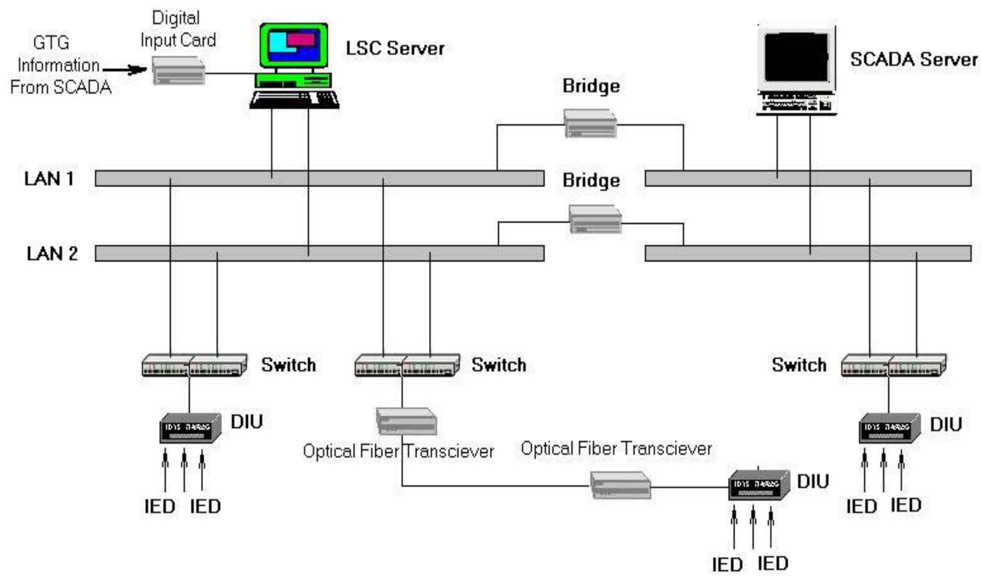

Figure 4.5 LSC Local Area Network Structure

As illustrated in Figure 4.5, the functionality of real time data acquisition and control system has a hierarchy structure. This structure has three sub-levels: Bay Level; Substation Level; and Control center level.

1. The functionality of bay level is to interface with the power system components such as relay, power system equipment (transformer and generator etc). Typical functions of the bay level are data acquisition and issuing control or protection commands.
2. Substation level is the communication gateway concerning with coordinating of measurement and control.
3. At the top level is the control center. Real time information will be processed to monitor the system running status or for further contingency analysis. Protection or control commands will also be issued from control center.

4.5 Main Technologies in the LSC Design

Several advanced computer and network technologies such as fast Ethernet, network programming, remote network management are used in the load shedding scheme design.

4.5.1 Ethernet for the Local Area Network

Local area network is widely used as data communication backbone in many power system control and monitoring systems due to its high performance and scalability. Among different LAN systems such as FDDI, Ethernet, Token Ring, Token Bus, Ethernet [64][69][83] is normally chosen as physical / data link layer network because of its predominant role the marketplace and the subsequence availability of low-cost implementation and associated network hardwire (bridge, router and switch). In addition, the scalability of Ethernet is well defined with 10/100 MB implementations. Processors are available today with multiple Ethernet ports integrated into the chip and next generation designs are planned with Gigabyte Ethernet. Ethernet also supports open system and cross-platform architecture, information exchange and communication can be done with minimum effort.

Due to the above reasons, more and more substations currently make use of Ethernet as the main data communication backbone. Another interesting feature of local area network is its ability to support cooperative client/server application.

4.5.2 Ethernet Traffic Analyses and Flow Control

Ethernet traffic [69] greatly influences the performance of LSC. For the fast emergency situation response, data transmission latency instead of network throughput (the number of packet the network can effectively transmitted per second) dominates the thinking of LSC design. From SCADA server point of view, the actual SCADA traffic is a mixture of three types of data:

- System real time data: Such kind of data can be measurement data from system digital or analog points; breaker or isolator status report; time-tagged event of alarm.
- System commands: Such kind of data can be protection control commands issued to open or close the circuit breakers; remote setting and other parameters; IED life sign checking.

- System historical or oscillographic data report. These transactions typically cause larger packets of data.

For the Ethernet, total latency can be defined as:

Latency = Propagation + Transmit + Queue

Where Propagation = Distance/Speed of Light

Transmit = size/bandwidth.

Queue = queuing delays inside the network

In the SCADA System, few Ethernet have more than 200 hosts connect to them and most Ethernet connections are far shorter than 2500m, with a round-trip delay of less than 5 microsecond. The Ethernet packet size generated due to SCADA traffic could be characterized as small packets (approximately 140 bytes) in regards to the maximum size of data, which could be carried in a single Ethernet frame (approximately 1500 bytes of link user data).

For Ethernet congestion control, TCP has its congestion control strategies such as slow start; fast retransmission and fast recovery for each source to determine how much capacity is available in the network, so that it knows how many packets it can safely have in transit. Network switch also has its way of managing buffer and routing to minimize the possibility of dropping packets.

During data transmission, Ethernet uses CSMA/CD (Carrier Sense Multiple Access / Collision Detection) as the collision detection algorithm. When two or more IEDs desire access to the LAN simultaneously, a data collision may occur. When this happens, all colliding devices set a random delay time and try the connection again. This raises a question. Will the Ethernet meet the timely request of the substation? Because for the substation environment, “timely” was defined to be 4ms in order to perform fast functions such as tripping.

EPRI has done several studies to evaluate Ethernet performance under a “worst case” scenario [104]. Results of these studies showed that either 100 MB Ethernet on a shared hub or 10 MB Ethernet connected via a switched hub could meet the 4ms network communication time request.

In the LSC design, several approaches were designed for further optimizing the congestion control and resource allocation:

- Centralized Information Management. Substation status information is gathered into IED. Each DIU manages multiple IED channels. DIU sends the upstream status information to LSC server and sends the downstream commands to open and close CB switches. This design reduces the possibility of data collision by minimize the hosts connected to the Ethernet.
- Cyclic polling: Instead of sending out the polling commands to all the IEDs at the same time, LSC sends cycling check command to a special IED every second. This approach reduces the bandwidth requirements of a polling mode and balances the network traffic and CPU usage.

4.5.3 Network Programming

Network programming [83] [106] enables programs to share information stored in computers located anywhere in the world. People can communicate with each other through network programming. Distributed applications can be harnessed to work on one problem. All devices in the SCADA system communicate with each other via TCP/IP socket communication. In the LSC system, BSD (Berkley Software Distribution) socket [106] and Winsock [107] are used for network programming.

4.5.4 Network Management

As the number of networks within a power system grows, along with the diversity of digital devices from various vendors comprising the network, managing all these systems within a coherent framework becomes important, especially in the substation where every datagram might be critical for the system control decision-making. Monitoring the operating status of the whole network and reporting the network communication failure becomes an essential function. In the LSC system described in this section, Simple Network Management Protocol (SNMP) [68][69] is employed to monitor the local area network communication status. Network management of a local area network consists of network management stations (managers) communicating with network elements (IED etc). The software in the network element that runs the management software is called agent. The manager can ask the agent for a particular value or the agent can report to the manager that something important happened (IED communication failure). Through this two-way communication, the whole local area network communication status could be monitored. When a network component is down, an error or warning message will be sent to the control center immediately to avoid system communication system malfunction.

4.5.5 Database Management System

System information is saved in LSC database, in case the connection with SCADA server fails, LSC will based on the database data for the generation/load management. System events are also saved in the LSC database for future historical event retrieval. ODBC (Open Database Connectivity) [108] is used as a bridge between LSC and the local database. ODBC is a way to embed the SQL and to reduce the development and maintenance costs that require Database connectivity. ODBC provides a simple model for programming language to communicate with multi-vendor databases using standard ODBC drivers.

4.6 Actual System Implementation

The LAN-based LSC design has been successfully implemented in an oil refinery facility power plant.

4.6.1 Actual Power Plant Configuration

The oil refinery plant internal electrical network is an isolated power system with 5 GTGs. Each GTG's full load is around 40 MW. One GTG is always running as the spinning reserve. The actual output and rated output are determined by on-line monitoring of out-going CB status (through protection relay), output power and ambient air temperature (through generator protection IED communication link). Normal operation condition is such that there is always one generator serves as spinning reserve.

About 56 loads at different voltage levels (33kV/6.6kV/3.3kV/415V) in 16 substations can be controlled by load shedding controller. There are three data communication methods: polling, exception report and continuous data transfer.

Load CB statuses are reported to LSC by exception report, which means the IED will report to LSC only when CB status changed. CB status will then be registered by LSC. Subsequent load shedding logic will exclude those CBs that are currently not in service. The operation of the load shedding is carried on by DCS (Distributed Control System) and by PLC (Programmable Logic Controller). Communication and integration of the whole system is by means of an optical Ethernet network in order to gain high speed, bandwidth and guarantee disturbance immunity.

LSC polls each IED by sending a LIFE SIGN signal to LSC at a preset interval (normally 10 seconds). This signal will be used to monitor the health of the communication link. If LSC does not receive response after 6 LIFE SIGNs, LSC will treat this connection as "died". Load shedding logic will also exclude those CBs that indicate a failed communication link. Upon re-establish communication, a general request will be sent to DIUs to request update for all related CB status. The same applies to all GTG parameters. Some IEDs will keep reporting the real data for overload checking, these IEDs monitor each output transmission line's power flow and report to the LSC. LSC based on these data to gain the snapshot of the system demand at that moment.

4.6.2 DIU Data Exchange Protocol Design

LSC can send various “request” commands to collect real-time IED data as well as control commands to get IED points. All the points in the IED are addressed as “bit in a telegram” with Modbus or other protocol addresses hidden within the DIU driver software. LSC does not have to bother with these protocol addresses but addresses all equipments using telegrams. Request commands exist to facilitate handling of disturbance. For instance, when a DIU becomes “Ready” after it was disturbed, a request for all the telegram is sent to update all changes lost during disturbance. The communication between LSC and DIU is through DDEP (DIU Data Exchange Protocol) runs on top of the TCP/IP protocol (Over IEEE 802.3 Ethernet network). Different codes and different telegram ranges represent different commands and digital or analog values. Table 4.2 and Table 4.3 show one example of LSC commands and DIU data report format.

Table 4.2 DDEP Protocol - LSC Commands

Command	Description
0x0001	Request for a Telegram
0x0002	Set a Telegram Value
……	……

Table 4.3 DDEP Protocol - DIU Data Report

Usage	Bytes
0x0002	2
Data Length	2
Telegram Number	2
Telegram Value	1
……	……

4.6.3 Hierarchical Local Area Network Structure

Load shedding data communication encompasses the data transfer between control center and LSC, and between LSC and IEDs. In order to reduce the bandwidth requirement, hierarchical network architecture is employed. Adjacent substations are grouped into sub systems and connected to a gateway server. Gateway server will manage the subsystem data transmission and handle the data exchange will other subsystem and LSC server. Figure 4.6 shows the hierarchical network architecture.

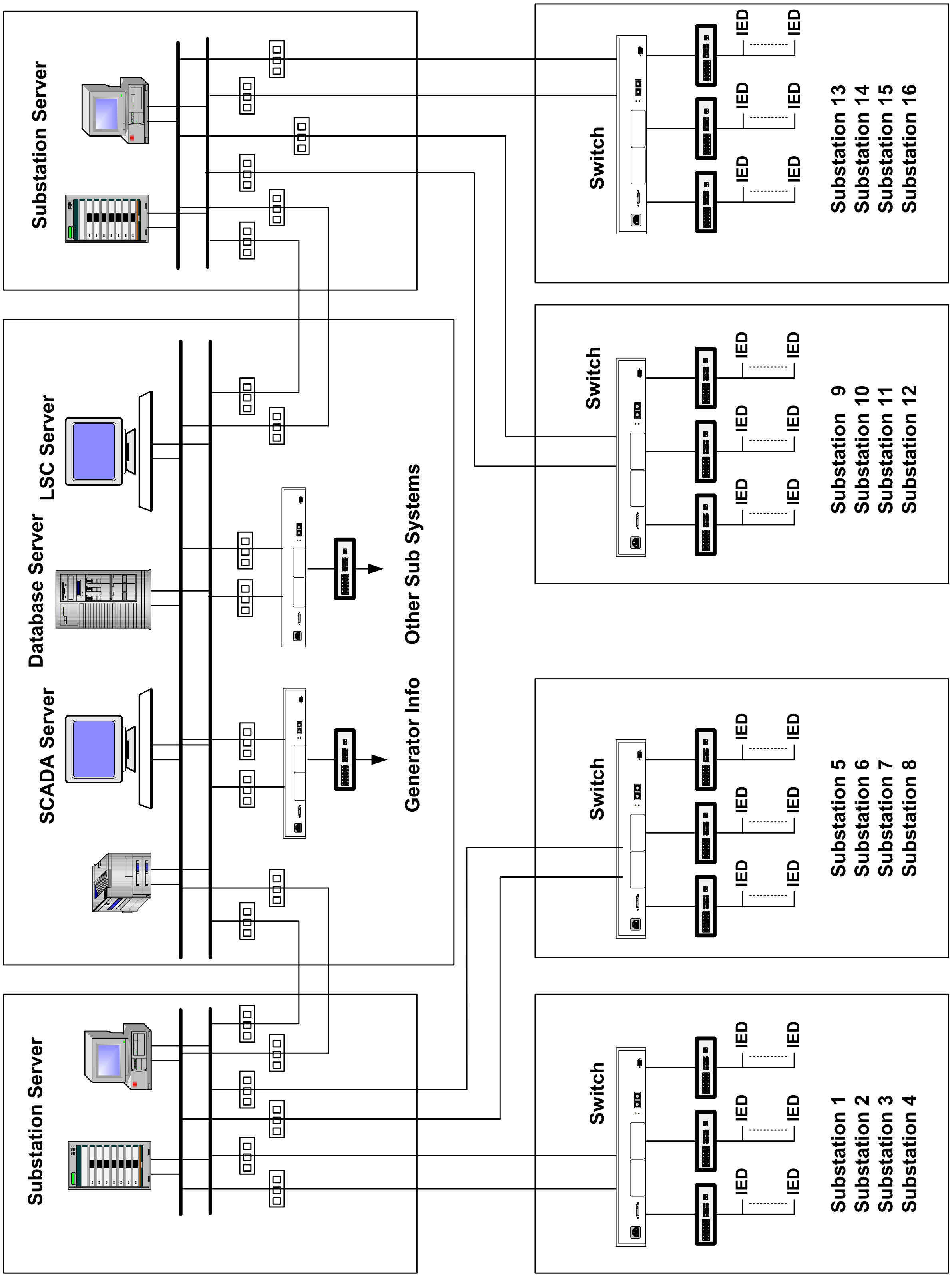

Figure 4.6 Network Configuration for Load Shedding Controller

4.6.4 LSC Configuration

The actual LSC application is running on an industrial PC with dual power supply and dual NIC. The operating system is Windows NT with SQL Server as the backend supporting database. The application on the LSC PC is developed using C++. The SCADA server is running on Unix Solaris system with Siemens Spectrum™ SCADA software.

4.6.5 Client/Server Architecture in the LSC Design

The communications among IEDs, LSC and SCADA server are through client/server architecture. In the client/server architecture, the computer that provides the service is called the server, and computer that requests the service is called the client. When LSC requests information from the IEDs, IED acts as a server providing. LSC also perform server's role when substation main server connects with LSC and asks for real time data. Two data transmission modes are used in the IED information transfer. In the polling mode, LSC client sequentially polls IEDs, each IED responds in an orderly fashion. This approach reduces the bandwidth requirements of a polling mode. However, polling cycle may be long if many IEDs want to report concurrently. Another data transmission mode is called exception report. In this mode, when the system component status is changed, the corresponding IED will generate exceptions and report to the LSC and SCADA servers. In this case, estimating traffic levels is relatively difficult.

4.6.6 Database Operation

A local database is used by the LSC to store power plant equipment parameters as well as historical event data. When the system starts, the power plant equipment information including IED name, DIU IP address, Data communication telegram, and mask etc. will be transmitted from SCADA server to the LSC. Different load shedding priority lists and current active list will also be downloaded to the LSC. All these information are stored in the LSC local database. In case the communication with SCADA server is lost, LSC will shed the loads according to database information. During operation, important messages such as system alarms, communication abnormal, and load shedding events will be stored in the database as well for the future historical data retrieval. In the actual system, SQL server and ODBC are used for the database storage and retrieval.

4.6.7 LSC Man Machine Interface

LSC MMI consists of displays that give the operator current system situation overview as required for load shedding. It enables interaction by input of selected parameters like priority numbers, deactivation of sequences.

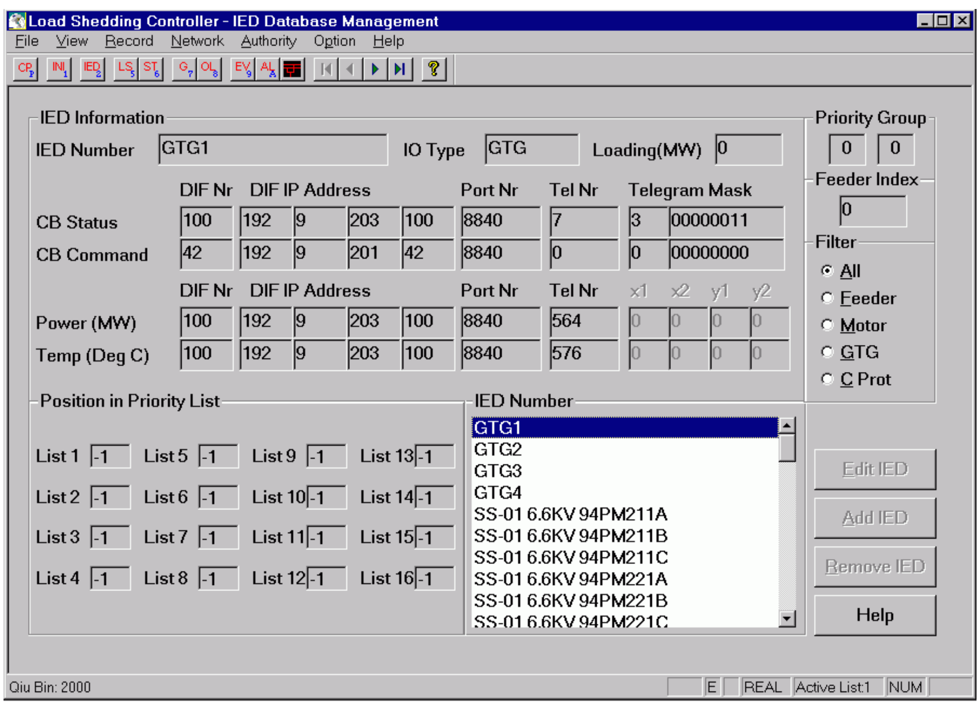

Figure 4.7 LSC IED Database

Device parameters are stored in the LSC local database. New devices such as GTG, load, and feeder can be dynamically added or deleted through IED database Management display shown in Figure 4.7. The data contains loads and generations, IED number, associated gateway number, load value, telegram number, mask for the signal control. System parameters are also set up in this display. Using this screen, operators can manually set and change and IED parameters. LSC parameters such as the life-sign checking interval, overload response time and overload scan interval are also configured in this display. LAN connection parameters can also be modified for different systems.

Figure 4.8 shows the main load shedding active priority list display. The load IED number, gateway number, IP address and load value are listed. The priority list is downloaded from the main SCADA server and saved to the local database. Up to 12 lists can be preset by the operators. The active list will be determined by the SCADA system administrator as well. Through this display, operator can manually move up and down a specific load as well as add or remove a load from the list.

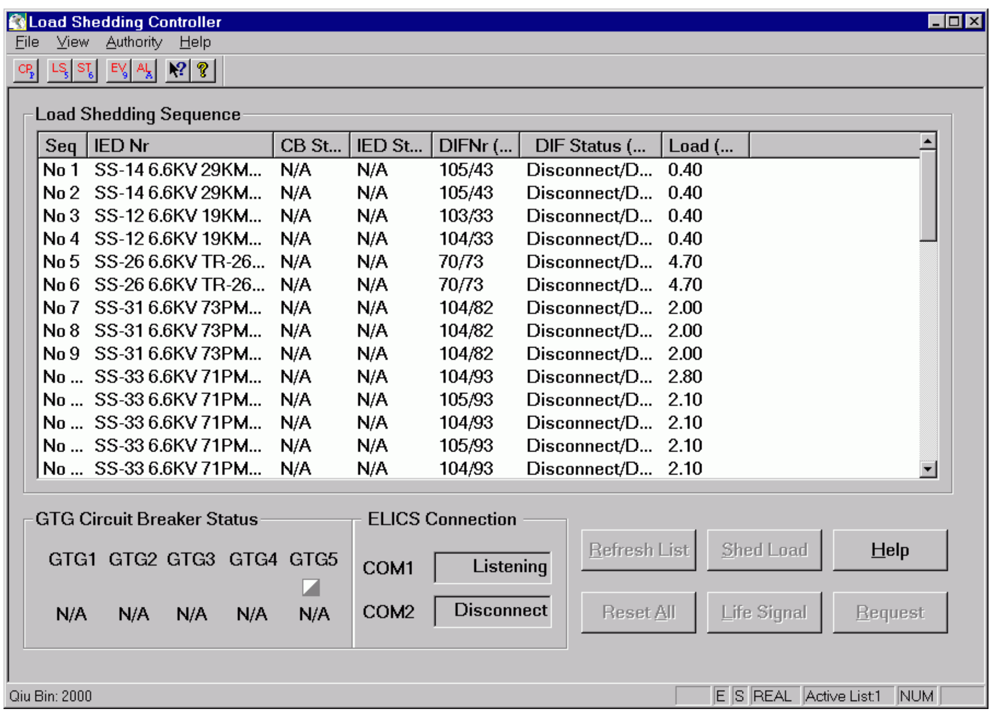

Figure 4.8 LSC Load Shedding Main Screen

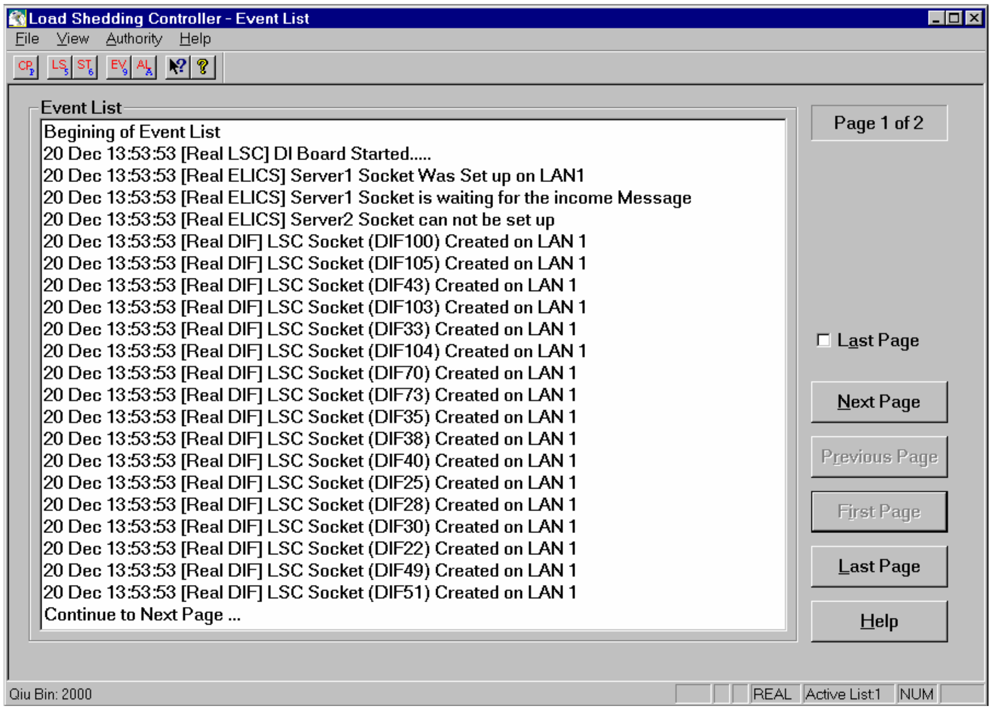

Figure 4.9 LSC Event List Screen

When event occurs, messages will be sent to two displays. Common system messages will be sent to alarm list for display. Event list is used for the warning or urgent messages. In the mean time, common messages will be saved to log file and events saved to database for the historical data retrieval. Figure 4.9 shows the event list display.

4.7 Summary

Load shedding scheme design is difficult for the isolated system due to its low inertia, insufficient spinning reserve and system dynamic characteristics. Progresses in data communication and network technologies provide the solution for fast and flexible load shedding design for isolated power system. This chapter described a local area network based load shedding controller. The load shedding controller makes use of advanced computer and network technologies such as fiber optic network and socket communication in the load shedding design. LSC directly gathers real time loads and generation information via local area network and makes load shedding decisions. The LAN based LSC system offers a fast solution to the isolated power system generation deficiency due to its reliability, scalability, flexibility, and efficiency. LAN based load shedding controller also allows operators to take active role in the load shedding policy. The LAN based load shedding controller has been successfully implemented into actual oil refinery facility power plant. Actual site tests showed that local area network could support the real time SCADA data transmission requirements. LAN-based load shedding controller has high performance and stability. It could achieve the event response time requirement of the isolated power system..

Chapter 5 Wide Area Load Shedding Based on Real time PMU Inputs

Different from isolated system, large power systems [109][110] are interconnected to enforce reliability. Electric power system receives many benefits by operating with such interconnection. Different utilities could exchange energy, share generation reserves. Individual system reliability could be enforced because of improved frequency response to contingencies such as loss of load or generation. Frequency changes for a given loss of load or generation are smaller for a large, interconnected system than the corresponding frequency changes for the isolated control areas.

However, frequency instability can be initiated by a large generation/demand mismatch which could lead to significant frequency deviation. Such a scenario can result in a cascaded loss of generation through under-or over-frequency load shedding operation that will eventually lead to a blackout.

Similar to isolated power system, UFLS is common practice for electric utilities around the world for the generation and load mismatch protection. UFLS uses under-frequency relays to shed loads as the frequency drops to certain level. Depending on the system situation and the power company requirements, the number of frequency steps could vary from two to fifteen. However, the load shedding relay settings are fixed values obtained from offline simulation results. Therefore the setting is subjected to under/over load shedding and also cannot adapt to prevailing system conditions.

Recent years, the rapid development of power system deregulation poses some new challenges on the load shedding scheme design. The new constraints placed by economical and stability factors require that the load shedding to be limited to the special area with minimum system disturbance.

Load area network based load shedding scheme mentioned in chapter 4 could also be employed for the interconnected power system should the communication network meet the bandwidth and time delay requirements. However, a large-scale power system normally has tens of IPPs (Independent Power Producer) with thousands of generators and load buses in a wide geographic area. Large volume of real time data transmission and processing will be a heavy burden for both the communication network and server processing. It is not a proper design from economical and technical point of views.

This chapter proposes a fast and accurate load shedding system design. The algorithm makes use of the synchronized real time frequency and area tie line power flow information to predict the generation deficiency. Generation deficiency can be accurately predicted and therefore activate the load shedding at the initial instant of the generation loss. The algorithm can also limit the load shedding in the disturbance area with minimum system upset.

There are four sections in this chapter: Introduction of the load shedding issues in the large scale interconnected system; Load shedding literature reviews; New AGE (Area Generation Error) load shedding scheme proposal; New load shedding system design and simulation.

5.1 Introduction

In the actual system, when load or generation rejection occurs, instead of following a linear frequency drop, the system frequency will experience a frequency oscillation. This scenario can be illustrated using the actual frequency record data [29]. Figure 5.1 and Figure 5.2 show the frequency versus time plots at four points in the Texas (ERCOT) system during a full load rejection test at Comanche II Nuclear Plant [29]. The location of the four monitoring points is shown in Figure 5.1. This simultaneous measurement revealed very complex and interesting frequency excursion patterns. As can be seen in Figure 5.2, every measurement point carries the area frequency information with its own local twist.

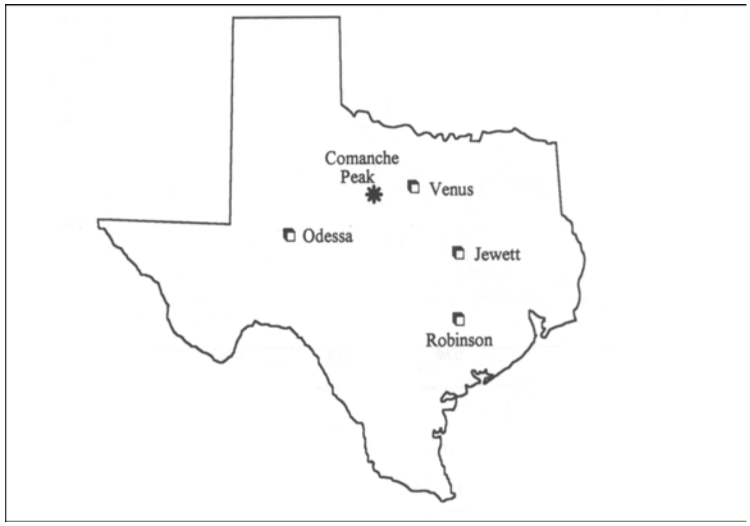

Figure 5.1 PMU Locations in the Texas System

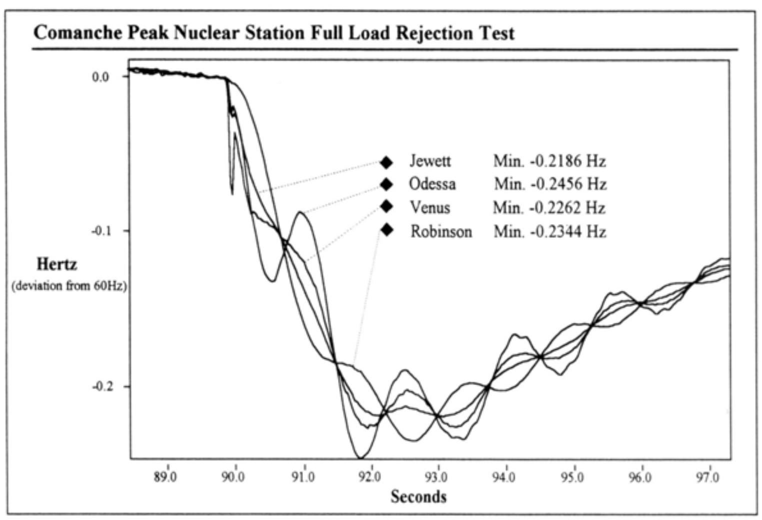

Figure 5.2 Comanche Full Load Rejection Test

When disturbance occurs, frequency forward traveling wave (in the direction of nominal power flow) grows over time while wave traveling in the reverse direction attenuates [111][112][113]. The frequency takes time (several hundreds milliseconds to several seconds) to progress from one bus to others. The frequency decline will be altered by many system and controller parameters. Due to the frequency waveform transmission and reflection on each bus and component, the actual frequency waveform is the effect of the superposition of all the wave reflected and transmitted at all the components. Therefore, frequency is sensitive to system structure and is not a clear, immediate indicator of the magnitude of a sudden change in the load/generation balance. However, for conventional frequency analysis, a uniform system frequency is normally assumed. This condition is only achieved in the steady state after all electromechanical oscillation has died out. In this sense, frequency dynamics should be considered as part of the long-time dynamics.

5.2 Load Shedding Controller Algorithms Review

Similar to isolated power system, frequency information and rate of change of frequency [114] - [116] are commonly used in the load shedding scheme design. However, large scale interconnected power system has its own features.

Power system interconnection can improve reliability because of improved frequency response to contingencies such as loss of load or generation. Frequency changes for a given loss of load or generation are smaller for a large, interconnected system than the corresponding frequency change for the isolated control area. Spinning reserves from one area can be used to compensate the generation deficiency in other areas. System stability characteristics are largely influenced by the strength of the interconnection. As power system evolves, some power systems are operated even close to transient and steady state stability limits. However, no corresponding modification of UFLS has been made for decades of years. The load shedding scheme still sheds pre-selected loads evaluated using off-line study throughout the entire power system.

Generally, the conventional under-frequency load shedding has several disadvantages:

1. Typical load shedding schemes are based on predetermined system scenarios. Table 5.1 lists the WSCC system relay load shedding setting [115]. The setting values of conventional load-shedding relay are obtained from offline simulation of different operating conditions. They are kept fixed at each point where relays have been installed and cannot adapt to prevailing system conditions.

2. Load is shed in discrete steps, since it is difficult to predict the actual power deficit, the exact amount of load may not be shed. This will cause under or over load shedding.
3. The change in machine speed is oscillatory in nature. These oscillations depend on the response of the generators and are seen differently at different locations. The oscillation will cause the load shedding controller using rate of change of frequency df/dt to be inaccurate.
4. Generator governor startup is a slow procedure and normally needs tens of seconds to minutes. Load shedding operation can not properly consider the spinning reserve and therefore also will cause over or under shedding.

Table 5.1 WSCC Load Shedding Relay Setting [115]

Load Shedding Block	% of customer load dropped	Pickup (Hz)	Tripping Time
1	5.3	59.1	-
2	5.9	58.9	-
3	6.5	58.7	-
4	6.7	58.5	-
5	6.7	58.3	-
Additional Automatic Load Shedding to Correct under-frequency Stalling			
	2.3	59.3	1.5 sec
	1.7	59.5	30 sec
	2.0	59.5	1 min
Load Automatically Restored from 59.1 Hz block to correct frequency overshoot			
	1.1	60.5	30 sec
	1.7	60.7	5 sec
	2.3	60.9	0.25 sec

Recent years, rapid development of deregulation poses new challenges on the load shedding scheme design. Historically, when the frequency drops to the certain level, the load shedding relay will be activated and shed the loads according to the pre-set value in all areas. Following the loss of the generation, there will be a different rate of initial frequency reduction in adjoining areas. In the area near the generation loss center, frequency drops immediately. In the undistributed area, there is a delay of frequency reduction. Generator outage in one area can result in load shedding in different areas. We can use an example in WSCC system to explain the problem. **Error! Reference source not found.** shows the WSCC 127 buses equivalent system. We simulate (detail simulation will be shown in the following sections) one generator NAVAJO at bus 62 with 1690 MW trips at time 1.5 second. Figure 5.3 shows the frequency variations in different buses of different areas. As seen from the figure, generation deficiency in one area can cause frequency drop in all areas. The bus closest to the incident event center has the greatest rate of change of frequency df/dt while the bus with the furthest distance to the event center has the smallest frequency variation. All buses have their own frequencies and they oscillate around the virtual system inertia center. Suppose we set the load shedding pick up frequency to be 59.5 Hz. Then at time equals to around 8 second, relays in different locations will activate the load shedding almost at the same time. As a consequence, the mismatch between load and generation would persist for a longer time with severer effect.

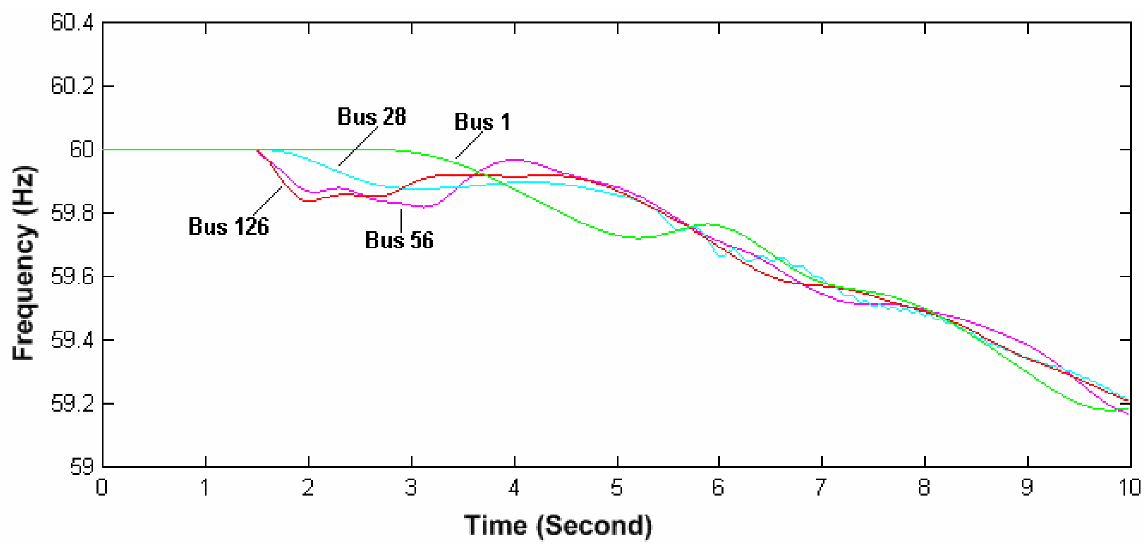

Figure 5.3 Average Area Frequencies

Facing the constraints placed by economical and stability factors, the new load shedding design needs to:

- Act fast when generation deficiency occurs to minimize the frequency excursion and maintain the system stability.
- Shed the load accurately to prevent under or over load shedding.

- Limit the load shedding to the generation deficiency area with minimum system disturbance and side effects.

With the development of computer, communication and advanced power system technologies, more “intelligent” method can be employed for the fast and accurate load shedding scheme design. Significant improvement in system performance could be archived through the use of high speed and accurate load shedding scheme and high performance communication tools.

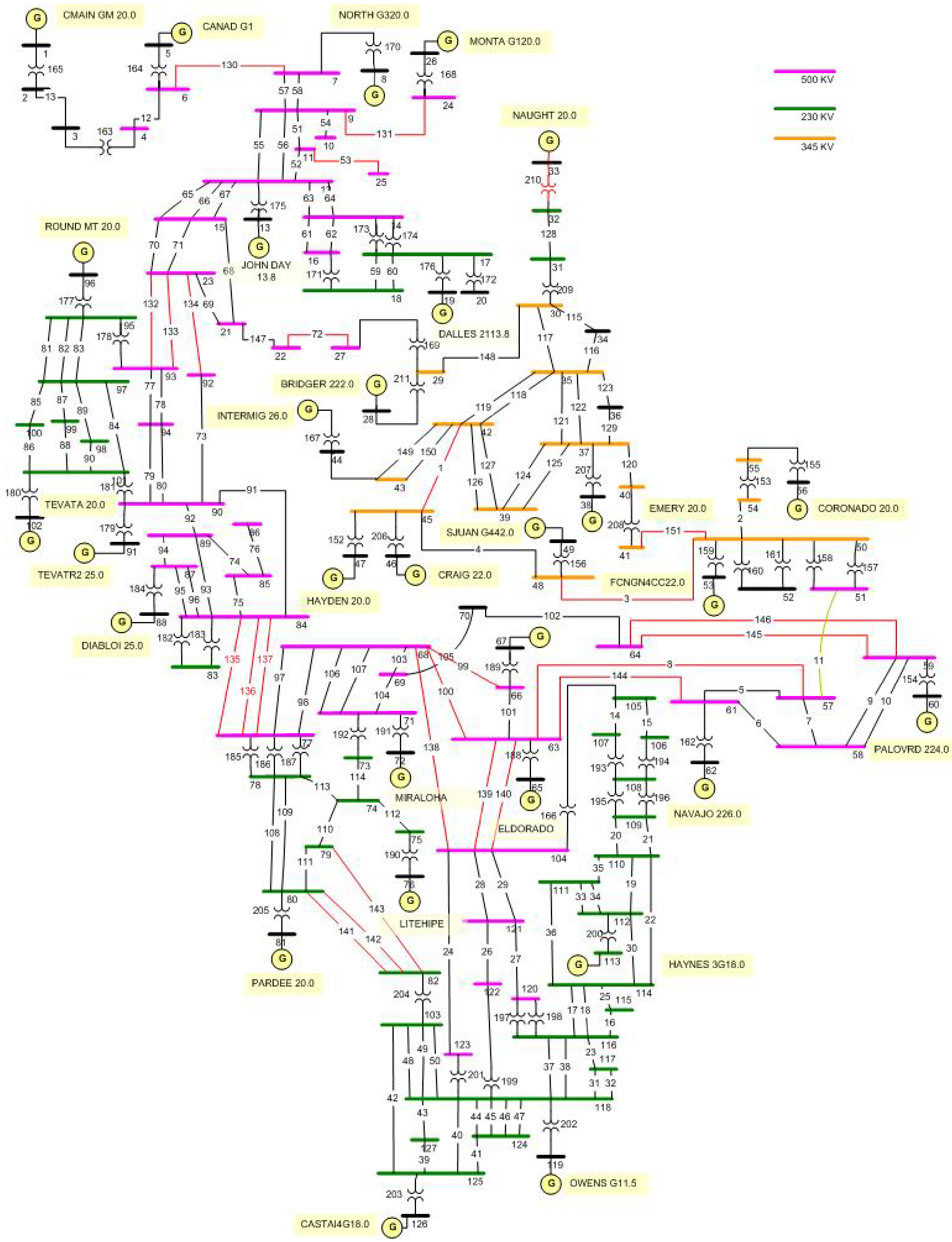

Figure 5.4 WSCC 127 Buses Equivalent Circuits

5.3 Area Control Error (ACE)

In the interconnected power systems [109][117], each sub system maintains a balance between generation and load under normal conditions [118]. This balance will be lost if the generation trip occurs or load is increased. When some areas are unable to maintain generation/demand balance, other areas will provide sustained assistance according to bias characteristics [119][120].

ACE [121][122] is defined as the difference between actual net area interchange and scheduled net area interchange, with a component for frequency bias. The ACE calculation uses instantaneous frequency and the power flow interchange information and is stated in power (Megawatts).

$$ACE = (P_a - P_s) - 10B(F_a - F_s) \quad 5.1$$

Where:

Pa – Actual net power interchange

Ps – Scheduled net power interchange

B – Bias (Megawatts/0.1Hz, unique for each control area)

Fa – Measured actual Frequency.

Fs – Scheduled Frequency (normally 60.000 Hz).

B: The frequency bias constant is the ratio of a change in power to a change in frequency. It is a negative number because an increased load results in a decreased speed.

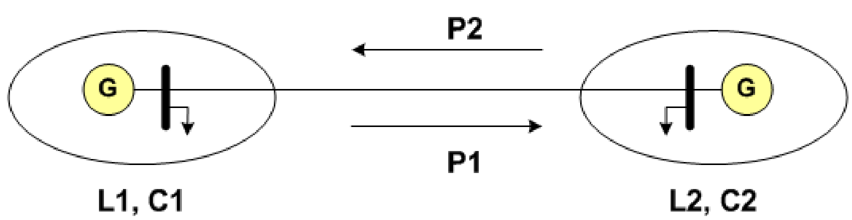

Figure 5.5 Interconnected Power Interchange

Figure 5.5 shows the interconnection of system 1 and system 2 through a single tie line. L1, L2 are the system loads and C1, C2 are the system corresponding FRC (Frequency Response Characteristic). C1 and C2 are measured in MW/0.1Hz.

When a load variation ΔL_2 occurs in system the common frequency f of the two systems will experience a steady state drop of:

$$\Delta f = \frac{\Delta L_s}{C_1 + C_2} \qquad 5.2$$

the export tie line load P1 and P2 will also be changed:

$$\Delta P = \frac{C_1 * \Delta L_s}{C_1 + C_2} \qquad 5.3$$

In case of flat frequency control, the Area Control Error (ACE) will be defined as:

$$\text{ACE}=\text{B}\,\Delta f \qquad 5.4$$

$$ACE_1 = B_c \Delta f - \Delta P \qquad 5.5$$

$$ACE_2 = B_2 \Delta f - \Delta P \qquad 5.6$$

where B1 and B2 are the system bias coefficients. We assume B1=C1 and B2=C2, it is obvious that the ACE of each system equals to the actual load change in that area, so that:

$$ACE_1 = 0 \qquad 5.7$$

$$ACE_2 = \Delta P \qquad 5.8$$

The same principle can be applied to multiple interconnection systems. When load changes in one area, the corresponding ACE will be ΔP , while ACE in other areas will be zero.

5.4 Proposed Wide Area Load Shedding Scheme

In the instant of generator trip, the generation deficiency is distributed to other generators based on the electrical location of the generation with respect to the bus at which the overload occurred [123][124][125]. According to the second order differential form of the swing equation, the frequency of each generator will decrease in a quati-oscillatory manner [126] following the load/generation mismatch. The magnitude and rate of change of frequency of these oscillations are depending on the rotor inertia constant and the electrical location of the generations. Summing the swing equation over all generators gives the expression

$$\frac{d(\Delta\omega_c)}{dt} = \frac{\Delta P_L \omega_r}{\sum_{i=1}^{n} 2H_i} \qquad 5.9$$

Where

H is the rotor inertia constant

$\Delta\omega_c$ is the power system frequency deviation.

Δp_L is the power system load deviation.

$\Delta\omega_r$ is the per unit nominal frequency

From equation 5.9, we can get

$$\frac{d(\Delta f_c)}{dt} = \frac{\Delta P_L f_r}{\sum_{i=1}^{n} 2H_i} \qquad 5.10$$

To a large interconnected system, each sub-system presents a balance between generation, load and power exchange. This balance will be interrupted by overload or generation loss. The disturbance can be described using the well known incremental equation

$$M\frac{d\Delta f}{dt} + D\Delta f = \Delta P_G - \Delta P_L - \Delta P_{Loss} + \Delta P_E \qquad 5.11$$

$M\frac{d\Delta f}{dt}$ is actually the transient area control area (ACE). By changing the position of each variable, we can get

$$\Delta P_G - \Delta P_L - \Delta P_{Loss} = M\frac{d\Delta f}{dt} + D\Delta f - \Delta P_E \qquad 5.12$$

We introduce $M\frac{d\Delta f}{dt} + D\Delta f - \Delta P_E$ as Area Generation Error (AGE). As seen from equation 5.12, the internal changes of generation/load will cause the negative AGE, as external disturbance will cause zero AGE. Also, by measuring the AGE, we can accurately estimate the generation deficiency within an area.

Earlier studies have shown that frequency dynamics propagate as electromechanical waves and frequency differs both in time and in space for large dynamic multi-machine power systems. When generation loss occurs, distinction between local and remote AGE are clear. Using synchronized real time frequency and tie line flow information, we can accurately compare the AGE in different areas and therefore make a quick decision on:

- Whether generation deficiency occurs.
- Where does it happen?
- How much is the generation deficiency.

Rather than passively waiting for local relays to activate load-shedding steps, with real-time frequency rate of change and power flow exchange information, pro-active load shedding scheme and overall coordination should be possible to achieve faster system recovery.

Another feature of the proposed new scheme is the concentration of load shedding to just the disturbance area. The internal changes in generation causing deficiency will determine a negative value of AGE, whereas external changes will give a zero value. Therefore, the disturbance area can be identified immediately after the generation loss. This allows loads to be shed closer to the target generation loss center than the conventional system load shedding procedure does. This is extremely important in the deregulation situation since it will minimize the power supply disturbance in other control centers. In addition, tie-line flow recovers in a shorter time, thus avoiding sustained increases in tie line flows with possible effect on stability.

Proposed wide area load shedding is based on the frequency changing rate and tie line power flow information to predict the generation deficiency. Therefore, the result is accurate which can reduce the under or over load shedding.

When other power system contingencies, such as three phase grounded fault, fault clearance, switch reconnection occur, sometimes they also could cause negative value of AGE in one area, whereas zero AGE in other areas. However, by monitoring the frequency, we can easily identify the system fault and therefore block the load shedding from activating in such situations.

5.4.1 AGE Calculation Area Grouping

In order to calculate the AGE, the large-scale interconnected system needs be divided into several sub areas. Under the deregulation situation, the AGC (Automatic Generation Control) is allowed to control the contract powers of IPPs rather than the outputs of generation units. Therefore, the power calculation area can be divided based on control center. Each control center will be treated as an individual AGE calculation area. The control center can be also sub-divided its control area into sub AGE calculation area according to generation geographical location or voltage level. Figure 5.6 shows the system splitting diagram based on control center.

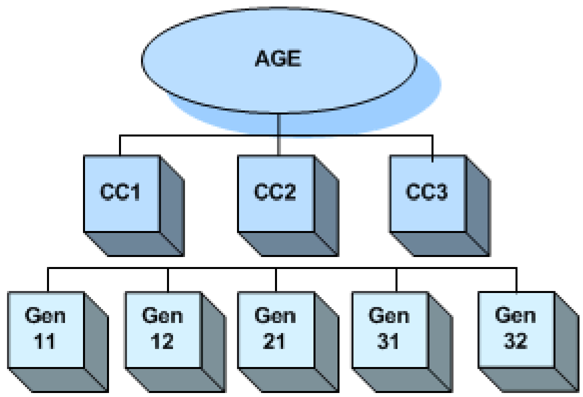

Figure 5.6 Generation Area Splitting

Control center stores each sub area's total generation and available loads information. Frequency, rate of change of frequency, and power exchange information will be sent to the control center in real time. Control center then calculates the AGE. When no overload occurs, AGE can be treat as ACE and controls the AGC based on the ACE calculation. If a generator trips in one area, the control center will identify the event location and calculate the generation deficiency. In the meantime, control center will also calculate the available spinning reserve and inter-area transmission line capacity. If the spinning reserve is greater than the generation lost and the transmission line also can handle the power needed, the load will not be shed.

In the actual WSCC system, there are 11 regional control centers as shown in Figure 5.7. Therefore, 11 AGE calculation areas can be allocated. Table 5.2 shows the detail system information of 11 control centers.

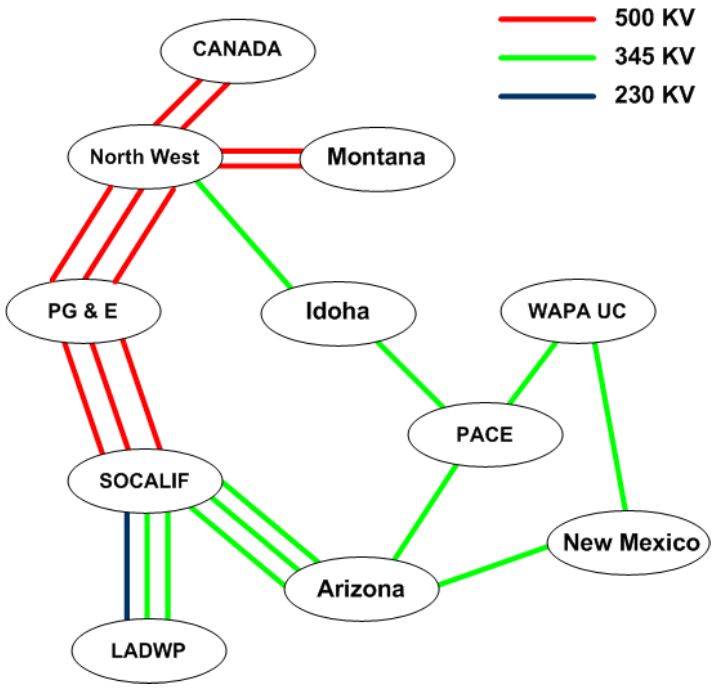

Figure 5.7 Control Center Allocation in WSCC Area

Table 5.2 Actual WSCC System Grouping

IPP	Generator	Total Generation
Canada	G25, G26, G27, G28, G29	8930 MW
North West	G31, G32, G33	16425.76 MW
Montana	G30	2910 MW
PG & E	G34, G35, G36, G37	5883 MW
SOCALIF	G19, G20, G21, G22, G23, G24	9747.7 MW
LADWP	G16, G17, G18	635 MW
Idaho	G7, G8	1640 MW
WAPA UC	G3, G5	3098 MW
New Mexico	G6	962 MW
Pace	G9, G10, G11	3890 MW
Arizona	G1, G2, G4, G12, G13, G14, G15	7290 MW

5.4.2 Area Generation Error Calculation

In order to calculate the area generation error, synchronized real time frequency and tie line power exchange information are needed.

5.4.3 Load Shedding Criteria

If the power system has sufficient spinning reserve to compensate the generation lost, the total amount of load to be shed will be

$$P_{LS} = \Delta P_G - k\Delta f_{ss} \qquad 5.13$$

If the spinning reserve is not enough to cover the generation lost, the load to be shed will be

$$P_{LS} > (\Delta P_G - SR - k\Delta f_{ss}) \qquad 5.14$$

Where

ΔP_G is the generation loss

k is the system stiffness

Δf_{ss} is the desired steady state frequency after load shedding.

SR is the interconnected system spinning reserve

5.4.4 Hierarchical Load Shedding Management

One of the advances of AGE load shedding method is that it can limit the load shedding to within the disturbance area. However, in some cases, the loads in the disturbance is less than the loads need to be shed, in this situation, the upper layer control center needs to distributes the additional load in other areas. As show in **Error! Reference source not found.**, when area Gen 11 has generation loss and the total load cannot match the load to be shed, other areas in control center 1 should share the extra load to be shed. The load shedding scheme needs the coordination of each layer control center.

5.5 PMU for the Synchronized Frequency Calculation

Wide area load shedding is the concept of using synchronized real time wide area frequency and tie line power flow information to perform fast and accurate load shedding. Since the AGE calculation will take effect only at the generation loss initial instant, the key points are how to get the accurate and synchronized real time information; How to transmit the information in real time. Phasor Measurement supports the solution for synchronized real time information measurement while fiber optic network gives the answer to the low latency data transmission.

The phasor measurement unit (PMU) is a key component of the power system to measure synchronized frequency, voltage and current phasor. PMU relies on GPS (Global Positioning System) to get the synchronized real-time sampling of voltage and current waveforms. By using the PMU, the power system can improve the monitoring and control of the system through same time, accurate system state information.

Phasor computation [127][128] is made by using recursive discrete Fourier transform to process data on a moving data window. The data window varies from a cycle to multiple cycles. Equation 5.15 shows the calculation of the fundamental frequency X from the collection of discrete waveform samples X_k

$$X = \frac{\sqrt{2}}{N}\sum_{k=1}^{N} X_k \varepsilon^{-j2k\pi/N} \qquad 5.15$$

Where N is sampling data window size.

For a frequency undergoing small change, the deviation can be approximately calculated using the rate of change of its phasor angle:

$$\Delta f = \frac{1}{2\pi}\frac{d\phi}{dt} \qquad 5.16$$

The phasor of a frequency waveform with N samples per cycle can be calculated using:

$$\bar{X} = \frac{1}{\sqrt{2}}(X_C + jX_S) \qquad 5.17$$

$$X_C = \frac{2}{N}\sum_{k=1}^{N} X_k \cos\left(\frac{2\pi}{N}k\right) \qquad 5.18$$

$$X_S = -\frac{2}{N}\sum_{k=1}^{N} X_k \sin\left(\frac{2\pi}{N}k\right) \qquad 5.19$$

Using the recursive formula [129], each successive phasor can be computed with:

$$X_C^{k+1} = X_C^k + \frac{2}{N}\sum_{k=1}^{N}(X_{k+1} - X_{k+1-N})\cos(\frac{2\pi}{N}k) \qquad 5.20$$

$$X_S^{k+1} = X_S^k + \frac{2}{N}\sum_{k=1}^{N}(X_{k+1} - X_{k+1-N})\sin(\frac{2\pi}{N}k) \qquad 5.21$$

Therefore, the phasor can be calculated on each incoming sample after the first cycle. The angle of the kth phasor is given by:

$$\phi(k) = \tan^{-1}\frac{-X_S^k}{X_C^k} \qquad 5.22$$

Assume phasor angle vary as a quadratic function

$$\phi(k) = a_0 + a_1 k + a_s k^2 \qquad 5.23$$

The factors a_0, a_1, a_2 can be solved using the least error square solution:

$$a = \left[X^T X\right]^{-1} X^T \phi \qquad 5.24$$

Where $a = [a_0, a_1, a_2]^T$, $\phi = [\phi_0, \phi_1, \phi_2]^T$, $X = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 2 & 2^2 \\ .. & .. & .. \\ 1 & M & M^2 \end{bmatrix}$

Once the a matrix is known, frequency and rate of change of frequency can be calculated using equation

$$\frac{d\phi}{dk} = a_1 + 2a_s k \qquad 5.25$$

$$\frac{d\phi}{dt} = Nf_0(a_1 + 2a_2 Nf_0 t) \qquad 5.26$$

Then

$$\Delta f = \frac{1}{2\pi}Nf_0(a_1 + 2a_2 Nf_0 t) \qquad 5.27$$

$$\frac{df}{dt} = \frac{1}{2\pi} 2(Nf_0)^2 a_2 \qquad 5.28$$

Synchronization of data sampling is achieved by using GPS synchronized crystal oscillator to generate common timing signal. Figure 5.8 illustrate the conception wide area load shedding system structure using real time synchronized phasor measurement information. By using PMU, timing accuracy in the order of millisecond can be achieved. All the communications are assumed to be setup through fiber optic network. Through fiber optic network, frequency, and tie line power flow data can be transmitted to the control center in real time. Control center will calculate the AGE to judge whether generation deficiency happens. Load shedding commands will be issued when there is generator loss.

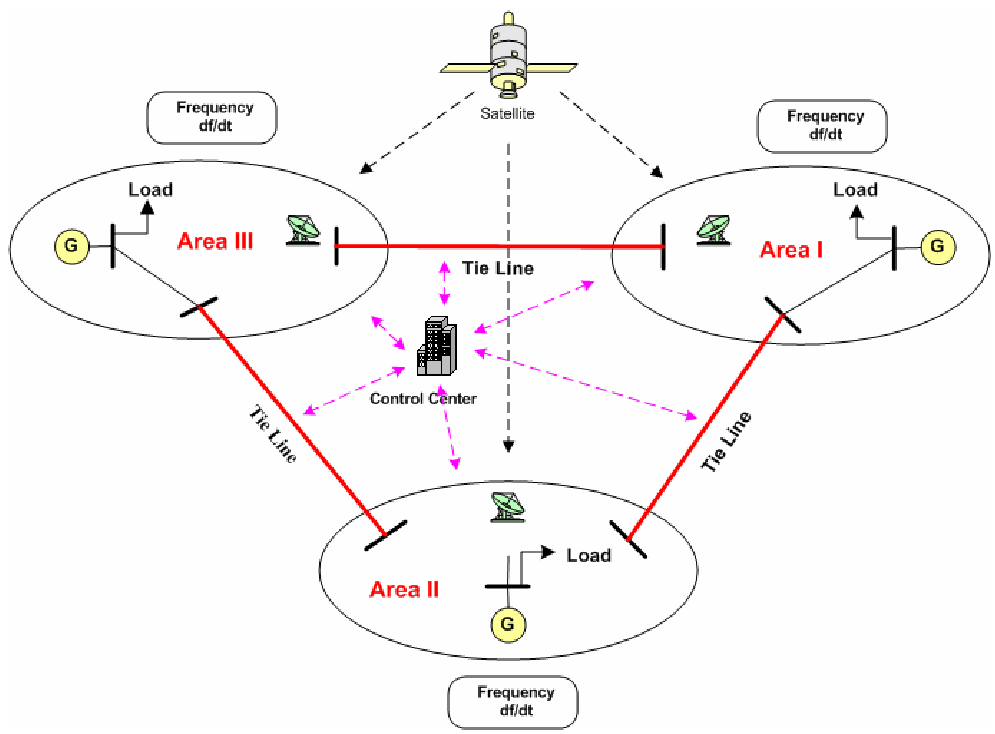

Figure 5.8 Connectional AGE based Wide Area Load Shedding Configuration

As stated in the previous section, in the instant of the generation loss, the generation deficiency is distributed to the residual generators based on the electrical location of the generation with respect to the bus at which the overload occurred. AGE actually calculates the system generation deficiency by calculating each generator's generation variation. Therefore, placing PMU near each generator allows for most accurate generation deficiency calculation. Equation 5.12 will be converted into

$$\Delta P_G - \Delta P_L - \Delta P_{Loss} = \sum_{i=1}^{n} M_i \frac{d\Delta f_i}{dt} + D\Delta f - \Delta P_E \qquad 5.29$$

Where n is the generator number. However, a ubiquitous placement near each generator is infeasible due to cost consideration. A worthwhile albeit simple solution is to use the area average frequency. As seen from Figure 5.3, even though frequency of each generator is different from area frequency, they all oscillate around the area center inertia frequency. Therefore, by using area center frequency, we also can get relatively accurate result. In the following section, we will present the calculation results in three cases.

5.6 System Simulations

The behavior of the proposed load shedding algorithm has been examined based on simplified 127-bus WSCC system illustrate in **Error! Reference source not found.**. EPRI's IPFlow (Interactive Power Flow) program is used to calculate the system steady state power flow. Extended Transient Midterm Stability Program (ETMSP) [117][129] is used to simulate the WSCC transient steady procedure. Output data is processed using Matlab.

5.6.1 WSCC Equivalent System Introduction

The simulation is set up on 127 buses WSCC equivalent system. The system has 37 generators with total generations of 61411.64 MW. There are 104 load buses with total loads of 60785.41 MW are connected by 211 transmission lines. All loads are modeled as constant PQ loads and the total transmission loss is of 625.05 MW. System has load reactive power of 15351.25 MVAR and reactive generation of 12332.47 MVAR. (Detail system information can be referred to Appendix I). Since the AGE based load shedding algorithm only makes use of the initial instant of the generation loss disturbance, the turbine governor response is neglected in the system dynamic model.

5.6.2 Simulation Parameter setting

In the simulation, we monitor each generator bus's frequency variation, and take the average to be the area center frequency. Generator inertia is calculated using equation 5.30.

$$M_i = \frac{\Delta P_i}{df_i / dt} \qquad 5.30$$

5.6.3 System Grouping

In order to calculate the system AGE, three virtual areas are defined for WSCC system as shown in Figure 5.9. Areas 1 and 2 are connected through a 500 kV transmission line 11 (Bus 51 – Bus 57). Areas 1 and 3 are connected through a 500 kV transmission line 72 (Bus 27 – Bus 29). Areas 2 and 3 are connected through three 500 kV transmission line 135/136/137 (Bus 77 – Bus 84). The area generation, load information, tie line information is shown in Table 5.3, Table 5.4 and Figure 5.9. According to equation 5.2, system AGE only related to the sub-system frequency response characteristic, therefore, the system can be randomly split. In the real case, we split the system into three virtual areas according to the region and voltage level.

Table 5.3 WSCC Grouping Information

Area	Generator No.	Generation (MW)	Load (MW)	Tie Line Flow (MW)
1	11	12,550	10567.2	1921.1
2	13	27,262	15780.4	-1250
3	13	34,149	34325.71	-653.8

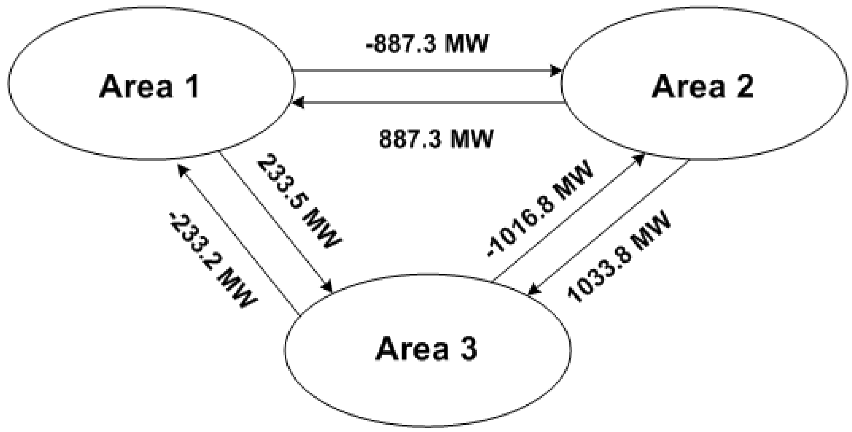

Figure 5.9 Three Area Power Flow Information

Table 5.4 Tie Line Power Flow between Each Area

Form Bus	To Bus	From Area	To Area	Power Flow
FOURCORN 500	MOENKOPI500	1	2	1033.8 MW
MIDPOINT345.	MIDPOINT500.	1	3	887.3 MW
MOENKOPI 500	FOURCORN 500	2	1	-1016.8 MW
VINCENT 500. (1)	MIDWAY 500. (1)	2	3	-77.8 MW
VINCENT 500. (2)	MIDWAY 500. (2)	2	3	-77.8 MW
VINCENT 500. (3)	MIDWAY 500. (3)	2	3	-77.8 MW
MIDPOINT500.	MIDPOINT345.	3	1	-887.3 MW
MIDWAY 500. (1)	VINCENT 500. (1)	3	2	77.8 MW
MIDWAY 500. (2)	VINCENT 500. (2)	3	2	77.8 MW
MIDWAY 500. (3)	VINCENT 500. (3)	3	2	77.8 MW

5.6.4 Simulation Study Cases

Different disturbance cases in different areas were simulated to study the generation trip transient and AGE application for the wide area load shedding. They are: three-phase fault and clearance; Generator trip in area 1; Generator trip in area 2.

For each case study, we calculate the AGE using multiple PMU and single PMU method. In the multiple PMU method, we assume each generator center has one PMU, AGE calculation will be based on equation

Table 5.5 Simulation Cases

Case	Area	Starting time	Location	Generation Loss
1	1	1.5s Generator trips; 1.6s Load shedding starts.	Bus 10, EMERY 20.0	1665 MW
2	3	1.5s Generator trips; 1.6s Load shedding starts.	Bus 88, DIABLO1 25.0	765 MW
3	2	1.5s three-phase short circuit fault starts; 1.65s fault cleared	Bus 111 RIVER 230. Bus 112 HAYNES 230.	N/A

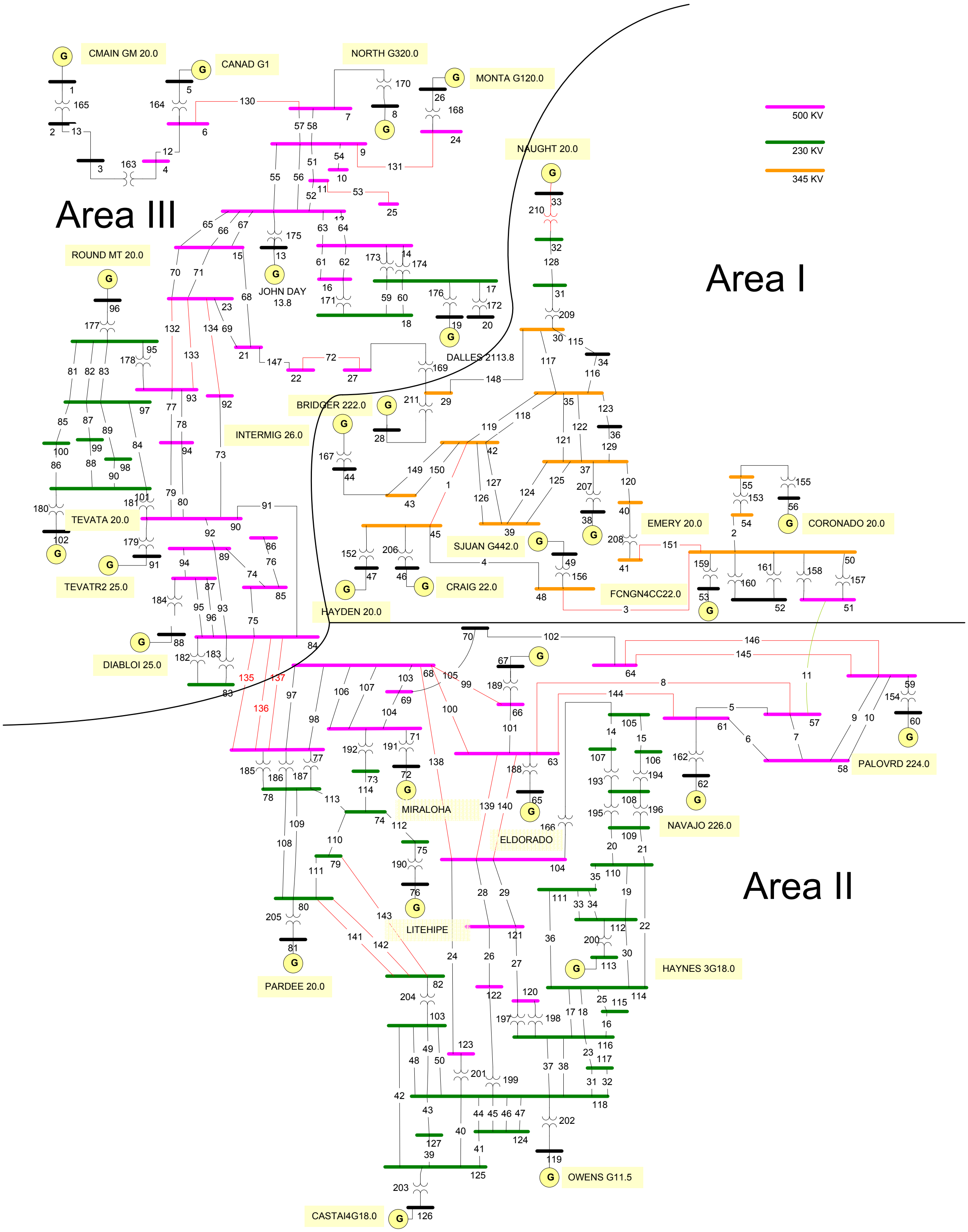

Figure 5.10 WSCC System Grouping Diagram

5.6.5 Case Study 1

Case 1 simulates a 1665 MW generator trip in area 2 at bus ELDORADO20.0. Detailed one line diagram is shown in Figure 5.11. Figure 5.12 shows the generator 1 CORONADO 20.0 output power variation after the generation loss contingency. As stated in the previous sections, the generation deficiency will be distributed to the residual generators. The big power jump at the initial instant shows the generation share taken by generator CORONADO 20.0. Figure 5.13 shows the frequency variations of different buses in each area. All frequency oscillates around a common oscillation center. As seen from Figure 5.14, bus frequency near event center has steeper frequency changing rate compared with the bus frequency far away. Figure 5.15 illustrates the area average frequency calculated using equation 5.29. Small power flow changes can also be observed in Figure 5.16.

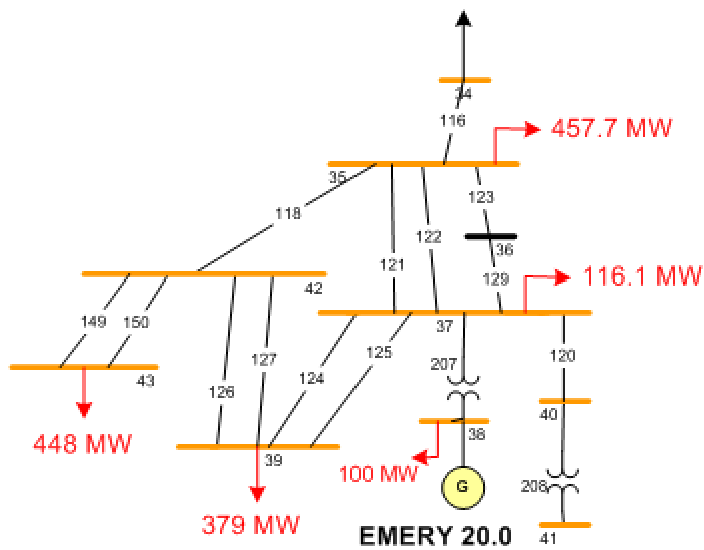

Figure 5.11 Detailed One Line Diagram Near Generator EMERY 20.0

Multiple PMU and single PMU AGE are calculated and shown in Figure 5.17 and Figure 5.18. In both figures, a significant difference can be observed between the AGE of area 1 from areas 2 and 3. During the initial instant, the AGE in area 1 is negative while AGE in area 2 and 3 are zero or a very small number. The AGE calculated in area 1 is the actual generation deficiency. By comparing the AGE in different areas, the generation deficiency can be identified and calculated immediately after the contingency. Proper actions can be taken to estimate the system running status, spinning reserves and determine how many loads to be shed and shed in which buses.

AGE calculation using multiple PMU is more accurate than the single PMU AGE method. In Figure 5.17, the AGE calculation is 1501 MW which is 9.84% variation. AGE in Figure 5.18 is 1480 MW which is 11.1% variation.

In the case study, we assume no spinning reserve is available in the system and the load shedding is activated right after the contingency. Multiple PMU AGE calculation is used to determine how many load to shed. Through the calculation, 1510 MW loads are shed in the surrounding areas. They are shown in red in Figure 5.11. Table 5.6 gives the detail load shedding information.

We assume fiber optic network is available to transmit the real time data and the time latency calculated to be 200 milliseconds.

$$\text{Time Delay} = T_T + T_P + T_Q + T_P$$

Where

T_T is Transmission Time

T_P is Propagation Time

T_Q is System Queuing Time

T_T is System Processing Time

We take the delay time to be 200 milliseconds and shed the load at time 1.7s.

Table 5.6 Case Study 1 Load Shedding List

Case	Load Shedding	Bus No.	Bus Name	Amount (MW)
1	1510 MW	35	CAMP WIL345.	457.7
		37	EMERY 345.	116.1
		38	EMERY 20.0	100
		39	SIGURD 345.	379
		43	INTERMT 345.	448

Figure 5.19 illustrates the three areas frequency variations after the load shedding. As seen from the figure, frequency drop is greatly reduced. Figure 5.20 shows the area frequency variation with and without the load shedding. AGE load shedding scheme shed the load immediately follow the generation loss disturbance while other methods will wait for 10 more seconds until the frequency drop hit the pick up setting.

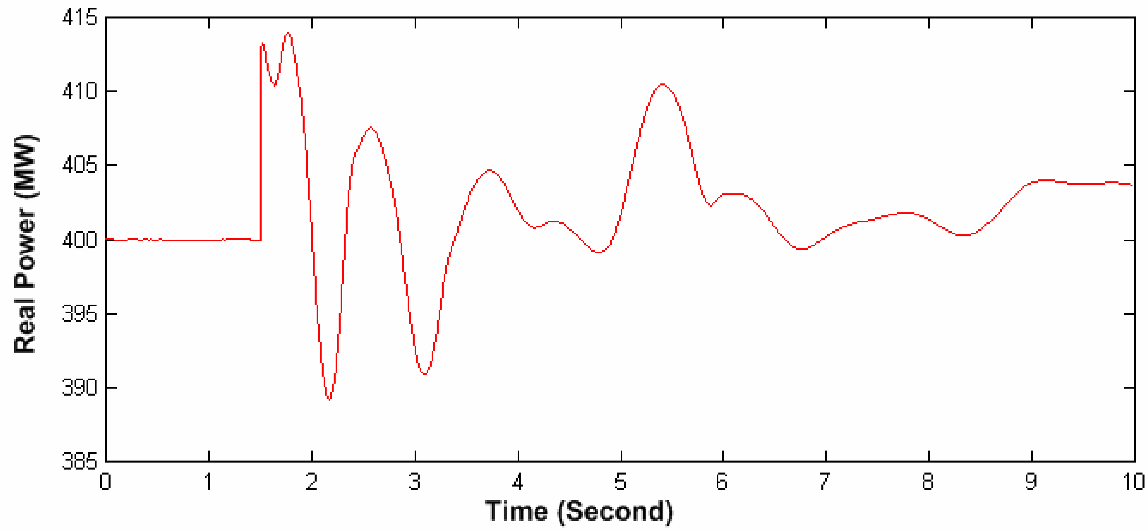

Figure 5.12 Generator 1 CORONADO 20.0 Power Variation (Case 1)

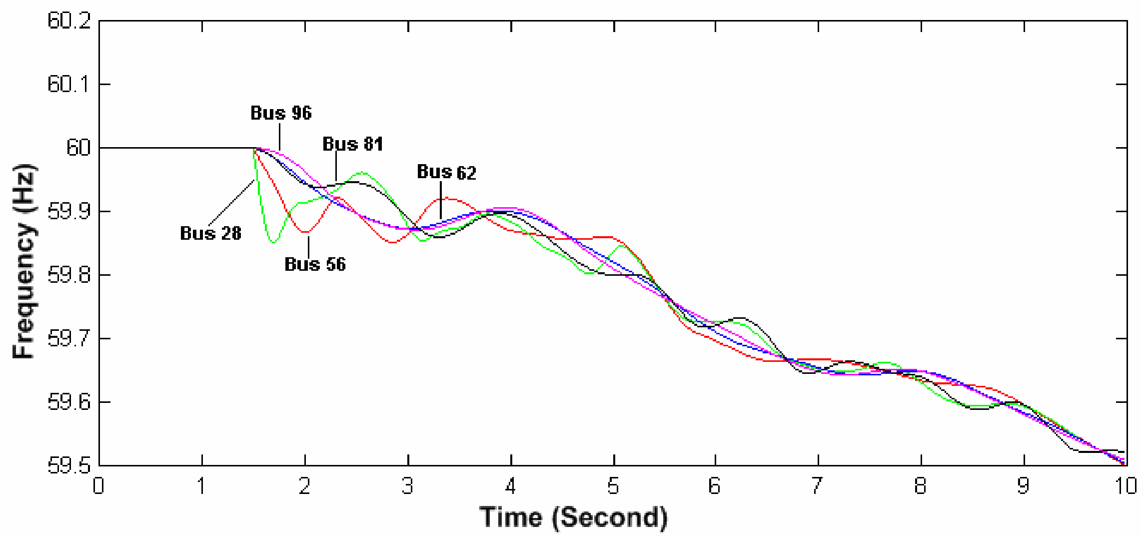

Figure 5.13 Bus Frequency Waveform in Different Areas (Case 1)

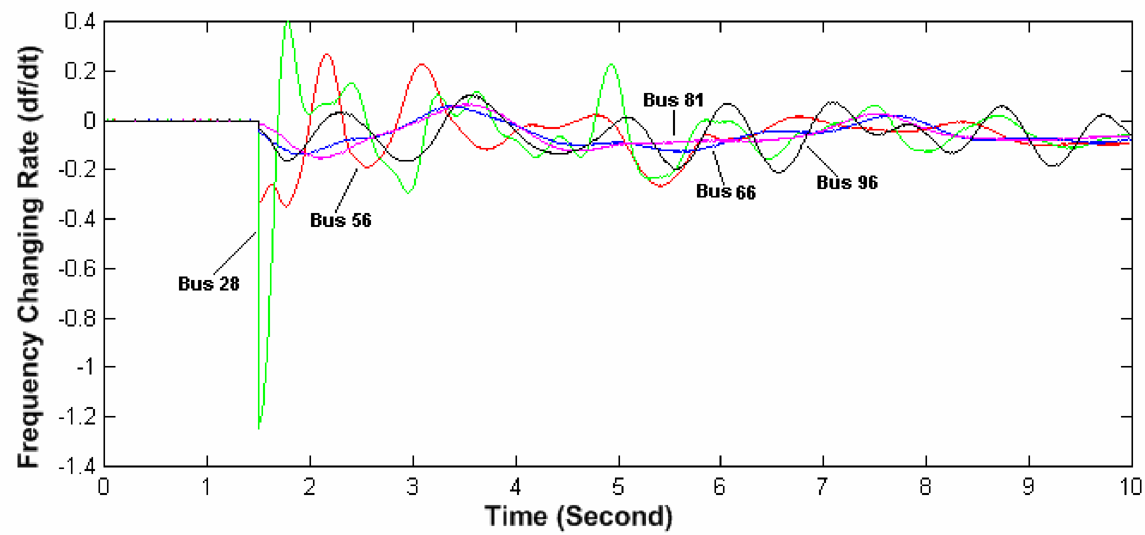

Figure 5.14 Bus Rate of Change of Frequency in Different Areas (Case 1)

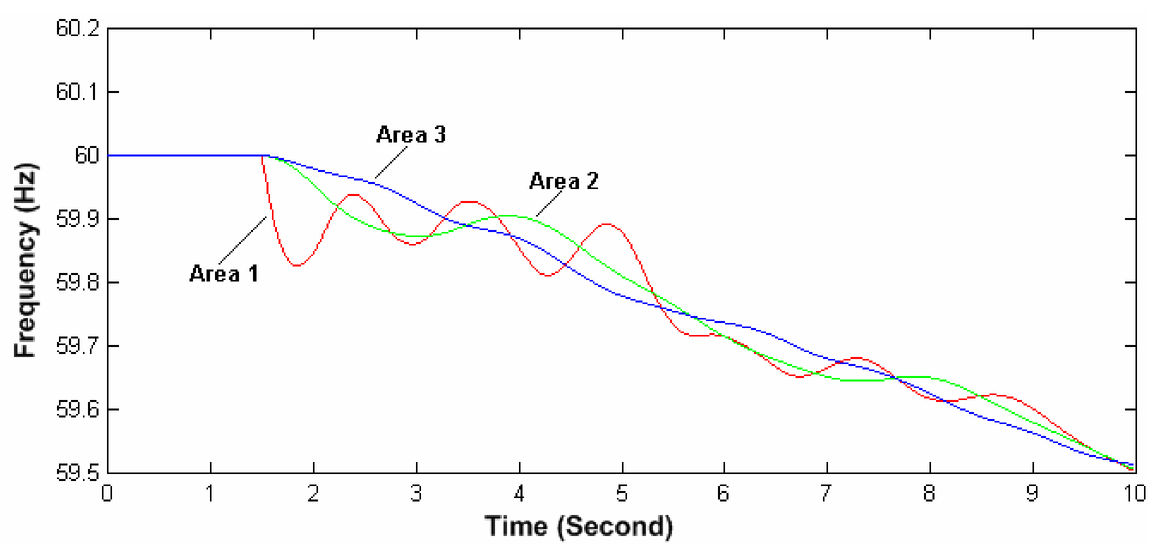

Figure 5.15 Three Areas Average Frequencies (Case 1)

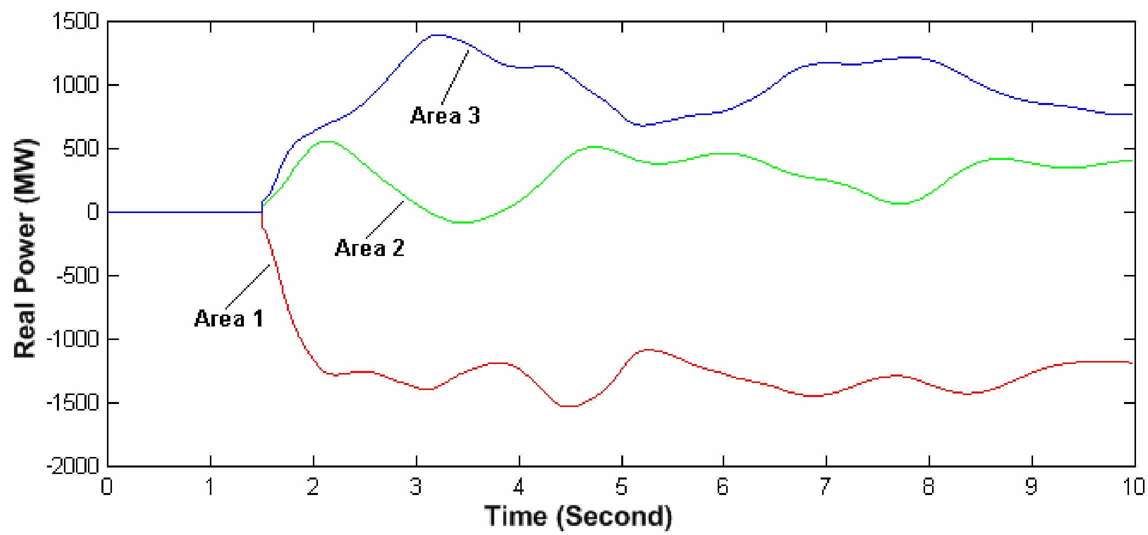

Figure 5.16 Tie Line Power Flow Variations (Case 1)

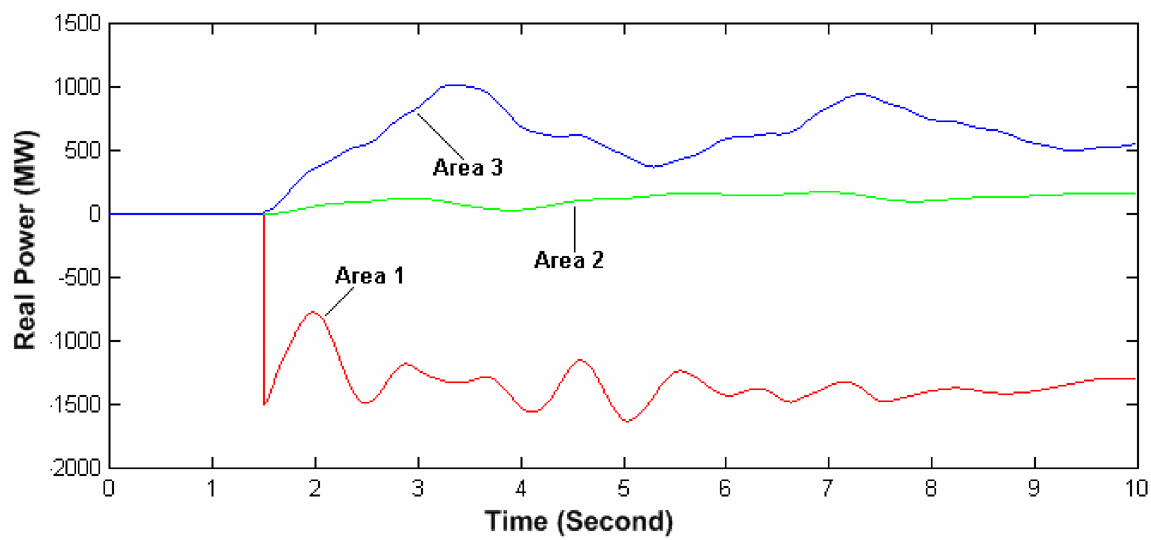

Figure 5.17 Multiple PMU AGE Calculation (Case 1)

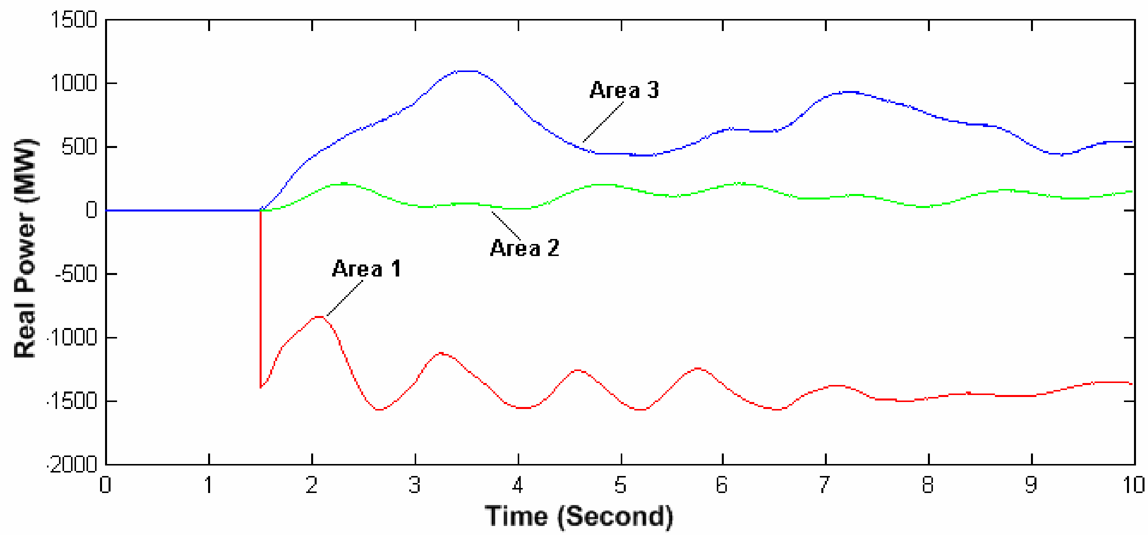

Figure 5.18 Single PMU AGE Calculation (Case 1)

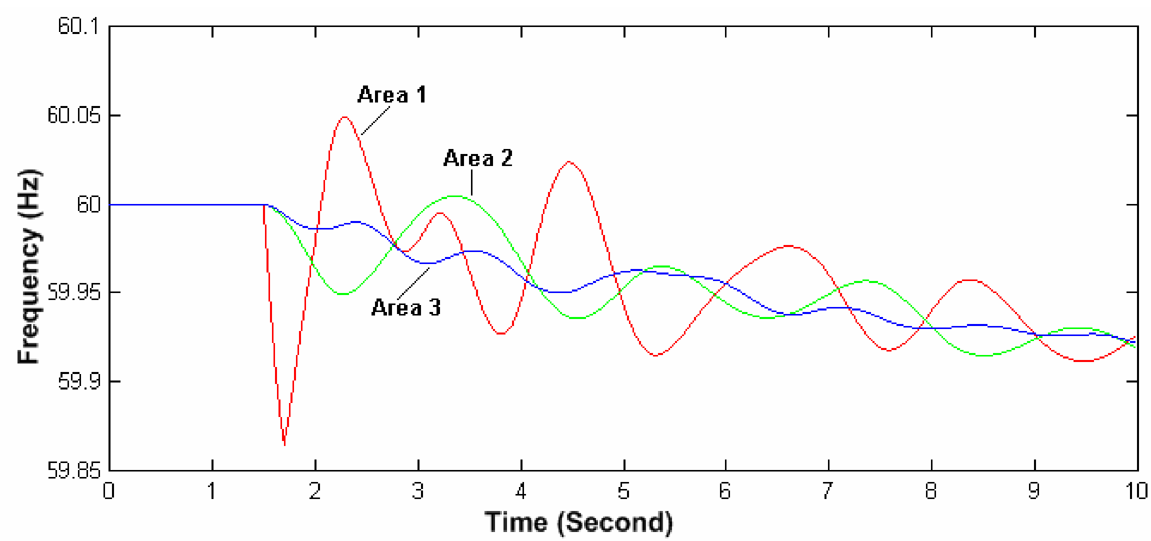

Figure 5.19 Area Frequency Variations with Load Shedding (Case 1)

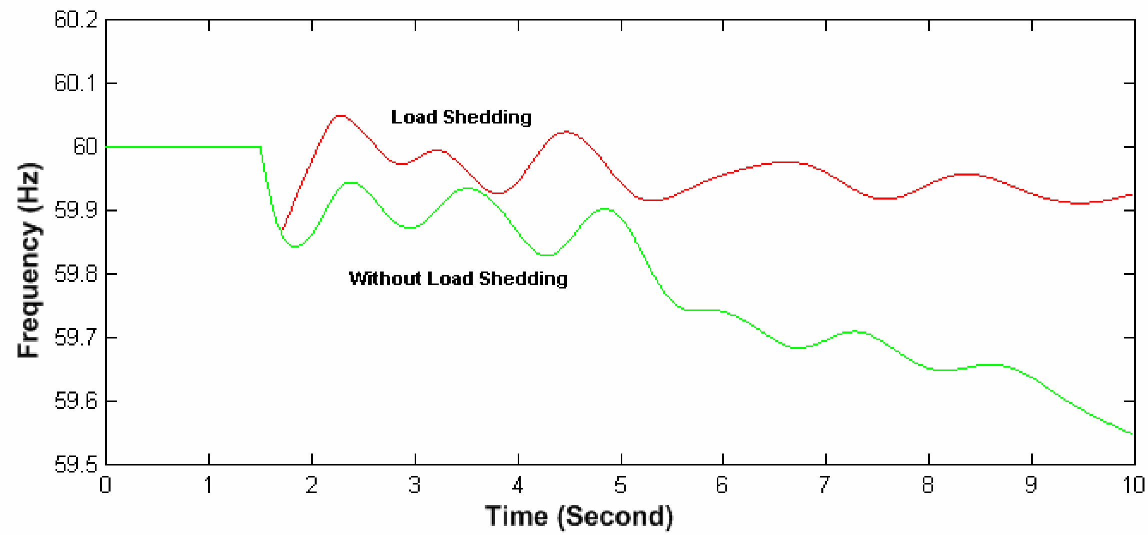

Figure 5.20 Frequency Variation with and Without Load Shedding (Case 1)

5.6.6 Case Study 2

Case 2 simulation chooses a generator trip in area 3. It is a 765.7 MW generator in bus 34 DIABLO1 25.0. Figure 5.22 shows the generator 1 CORONADO 20.0 output power variation after the generation loss contingency. Since the generation loss is in area 3 which is far from generator 1 CORONADO 20.0. Compare to the power variation in case 1 Figure 5.12, the value is relatively small. Figure 5.23 and Figure 5.24 show the frequency and frequency changing rate of different buses in different areas. DIABLO1 25.0 generator is a relatively small unit, the frequency oscillation is also slighter compared with case 1. Figure 5.25 illustrates the area average frequencies.

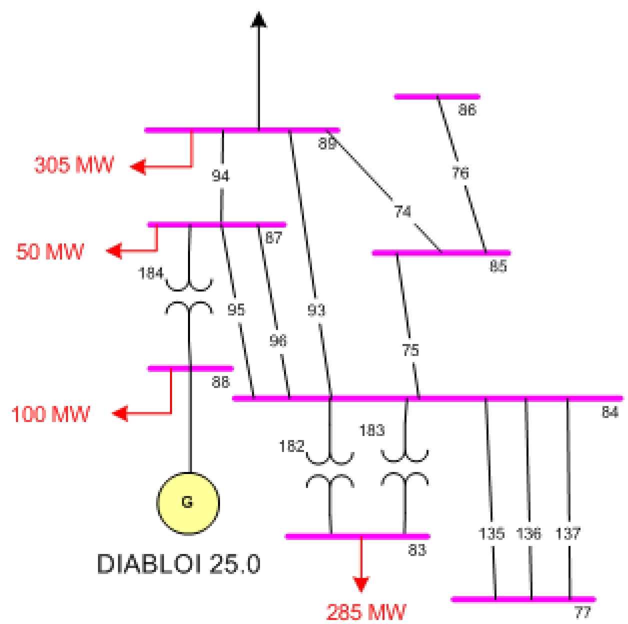

Figure 5.21 Detail One Line Diagram near Generator DIABLO1 25.0

Multiple PMU and single PMU AGE are calculated and shown in Figure 5.27and Figure 5.28. In both figures, a significant difference can be observed between he AGE of area 3 from areas 1 and 2. During the initial instant, the AGE in area 3 is negative while AGE in area 1 and 2 are zero or a very small number. The AGE calculated in area 3 is the actual generation deficiency. By comparing the AGE in different areas, the generation deficiency can be identified and calculated immediately after the contingency.

Again, AGE calculation using multiple PMU is more accurate than the single PMU AGE method. In Figure 5.17, the AGE is 752 MW which is 1.69%. AGE in Figure 5.18 is 740 MW which is 1.96%.

In the case study, we assume no spinning reserve is available in the system and the load shedding is activated right after the contingency. Multiple PMU AGE calculation is used to determine how many load to shed. Through the calculation, 740 MW loads are shed in the surrounding areas. Table 5.7 gives the detail load shedding information.

Table 5.7 Case Study 2 Load Shedding List

Case	Load Shedding	Bus No.	Bus Name	Amount (MW)
2	740 MW	87	DIABLO 500.	50
		88	DIABLO1 25.0	100
		89	GATES 500.	305
		83	MIDWAY 200.	285

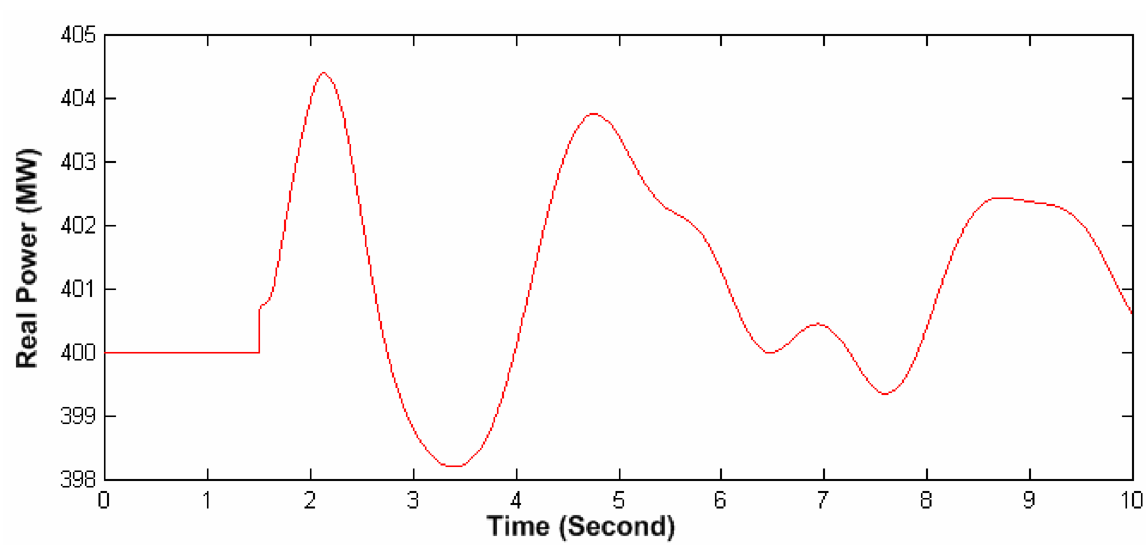

Figure 5.22 Generator 1 CORONADO 20.0 Power Variation (Case 2)

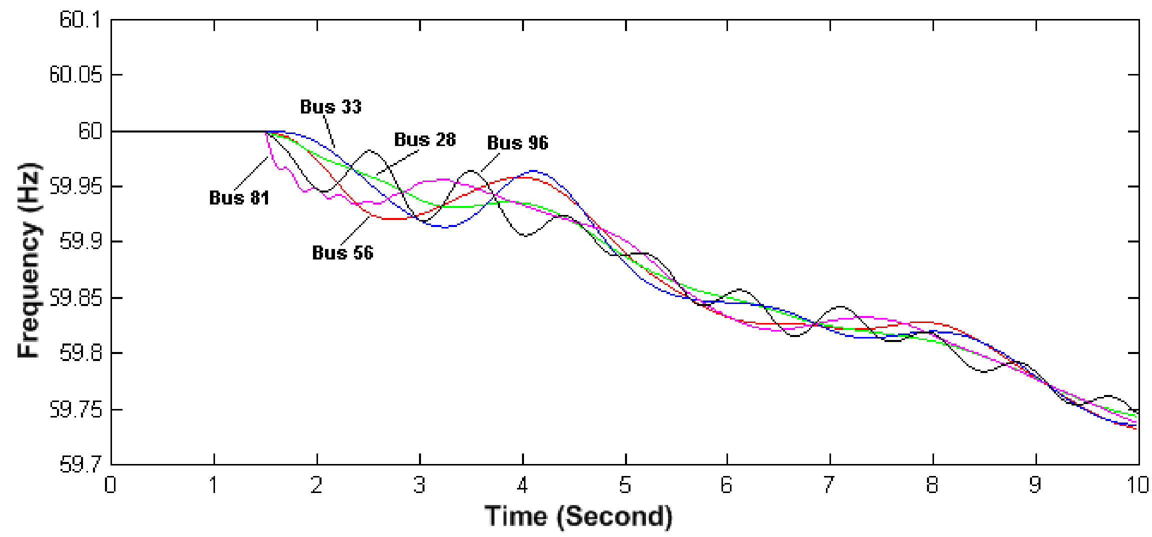

Figure 5.23 Bus Frequency Waveform in Different Areas (Case 2)

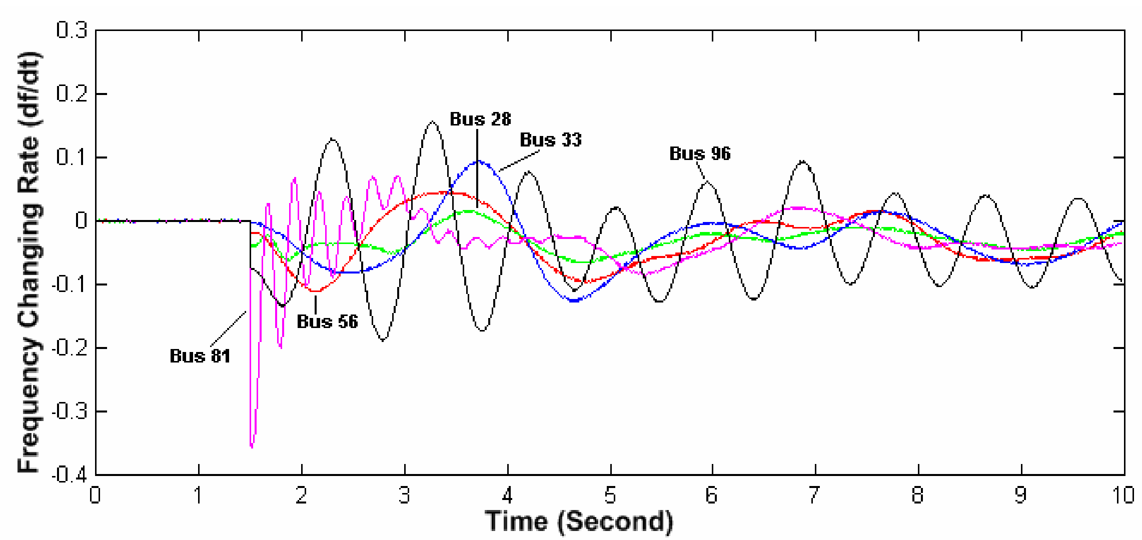

Figure 5.24 Bus Frequency Changing Rate in Different Areas (Case 2)

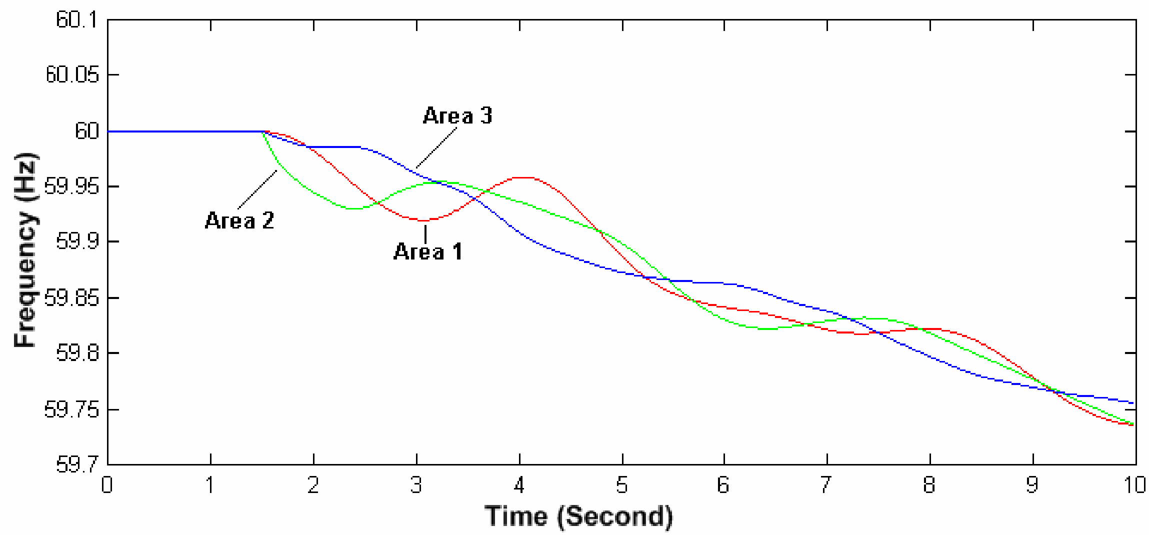

Figure 5.25 Three Areas Average Frequencies (Case 2)

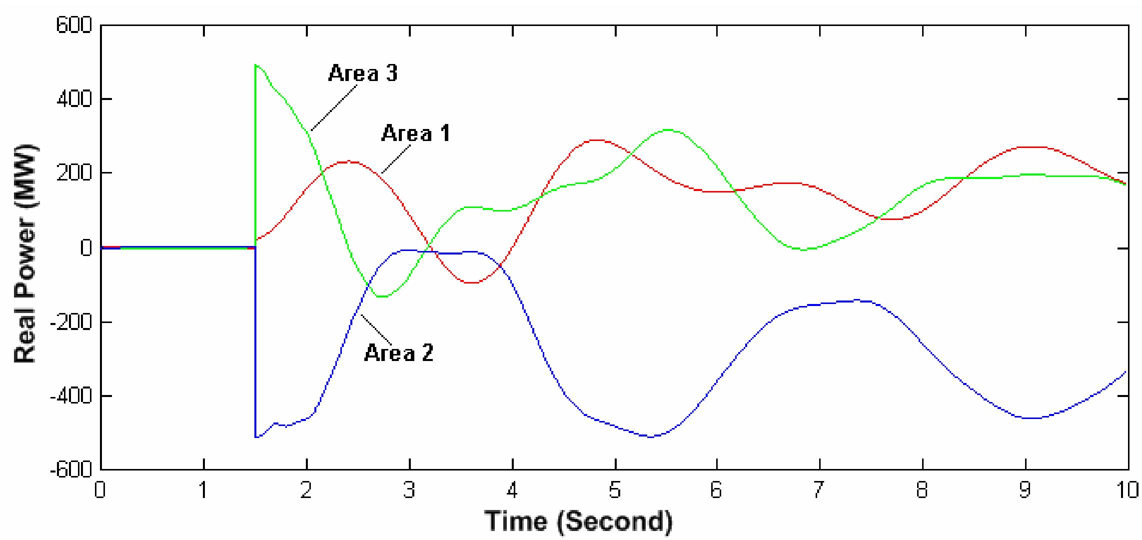

Figure 5.26 Tie Line Power Flow Variations (Case 2)

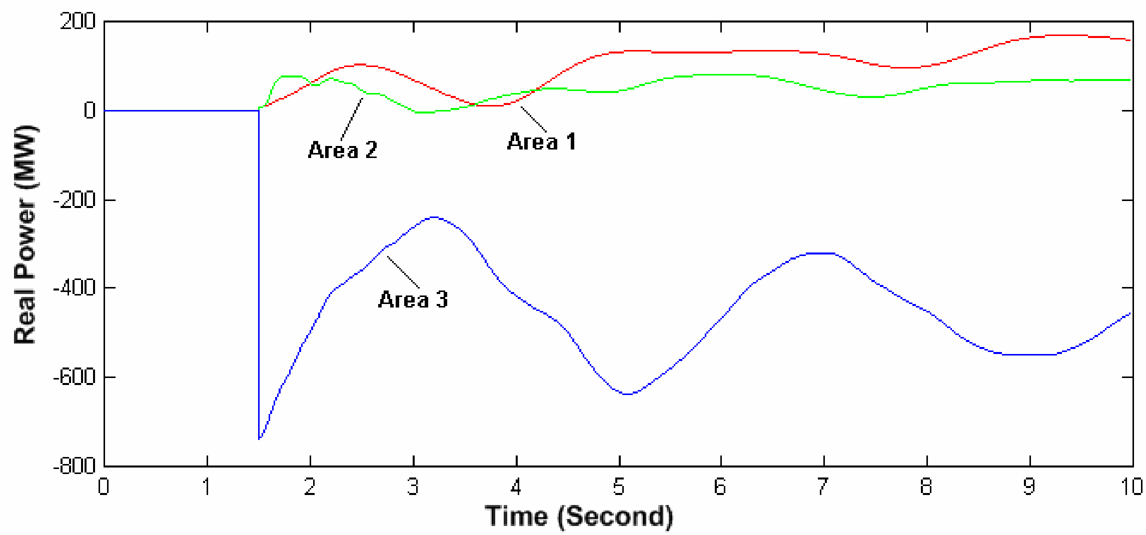

Figure 5.27 Multiple PMU AGE Calculation (Case 2)

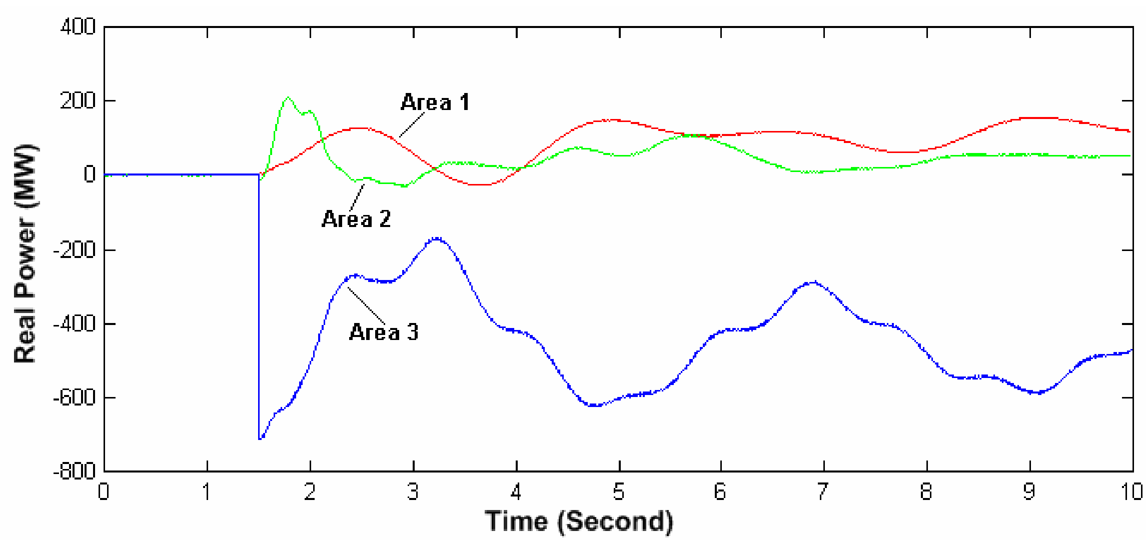

Figure 5.28 Single PMU AGE Calculation (Case 2)

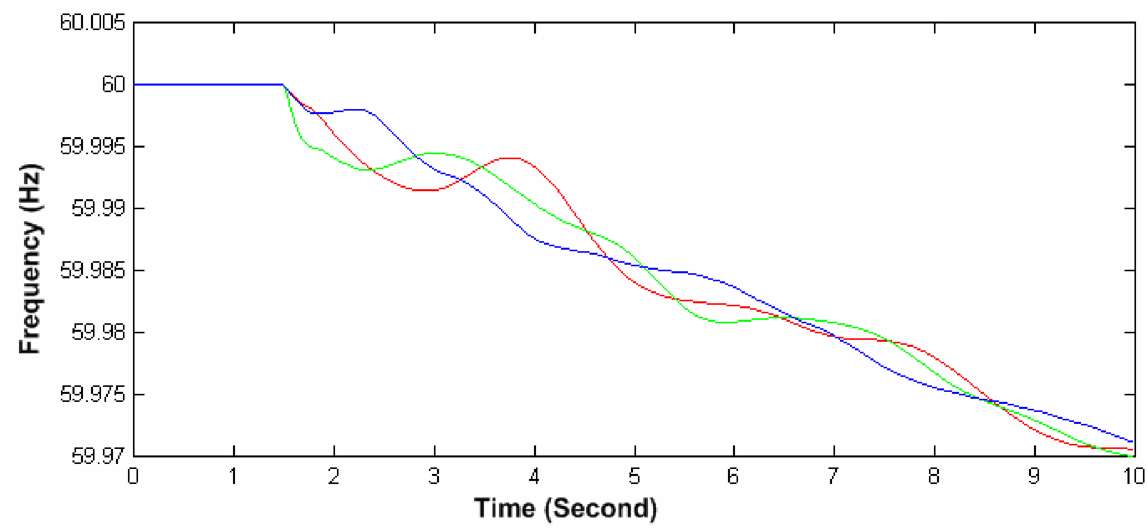

Figure 5.29 Area Frequency Variations with Load Shedding (Case 2)

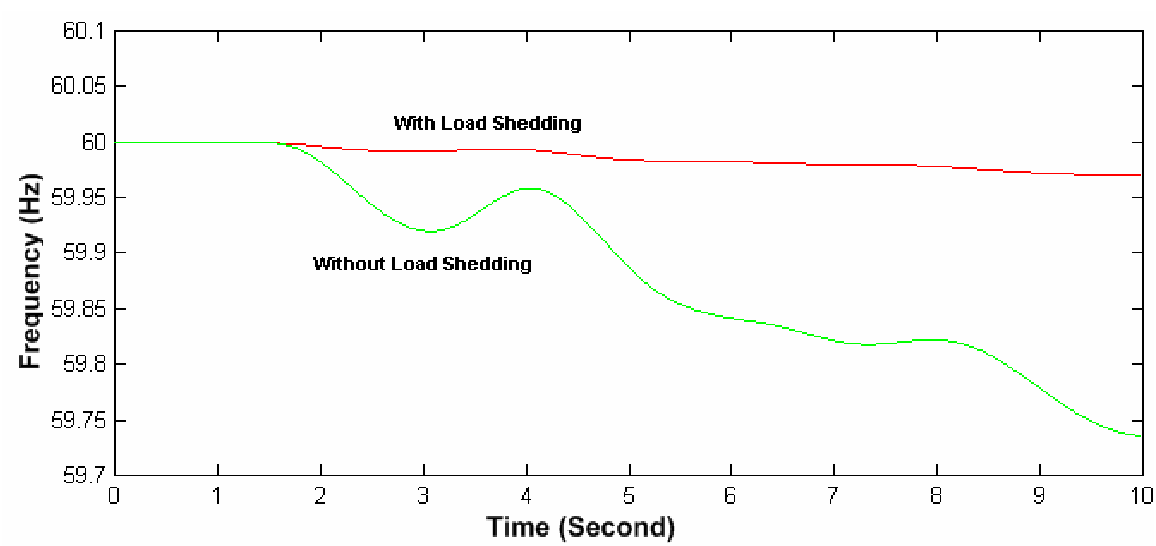

Figure 5.30 Area Frequency Variations with and Without Load Shedding (Case 2)

5.6.7 Case Study 3

Case 3 consists of a complex instant fault. The three-phase fault occurs on transmission line 33 between buses "RIVER 230." and "HAYNES 230." at time 1.50s. Detailed one line diagram near fault line 33 is shown in Figure 5.31. The fault is cleared off at time 1.65s by protection relay. At time 1.75s, the line is successfully reconnected back. Figure 5.32 shows the bus frequency variation in different areas. Figure 5.33 shows the area average frequency variation. Different from previous two cases, the frequency does not drop. Figure 5.34 shows the area AGE calculation. From Figure 5.34, we can see that the AGE no longer follows the similar variation as those in test case 1 and case 2. The load shedding should not be activated in this situation.

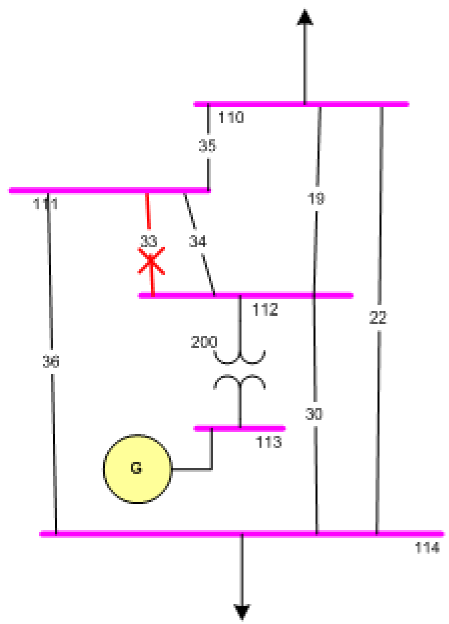

Figure 5.31 Detail One Line Diagram Near Short Circuit Fault Line

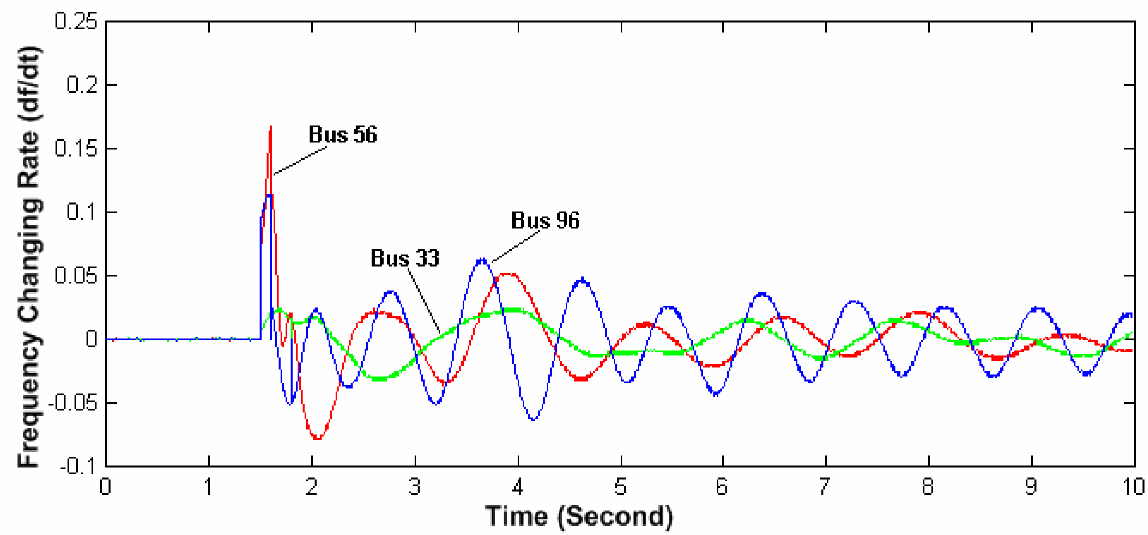

Figure 5.32 Bus Rate of Chance of Frequency in Different Areas (Case 3)

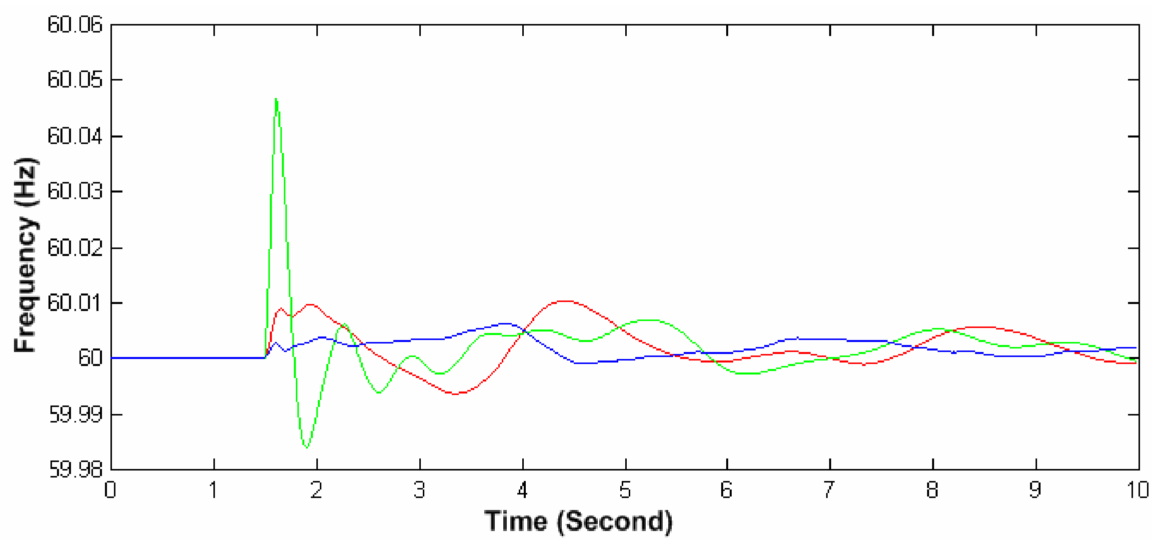

Figure 5.33 Area Frequency Variations (Case 3)

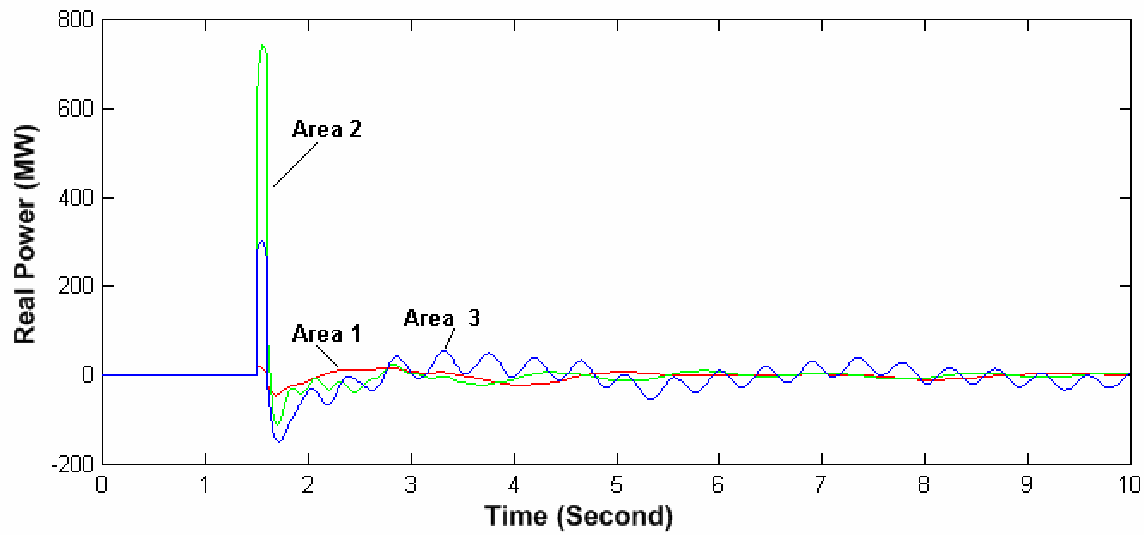

Figure 5.34 Multiple PMU AGE Calculation (Case 3)

5.7 Summary

Power industry restructuring poses challenges in the power system operation and control. Transmission line power flows are increasing as wheeling load grows. The power system stress and danger of losing synchronous and voltage stability are also increasing. Fast, accurate control function is needed for each contingency.

This section describes a wide area load shedding scheme based on real time, synchronized frequency and tie line power flow information. Rather than passively waiting for local relays to active load shedding steps, with real time AGE calculation, the disturbance area can be identified immediately after the generation loses. Internal changes in generation deficit or over load will determine a negative value of AGE, which equals to generation deficit, whereas external changes will give a small or zero value. The signal then can be sent to the disturbance area immediately to accurately shed the loads while prevent other areas from mis-shedding the loads.

Chapter 6 Conclusion and Future Research

As power system evolves, more and more real time information is needed to support the advanced service and functions in order to make the power system more stable and reliable. The new challenges bring the new requirements to the power system communication infrastructure. This thesis has addressed two important aspects of the strategy power infrastructure defense system: communication network investigation and associated power system real time applications.

The particular characteristics of the fiber optic network such as low attenuation, high bandwidth, small physical cross section, electromagnetic interface immunity, and security, make it the most suitable transmission medium for the future power system control, protection and monitoring functions. Fiber optic network is becoming the predominant network in the future to support new services and functions that drive increased bandwidth and time latency requirements. This trend poses new challenges to the areas of medium access, network topology design, information exchange and management. Based on IP over WDM technology, we proposed an all-fiber optic network architecture for the wide area and local area network real time data communication. We also proposed XML technology for wide area non time critical protocol design to address the increasing need of the universal data interchange format that enables information exchange between disparate power systems and applications.

The use of fiber optic network can greatly improve the power system control and protection functions. In this thesis, we presented three advanced applications that make use of the high bandwidth, low time latency fiber optic network.

- Internet-based SCADA System
- Local area network based load shedding scheme design and implementation
- AGE based wide area load shedding scheme design using PMU and fiber optic network

Future power system needs more bandwidth and high QoS communication system to meet its information exchange requirements. The first objective of the thesis is to address this challenge. By analyzing different transmission media and fiber optic network, we proposed an all fiber optic network to meet the future power system data transmission requirement. An XML based wide area transmission protocol design is also proposed to facilitate the multiple platforms and formats data exchange.

Power system development needs SCADA system to perform more advanced functions than it did before. The second objective of this thesis is to address the problem of SCADA system information exchange through public network. In an early study [21], we first proposed and setup a prototype for Internet based SCADA display system for access via Internet. However, an important issue is how to integrate new services and network elements to the existing system. We have set up SpecNet system to integrate the existing SCADA system with Internet/Intranet. The result showed that by using the advanced IT technologies, the existing SCADA system can be reused and extended to provide new services. Another innovative contribution is that we introduced VLSI technology into substation one line diagram auto generation. With the power system becomes more and more complex, one-line diagram layout is becoming increasingly complex. Manual draw of one line diagram is tedious and time consuming. In this thesis, we borrowed the VLSI design approaches for the substation one line diagram generation. Modified placement method was used to determine the location of each substation component. After placement, Hightower placement method was used to connect the component together with minimum crossovers and total connection length. Dynamic linkage will be added to display the real time data. The auto-generation algorithm can greatly reduce the one line diagram generation time.

Fiber optic network is especially suitable for the substation data communication due to its electromagnetic interface immunity characteristics besides the high bandwidth and low latency. The thesis presented one of its real time applications for the substation communication – LAN-based load shedding controller. LSC serves as an emergency protection in case of fast frequency drops. Traditional load shedding schemes were based on system dynamic simulation. Due to the system complexity, system is suffered from over or under load shedding which also could cause severe stability and reliability problems. The third objective of the thesis is to design a fast and accurate load shedding scheme for isolated power system. The current network and communication technologies can support high bandwidth, low time latency channels for reliable real time data transmission. Isolated power system is relatively located in a small geographical area. Fast local area network will be a suitable tool to monitor all the system running statuses. Therefore, we set up the load shedding controller based on substation fast fiber Ethernet. The system generation and load information can be fed in through local area network in real time for LSC to calculate the generation/load mismatch. Generator loss is one trigger to activate the LSC. LSC will check the system generation, spinning reserve as well as demand information to make the load shedding decision. Overload is another trigger to start the system. A timer will be set to allow system to absorb the extra load. If the system cannot handle that, LSC will start shedding loads based on preset priority list. The LAN based LSC scheme also gives system operator great flexibility and easy way to manipulate the priority dynamically through SCADA server. The load shedding priority list will automatically be updated to reflect the changes. LAN-based LSC has been implemented and tested in the actual oil refinery plant. The site tests showed that the fiber fast Ethernet can process the plant data traffic without any long time delay and packet drop. The LSC can shed the loads within 200 ms when the generation deficiency happens.

Local area network based load shedding scheme could also be employed for the interconnected power system load shedding scheme design. However, large interconnected systems are far more complex than isolated system. Heavy traffic and calculation burden for both the wide area network and LSC server will be introduced for generation/load calculation. The thesis addresses this problem by using PMU and wide area fiber optic network. PMU is considered to be one of the most important measuring device for the future power system, it support synchronized frequency information for further processing. Power system can greatly benefit from its unique ability to provide synchronized phasor measurements. We propose a wide area load shedding scheme based on the area generation error calculation making use of synchronized area frequency and tie line power flow information. When generation loss occurs, in the instant of contingency, the lost generation will be distributed to the rest generators based on the electrical location of the generation with respect to the bus at lost generator. According to the second order differential form of the swing equation, the frequency of each generator will decrease in a quati-oscillatory manner following the load/generation mismatch. The magnitude and frequency of these oscillations are depending on the rotor inertia constant and the electrical location of the generations. Therefore, when generation/demand mismatch happens, instead of waiting for frequency drop to the preset value to activate the load shedding relay, by monitoring the synchronized real time system area frequency and tie line information, the generation deficiency can be predicted at the initial instant of the contingency. Proper actions can be taken to shed the accurate amount of loads. In addition, in stead of shed the loads system wide, the AGE based load shedding scheme can limit the load shedding only in the disturbance area. This point is especially important for the system deregulation. Different generation loss contingencies have been simulated to test the load shedding scheme performance. The results showed that the scheme could identify the generation deficiency area right after the generation loss occurred with accurate amount.

The following research is recommended for the future work.

1. The LAN-based load shedding controller design is based on the steady state analysis, however, system dynamic characteristics might also needs to be considered to meet the dynamic stability requirements. More research work can be done to further optimize the load shedding controller.
2. Different location of the generation loss will have different effects on the AGE based load shedding controller design. By using AGE calculation, we also can predict the system stability and check the tie line transmission limits.

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Appendix A WSCC System Data

Western System Coordinating Council [131] is one of the nine regional electric reliability councils in North America. It is an international organization responsible for promoting electric system reliability and providing a forum for coordinating the operating and planning activities for its 88 member systems. WSCC members provide electric service to 59 million people in 14 western states, 2 Canadian provinces, and portions of 1 Mexican state.

The WSCC 127-bus equivalent system has been chosen for the simulation study. The actual WSCC system has more than 2000 buses. The system has 127 buses, 37 generators, 211 transmission lines. Detailed bus, generator, load and line information are given below. Details were taken care of to retain the accuracy of the major system static and dynamic characteristics.

Generator Models

The WSCC system has been divided into 5 major areas. Area generation was grouped into one or more equivalent machines. Smaller generation units were either grouped together to form a single machine or clustered with a larger machine. Detailed generation model set up information can refer to Table A.4.

Network Configuration

The transmission system has three major voltage levels: 500 kV, 345 kV and 230 kV.

Load Models

The load was modeled as PQ constant for the simplicity. The load information is listed in Table A.2 and Table A.3.

Table A.1 WSCC System Bus Data

Bus Number	Bus Name	Area
1	CMAIN GM20.0	3
2	CA230 230.	3
3	CA230TO 230.	3
4	CANALB 500.	3
5	CANAD G120.0	3
6	CANADA 500.	3
7	NORTH 500.	3
8	NORTH G320.0	3
9	HANFORD 500.	3
10	COULEE 500.	3
11	GARRISON500.	3
12	JOHN DAY500.	3
13	JOHN DAY13.8	3
14	BIG EDDY500.	3
15	GRIZZLY 500.	3
16	CELILOCA500.	3
17	BIG EDDY230.	3
18	CELILO 230.	3
19	DALLES2113.8	3
20	BIG EDDY115.	3
21	SUMMER L500.	3
22	BURNS2 500.	3
23	MALIN 500.	3
24	MONTANA 500.	3
25	COLSTRP 500.	3
26	MONTA G120.0	3
27	MIDPOINT500.	3
28	BRIDGER222.0	1
29	MIDPOINT345.	1
30	BENLOMND345.	1
31	BENLOMND230.	1
32	NAUGHTON230.	1
33	NAUGHT 20.0	1
34	SIGURD 345.	1

Bus Number	Bus Name	Area
35	CAMP WIL345.	1
36	SPAN FRK345.	1
37	EMERY 345.	1
38	EMERY 20.0	1
39	SIGURD 345.	1
40	PINTO 345.	1
41	PINTO PS345.	1
42	MONA 345.	1
43	INTERMT 345.	1
44	INTERM1G26.0	1
45	CRAIG 345.	1
46	CRAIG 22.0	1
47	HAYDEN 20.0	1
48	SAN JUAN345.	1
49	SJUAN G422.0	1
50	FOURCORN345.	1
51	FOURCORN500.	1
52	FOURCORN230.	1
53	FCNGN4CC22.0	1
54	CHOLLA 345.	1
55	CORONADO500.	1
56	CORONADO20.0	1
57	MOENKOPI500.	2
58	WESTWING500.	2
59	PALOVRDE500.	2
60	PALOVRD224.0	2
61	NAVAJO 500.	2
62	NAVAJO 226.0	2
63	ELDORADO500.	2
64	DEVERS 500.	2
65	ELDORADO20.0	2
66	MOHAVE 500.	2
67	MOHAV1CC22.0	2
68	LUGO 500.	2
69	SERRANO 500.	2
70	VALLEY 500.	2

Bus Number	Bus Name	Area
71	MIRALOMA500.	2
72	MIRALOMA20.0	2
73	MIRALOMA230.	2
74	MESA CAL230.	2
75	LITEHIPE230.	2
76	LITEHIPE20.0	2
77	VINCENT 500.	2
78	VINCENT 230.	2
79	EAGLROCK230.	2
80	PARDEE 230.	2
81	PARDEE 20.0	2
82	SYLMAR S230.	2
83	MIDWAY 200.	3
84	MIDWAY 500.	3
85	LOSBANOS500.	3
86	MOSSLAND500.	3
87	DIABLO 500.	3
88	DIABLO1 25.0	3
89	GATES 500.	3
90	TEVATR 500.	3
91	TEVATR2 20.0	3
92	OLINDA 500.	3
93	ROUND MT500.	3
94	TABLE MT500.	3
95	ROUND MT200.	3
96	ROUND MT20.0	3
97	COTWDPGE200.	3
98	LOGAN CR200.	3
99	GLENN 200.	3
100	CORTINA 200.	3
101	TEVATR 200.	3
102	TEVATR 20.0	3
103	SYLMARLA230.	2
104	VICTORVL500.	2
105	VICTORVL287.	2
106	STA B2 287.	2

Bus Number	Bus Name	Area
107	STA B1 287.	2
108	STA B 138.	2
109	STA BLD 230.	2
110	STA F 230.	2
111	RIVER 230.	2
112	HAYNES 230.	2
113	HAYNES3G18.0	2
114	STA G 230.	2
115	GLENDAL 230.	2
116	STA E 230.	2
117	VALLEY 230.	2
118	RINALDI 230.	2
119	OWENS G 11.5	2
120	STA E 500.	2
121	ADELANTO500.	2
122	ADELAN&1500.	2
123	RINALDI 500.	2
124	STA J 230.	2
125	CASTAIC 230.	2
126	CASTAI4G18.0	2
127	OLIVE 230.	2

Table A.2 WSCC System Load Information

Bus Number	Bus Name	Load (MW)	Area
28	BRIDGER222.0	100	1
29	MIDPOINT345.	610	1
30	BENLOMND345.	33.9	1
31	BENLOMND230.	148	1
32	NAUGHTON230.	255	1
33	NAUGHT 20.0	100	1
34	SIGURD 345.	185	1
35	CAMP WIL345.	457.7	1
36	SPAN FRK345.	141.2	1
37	EMERY 345.	116.1	1
38	EMERY 20.0	100	1
39	SIGURD 345.	379	1
40	PINTO 345.	31.6	1
42	MONA 345.	-62	1
43	INTERMT 345.	2053	1
44	INTERM1G26.0	100	1
45	CRAIG 345.	2350	1
46	CRAIG 22.0	100	1
47	HAYDEN 20.0	100	1
48	SAN JUAN345.	840	1
49	SJUAN G422.0	100	1
50	FOURCORN345.	239	1
51	FOURCORN500.	0.58	1
52	FOURCORN230.	139.7	1
53	FCNGN4CC22.0	100	1
55	CORONADO500.	1750	1
56	CORONADO20.0	100	1
58	WESTWING500.	617	2
59	PALOVRDE500.	793.4	2
60	PALOVRD224.0	100	2
61	NAVAJO 500.	90	2
62	NAVAJO 226.0	100	2
63	ELDORADO500.	902.3	2
64	DEVERS 500.	856	2
65	ELDORADO20.0	100	2

Bus Number	Bus Name	Load (MW)	Area
67	MOHAV1CC22.0	100	2
68	LUGO 500.	204.2	2
69	SERRANO 500.	1230	2
70	VALLEY 500.	406	2
71	MIRALOMA500.	3098	2
72	MIRALOMA20.0	100	2
74	MESA CAL230.	377.4	2
75	LITEHIPE230.	3191	2
76	LITEHIPE20.0	100	2
78	VINCENT 230.	1066	2
79	EAGLROCK230.	175	2
80	PARDEE 230.	3118	2
81	PARDEE 20.0	100	2
82	SYLMAR S230.	401	2
103	SYLMARLA230.	-2771	2
105	VICTORVL287.	-129	2
108	STA B 138.	237.2	2
109	STA BLD 230.	138	2
110	STA F 230.	117	2
111	RIVER 230.	320	2
113	HAYNES3G18.0	100	2
114	STA G 230.	121	2
115	GLENDAL 230.	135	2
116	STA E 230.	807.8	2
117	VALLEY 230.	205.2	2
118	RINALDI 230.	121	2
119	OWENS G 11.5	100	2
121	ADELANTO500.	-1862	2
124	STA J 230.	887.7	2
126	CASTAI4G18.0	100	2
127	OLIVE 230.	-72.8	2
1	CMAIN GM20.0	100	3
2	CA230 230.	3600	3
5	CANAD G120.0	100	3
6	CANADA 500.	4400	3
7	NORTH 500.	5000	3

Bus Number	Bus Name	Load (MW)	Area
8	NORTH G320.0	100	3
9	HANFORD 500.	3500	3
11	GARRISON500.	2584	3
12	JOHN DAY500.	3200	3
13	JOHN DAY13.8	100	3
14	BIG EDDY500.	-44.2	3
15	GRIZZLY 500.	-66.6	3
17	BIG EDDY230.	-67.5	3
18	CELILO 230.	3137	3
19	DALLES2113.8	100	3
20	BIG EDDY115.	160	3
22	BURNS2 500.	1120.9	3
23	MALIN 500.	-339	3
24	MONTANA 500.	1700	3
25	COLSTRP 500.	-1525	3
26	MONTA G120.0	100	3
27	MIDPOINT500.	-1233	3
83	MIDWAY 200.	777.6	3
84	MIDWAY 500.	55.6	3
85	LOSBANOS500.	265	3
86	MOSSLAND500.	40	3
87	DIABLO 500.	50	3
88	DIABLO1 25.0	100	3
89	GATES 500.	305	3
90	TEVATR 500.	5661	3
91	TEVATR2 20.0	100	3
92	OLINDA 500.	-189	3
94	TABLE MT500.	-0.7	3
95	ROUND MT200.	148	3
96	ROUND MT20.0	100	3
97	COTWDPGE200.	210.4	3
98	LOGAN CR200.	8.01	3
99	GLENN 200.	27.5	3
100	CORTINA 200.	-43.3	3
101	TEVATR 200.	884	3
102	TEVATR 20.0	100	3

Table A.3 WSCC Load Statistics

	Total:	**60673.89**			
	Area 1 Load:	10567.78			
	Area 2 Load:	15780.4			
	Area 3 Load:	34325.71			
Area	**Load**	**Generation**	**Tie Line Flow**	**Trans Loss**	**Difference**
1	10567.2	12550	1921.1	60.9	0.8
2	15780.4	14712.7	-1250	188.6	-6.3
3	34325.71	34148.76	-653.8	471.4	5.45
Total:	60673.31	61411.46	738.15		
		Tie Line Power Flow			
From Bus	**To Bus**	**Areas**	**Power Flow**		
29	27	1 --> 3	887.3		
51	57	1 --> 2	1033.8		
57	51	2 --> 1	-1016.8		
77	84	2 --> 3	-81.1		
77	84	2 --> 3	-76.3		
77	84	2 --> 3	-75.8		
27	29	3 --> 1	-887.3		
84	77	3 --> 2	81.2		
84	77	3 --> 2	76.4		
84	77	3 --> 2	75.9		
		Tie Line Transmission Power Loss			
Bus	**Power (MW)**				
27 --> 29	0				
51 -->57	17				
77 -- > 84	0.1				
77 -- > 84	0.1				
77 -- > 84	0.1				
Area Power Flow Exchange					
Tie Line Load 1 --> 2		1033.8			
Tie Line Load 2 --> 1		-1016.8			
Tie Line Load 1 --> 3		887.3			
Tie Line Load 3 --> 1		-887.3			
Tie Line Load 2 --> 3		-233.2			
Tie Line Load 3 --> 2		233.5			

Table A.4 WSCC System Generation Information

No.	Bus	Name	Area	Power (MW)	Load (MW)	Inertia (J S)
1	56	CORONADO20.0	1	400	100	32.0131
2	56	CORONADO20.0	1	400	100	32.0131
3	46	CRAIG 22.0	1	1048	100	106.223
4	53	FCNGN4CC22.0	1	2160	100	227.7903
5	47	HAYDEN 20.0	1	2050	100	199.9384
6	49	SJUAN G422.0	1	962	100	148.2333
7	28	BRIDGER2 22	1	820	100	53.3746
8	28	BRIDGER2 22	1	820	100	53.3746
9	44	INTERM1G26.0	1	1780	100	163.5972
10	38	EMERY 20.0	1	1665	100	174.3213
11	33	NAUGHT 20.0	1	445	100	70.0953
12	62	NAVAJO 226.0	2	1690	100	351.31
13	60	PALOVRD224.0	2	880	100	107.502
14	60	PALOVRD224.0	2	880	100	107.502
15	60	PALOVRD224.0	2	880	100	107.502
16	126	CASTAI4G18.0	2	200	100	87.2946
17	113	HAYNES3G18.0	2	325	100	61.3488
18	119	OWENS G 11.5	2	110	100	11.6397
19	65	ELDORADO20.0	2	982.7	100	350.7077
20	76	LITEHIPE20.0	2	3195	100	702.9051
21	72	MIRALOMA20.0	2	1690	100	224.225
22	67	MOHAV1CC22.0	2	840	100	86.0167
23	67	MOHAV1CC22.0	2	840	100	86.0167
24	81	PARDEE 20.0	2	2200	100	204.0135
25	5	CANAD G120.0	3	4450	100	1068.8
26	1	CMAIN GM20.0	3	1120	100	126.3784
27	1	CMAIN GM20.0	3	1120	100	126.3784
28	1	CMAIN GM20.0	3	1120	100	126.3784
29	1	CMAIN GM20.0	3	1120	100	126.3784
30	26	MONTA G120.0	3	2910	100	280.8265
31	19	DALLES2113.8	3	1301	100	96.1731
32	13	JOHN DAY13.8	3	5174.76	100	534.1591
33	8	NORTH G320.0	3	9950	100	1225.8
34	88	DIABLO1 25.0	3	765	100	158.7561
35	96	ROUND MT20.0	3	1057	100	124.0851

No.	Bus	Name	Area	Power (MW)	Load (MW)	Inertia (J S)
36	102	TEVATR 20.0	3	594	100	101.5907
37	91	TEVATR2 20.0	3	3467	100	720.5455
	Area 1	**Generation**	**12550**	**(MW)**	**Intertia**	1260.9742
	Area 2	**Generation**	**14712.7**	**(MW)**	**Intertia**	2487.9838
	Area 3	**Generation**	**34148.76**	**(MW)**	**Intertia**	4816.2497
		Total Gen:	**61411.46**	**(MW)**	**Total Inertia**	8565.2077
		Total load:	**60785.41**	**(MW)**		
		Total Loss:	**626.05**	**(MW)**		
			1.0194%			

Table A.5 WSCC System Shunt Information

Bus Nr	Bus Name	Load	Area	
51	FOURCORN500.	0.58	1	0.58
57	MOENKOPI500.	-0.58	2	
77	VINCENT 500.	2	2	1.42
27	MIDPOINT500.	-1233	3	
15	GRIZZLY 500.	-10.6	3	
21	SUMMER L500.	-0.3	3	
22	BURNS2 500.	1120.9	3	
23	MALIN 500.	8.9	3	
84	MIDWAY 500.	-15.1	3	
89	GATES 500.	13.1	3	
90	TEVATR 500.	3.2	3	
92	OLINDA 500.	-1	3	
93	ROUND MT500.	13.7	3	
94	TABLE MT500.	12.3	3	-87.9
			TOTAL	-85.9

Table A.6 WSCC System Transmission Line Loss Information

Line Sr.	Bus From	Bus Name	Bus To	Bus Name	Losses	Area
1	33	NAUGHT 20.0	32	NAUGHTON230.	0.6	1
2	32	NAUGHTON230.	31	BENLOMND230.	0.8	1
3	31	BENLOMND230.	30	BENLOMND345.	0	1
4	30	BENLOMND345.	29	MIDPOINT345.	0.4	1
5	30	BENLOMND345.	35	CAMP WIL345.	0.1	1
6	30	BENLOMND345.	34	TERMINAL345.	0	1
7	34	TERMINAL345.	35	CAMP WIL345.	0.2	1
8	29	MIDPOINT345.	28	BRIDGER222.0	0	1
9	35	CAMP WIL345.	36	SPAN FRK345.	0.3	1
10	35	CAMP WIL345.	37	EMERY 345.	3	1
11	35	CAMP WIL345.	37	EMERY 345.	2.6	1
12	35	CAMP WIL345.	42	MONA 345.	0	1
13	35	CAMP WIL345.	42	MONA 345.	0	1
14	42	MONA 345.	43	INTERMT 345.	0.6	1
15	42	MONA 345.	43	INTERMT 345.	0.6	1
16	43	INTERMT 345.	44	INTERM1G26.0	0	1
17	36	SPAN FRK345.	37	EMERY 345.	2.6	1
18	37	EMERY 345.	39	SIGURD 345.	2.4	1
19	37	EMERY 345.	39	SIGURD 345.	2.4	1
20	37	EMERY 345.	38	EMERY 20.0	4.4	1
21	37	EMERY 345.	40	PINTO 345.	1.6	1
22	39	SIGURD 345.	42	MONA 345.	0.2	1
23	39	SIGURD 345.	42	MONA 345.	0.2	1
24	40	PINTO 345.	41	PINTO PS345.	0	1
25	41	PINTO PS345.	50	FOURCORN345.	0.6	1
26	42	MONA 345.	45	CRAIG 345.	4.8	1
27	45	CRAIG 345.	46	CRAIG 22.0	0	1
28	45	CRAIG 345.	47	HAYDEN 20.0	0	1
29	45	CRAIG 345.	48	SAN JUAN345.	10.2	1
30	48	SAN JUAN345.	49	SJUAN G422.0	0	1
31	48	SAN JUAN345.	50	FOURCORN345.	1.6	1
32	50	FOURCORN345.	53	FCNGN4CC22.0	0	1
33	50	FOURCORN345.	52	FOURCORN230.	0	1
34	50	FOURCORN345.	52	FOURCORN230.	0	1
35	50	FOURCORN345.	51	FOURCORN500.	0	1

Line Sr.	Bus From	Bus Name	Bus To	Bus Name	Losses	Area
36	50	FOURCORN345.	51	FOURCORN500.	0	1
37	50	FOURCORN345.	54	CHOLLA 345.	20.7	1
38	54	CHOLLA 345.	55	CORONADO500.	0	1
39	55	CORONADO500.	56	CORONADO20.0	0	1
			AREA 2			
	Bus From		**Bus To**		**Losses**	**Area**
40	57	MOENKOPI500.	63	ELDORADO500.	19.9	2
41	58	WESTWING500.	57	MOENKOPI500.	2	2
42	58	WESTWING500.	61	NAVAJO 500.	2	2
43	59	PALOVRDE500.	60	PALOVRD224.0	4.3	2
44	59	PALOVRDE500.	64	DEVERS 500.	18.6	2
45	59	PALOVRDE500.	64	DEVERS 500.	18.6	2
46	59	PALOVRDE500.	58	WESTWING500.	0	2
47	59	PALOVRDE500.	58	WESTWING500.	0	2
48	61	NAVAJO 500.	62	NAVAJO 226.0	0	2
49	61	NAVAJO 500.	63	ELDORADO500.	18	2
50	61	NAVAJO 500.	57	MOENKOPI500.	0.8	2
51	63	ELDORADO500.	104	VICTORVL500.	8.3	2
52	63	ELDORADO500.	104	VICTORVL500.	8.3	2
53	63	ELDORADO500.	68	LUGO 500.	14.1	2
54	63	ELDORADO500.	66	MOHAVE 500.	1.4	2
55	63	ELDORADO500.	65	ELDORADO20.0	0	2
56	64	DEVERS 500.	70	VALLEY 500.	3	2
57	66	MOHAVE 500.	67	MOHAV1CC22.0	0	2
58	66	MOHAVE 500.	68	LUGO 500.	18.9	2
59	68	LUGO 500.	104	VICTORVL500.	5.3	2
60	68	LUGO 500.	69	SERRANO 500.	2	2
61	68	LUGO 500.	71	MIRALOMA500.	2.8	2
62	68	LUGO 500.	71	MIRALOMA500.	2.3	2
63	69	SERRANO 500.	71	MIRALOMA500.	0	2
64	69	SERRANO 500.	70	VALLEY 500.	0.8	2
65	71	MIRALOMA500.	72	MIRALOMA20.0	0	2
66	71	MIRALOMA500.	73	MIRALOMA230.	0	2
67	73	MIRALOMA230.	74	MESA CAL230.	0.4	2
68	74	MESA CAL230.	75	LITEHIPE230.	0.1	2
69	74	MESA CAL230.	78	VINCENT 230.	0.7	2

	Bus From		Bus To		Losses	Area
70	74	MESA CAL230.	79	EAGLROCK230.	9.5	2
71	75	LITEHIPE230.	76	LITEHIPE20.0	0	2
72	77	VINCENT 500.	68	LUGO 500.	1	2
73	77	VINCENT 500.	68	LUGO 500.	1	2
74	77	VINCENT 500.	78	VINCENT 230.	0	2
75	77	VINCENT 500.	78	VINCENT 230.	0	2
76	77	VINCENT 500.	78	VINCENT 230.	0	2
77	78	VINCENT 230.	80	PARDEE 230.	0	2
78	78	VINCENT 230.	80	PARDEE 230.	0	2
79	79	EAGLROCK230.	80	PARDEE 230.	0	2
80	79	EAGLROCK230.	82	SYLMAR S230.	1.3	2
81	80	PARDEE 230.	81	PARDEE 20.0	0	2
82	80	PARDEE 230.	82	SYLMAR S230.	1.8	2
83	80	PARDEE 230.	82	SYLMAR S230.	1.8	2
84	82	SYLMAR S230.	103	SYLMARLA230.	0	2
85	103	SYLMARLA230.	118	RINALDI 230.	0	2
86	103	SYLMARLA230.	118	RINALDI 230.	0	2
87	103	SYLMARLA230.	118	RINALDI 230.	0	2
88	103	SYLMARLA230.	125	CASTAIC 230.	0.1	2
89	104	VICTORVL500.	105	VICTORVL287.	0.1	2
90	104	VICTORVL500.	121	ADELANTO500.	0	2
91	104	VICTORVL500.	121	ADELANTO500.	0	2
92	104	VICTORVL500.	123	RINALDI 500.	0.8	2
93	105	VICTORVL287.	106	STA B2 287.	2.2	2
94	105	VICTORVL287.	107	STA B1 287.	2.2	2
95	106	STA B2 287.	108	STA B 138.	0.1	2
96	107	STA B1 287.	108	STA B 138.	0.1	2
97	108	STA B 138.	109	STA BLD 230.	0	2
98	108	STA B 138.	109	STA BLD 230.	0	2
99	109	STA BLD 230.	110	STA F 230.	0	2
100	109	STA BLD 230.	110	STA F 230.	0	2
101	110	STA F 230.	111	RIVER 230.	0	2
102	110	STA F 230.	112	HAYNES 230.	0.1	2
103	110	STA F 230.	114	STA G 230.	0.1	2
104	111	RIVER 230.	112	HAYNES 230.	0.1	2
105	111	RIVER 230.	112	HAYNES 230.	0.1	2

	Bus From		Bus To		Losses	Area
106	111	RIVER 230.	114	STA G 230.	0.2	2
107	112	HAYNES 230.	113	HAYNES3G18.0	0.3	2
108	112	HAYNES 230.	114	STA G 230.	0.1	2
109	114	STA G 230.	115	GLENDAL 230.	0	2
110	114	STA G 230.	116	STA E 230.	0.3	2
111	114	STA G 230.	116	STA E 230.	0.3	2
112	115	GLENDAL 230.	116	STA E 230.	0.2	2
113	116	STA E 230.	117	VALLEY 230.	0.4	2
114	116	STA E 230.	118	RINALDI 230.	1.5	2
115	116	STA E 230.	118	RINALDI 230.	1.5	2
116	116	STA E 230.	120	STA E 500.	0.1	2
117	116	STA E 230.	120	STA E 500.	0.1	2
118	117	VALLEY 230.	118	RINALDI 230.	0.5	2
119	117	VALLEY 230.	118	RINALDI 230.	0.5	2
120	118	RINALDI 230.	122	ADELAN&1500.	0.3	2
121	118	RINALDI 230.	123	RINALDI 500.	0.3	2
122	118	RINALDI 230.	124	STA J 230.	0.6	2
123	118	RINALDI 230.	124	STA J 230.	0.6	2
124	118	RINALDI 230.	124	STA J 230.	0.6	2
125	118	RINALDI 230.	124	STA J 230.	0.6	2
126	118	RINALDI 230.	119	OWENS G 11.5	0	2
127	118	RINALDI 230.	125	CASTAIC 230.	0	2
128	118	RINALDI 230.	127	OLIVE 230.	0	2
129	120	STA E 500.	121	ADELANTO500.	3.1	2
130	121	ADELANTO500.	122	ADELAN&1500.	1.3	2
131	124	STA J 230.	125	CASTAIC 230.	0.1	2
132	125	CASTAIC 230.	126	CASTAI4G18.0	0.1	2
133	125	CASTAIC 230.	127	OLIVE 230.	0	2
			AREA 3			
	Bus From		**Bus To**		**Losses**	**Area**
134	1	CMAIN GM20.0	2	CA230 230.	0	3
135	2	CA230 230.	3	CA230TO 230.	12.3	3
136	3	CA230TO 230.	4	CANALB 500.	0	3
137	4	CANALB 500.	6	CANADA 500.	19.2	3
138	5	CANAD G120.0	6	CANADA 500.	0	3
139	6	CANADA 500.	7	NORTH 500.	3.8	3

	Bus From		Bus To		Losses	Area
140	7	NORTH 500.	8	NORTH G320.0	0	3
141	7	NORTH 500.	9	HANFORD 500.	14.1	3
142	7	NORTH 500.	9	HANFORD 500.	14.1	3
143	9	HANFORD 500.	10	COULEE 500.	0.1	3
144	9	HANFORD 500.	11	GARRISON500.	14.1	3
145	9	HANFORD 500.	12	JOHN DAY500.	3.4	3
146	9	HANFORD 500.	12	JOHN DAY500.	10.2	3
147	9	HANFORD 500.	24	MONTANA 500.	0.7	3
148	11	GARRISON500.	12	JOHN DAY500.	0.4	3
149	11	GARRISON500.	25	COLSTRP 500.	36.9	3
150	12	JOHN DAY500.	13	JOHN DAY13.8	0	3
151	12	JOHN DAY500.	14	BIG EDDY500.	1.7	3
152	12	JOHN DAY500.	14	BIG EDDY500.	1.9	3
153	12	JOHN DAY500.	15	GRIZZLY 500.	2.5	3
154	12	JOHN DAY500.	15	GRIZZLY 500.	2.5	3
155	12	JOHN DAY500.	15	GRIZZLY 500.	4.1	3
156	14	BIG EDDY500.	16	CELILOCA500.	0	3
157	14	BIG EDDY500.	16	CELILOCA500.	0	3
158	14	BIG EDDY500.	17	BIG EDDY230.	0.1	3
159	14	BIG EDDY500.	17	BIG EDDY230.	0.1	3
160	15	GRIZZLY 500.	21	SUMMER L500.	1.9	3
161	15	GRIZZLY 500.	23	MALIN 500.	11.1	3
162	15	GRIZZLY 500.	23	MALIN 500.	10.2	3
163	16	CELILOCA500.	18	CELILO 230.	0	3
164	17	BIG EDDY230.	18	CELILO 230.	0.5	3
165	17	BIG EDDY230.	18	CELILO 230.	0.4	3
166	17	BIG EDDY230.	19	DALLES2113.8	0	3
167	17	BIG EDDY230.	20	BIG EDDY115.	0.2	3
168	21	SUMMER L500.	22	BURNS2 500.	10.3	3
169	21	SUMMER L500.	23	MALIN 500.	12.4	3
170	22	BURNS2 500.	27	MIDPOINT500.	134.1	3
171	23	MALIN 500.	92	OLINDA 500.	12.6	3
172	23	MALIN 500.	93	ROUND MT500.	9	3
173	23	MALIN 500.	93	ROUND MT500.	9.6	3
174	24	MONTANA 500.	26	MONTA G120.0	0	3
175	83	MIDWAY 200.	84	MIDWAY 500.	0.4	3

	Bus From		Bus To		Losses	Area
176	83	MIDWAY 200.	84	MIDWAY 500.	0.3	3
177	84	MIDWAY 500.	85	LOSBANOS500.	0.3	3
178	84	MIDWAY 500.	89	GATES 500.	0.9	3
179	84	MIDWAY 500.	87	DIABLO 500.	0.5	3
180	84	MIDWAY 500.	87	DIABLO 500.	0.5	3
181	84	MIDWAY 500.	90	TEVATR 500.	4	3
182	85	LOSBANOS500.	86	MOSSLAND500.	0	3
183	85	LOSBANOS500.	89	GATES 500.	0.2	3
184	87	DIABLO 500.	89	GATES 500.	0.2	3
185	87	DIABLO 500.	88	DIABLO1 25.0	0	3
186	89	GATES 500.	90	TEVATR 500.	3.8	3
187	90	TEVATR 500.	92	OLINDA 500.	27	3
188	90	TEVATR 500.	94	TABLE MT500.	15.7	3
189	90	TEVATR 500.	94	TABLE MT500.	13.6	3
190	90	TEVATR 500.	91	TEVATR2 20.0	0	3
191	90	TEVATR 500.	101	TEVATR 200.	0.1	3
192	93	ROUND MT500.	94	TABLE MT500.	17.1	3
193	93	ROUND MT500.	94	TABLE MT500.	17.1	3
194	93	ROUND MT500.	95	ROUND MT200.	0.1	3
195	95	ROUND MT200.	96	ROUND MT20.0	0	3
196	95	ROUND MT200.	97	COTWDPGE200.	2.8	3
197	95	ROUND MT200.	97	COTWDPGE200.	2.7	3
198	95	ROUND MT200.	97	COTWDPGE200.	2.7	3
199	97	COTWDPGE200.	98	LOGAN CR200.	0.8	3
200	97	COTWDPGE200.	99	GLENN 200.	0.8	3
201	97	COTWDPGE200.	100	CORTINA 200.	0.6	3
202	97	COTWDPGE200.	101	TEVATR 200.	1.7	3
203	98	LOGAN CR200.	101	TEVATR 200.	0.9	3
204	99	GLENN 200.	101	TEVATR 200.	0.9	3
205	100	CORTINA 200.	101	TEVATR 200.	1.2	3
206	101	TEVATR 200.	102	TEVATR 20.0	0	3
		LOSS	**720.9**	**SHUNT**	**-85.9**	**TOTAL**

Appendix B Internet based Frequency Monitoring System

B.1 Motivation for FNET

The electric power system is a complex and interlocked transport system like many other transport systems, yet very special in that the transported "goods" has to be generated, transmitted, and consumed at the same time. Various power systems are usually interconnected to form a larger power system in order to maintain a stable, reliable and economical condition. Each interconnected system is responsible for meeting its own obligations, with matters of mutual obligation or concern being governed by the operating guides. The load on any interconnected power system is changing continuously and independently of other power system in the network. The changing load is reflected by the fluctuating instantaneous frequency in different areas.

System frequency is one of the most important parameters of the electric power system. Area frequency can vary over a small range due to generation-load mismatches. Some power system protection and control application, e.g. frequency relay for load frequency controller, generator protection and control, synchronism checking required accurate and fast estimation of the frequency; it also has been used routinely in the control and management of generation. Fast and accurate real time measurement of frequency is an important component in the future operation of the transmission system. With an accurate system frequency measurement, one will know how much load or generation power needs to be shed during load unbalance in a power system. Moreover, if the rate of changes of frequency is known, more accurate adjustment can be made to restore the operating frequency back to normal in the shortest period.

Existing frequency monitors are sparsely located, limited in recording length, and many are based upon technology that is difficult to integrate, which reduces the likelihood that critical events be adequately recorded. The most common approach used is to measure three phase voltage and currents at high voltage level in substations, which translate into more expensive units cost, installation cost, and maintenance cost beside the costs associated with translating the acquired data into useful information. Cost and integrate difficulty made massive deployment unpractical. Prior efforts have been made to share frequency measurement value between utilities, due to the network technology limitation, it was difficult to facilitate comprehensive data access and real time integration. Today, the Internet [13][21] no doubt will be the choice for easy and fast data transmission and integration. In this document, an Internet-based real time frequency measurement system is proposed.

In Addition, the complete picture of how the entire US power system behaves during disturbances is not well understood. Any information we have is from computer simulations that are subject to model errors and simplifications. Complete models for nonlinear loads are not available despite the critical roles they play in system dynamics. Most of all, no model could capture the time varying nature of power system operational conditions over long time spans. System frequency (and its rate of change) is one of the most important measures of the electric power system behavior. Individual frequency measurements made so far are meant for limited local use and do not have the accuracy and synchronization necessary for system level analysis. System frequency is normally the same at all points of the power network. It is a characteristic that is shared by networks at all voltage levels: from generation all the way through transmission, distribution, and consumption nodes. However, when a significant disturbance occurs, the frequency varies in time and space.

B.2 Objectives of the FNET

The objectives of the FNET is to establish a Internet-based real time GPS time synchronized wide area frequency monitoring network, which will have applications in the following areas.

- Electro-mechanical oscillations between interconnected synchronous generators are phenomena inherent to power system. The characteristics of inter-area oscillations are very complex and are not well understood. Analytical tools for investigation of the problems have their limitations; therefore, the real time frequency measurement can be used to obtain first hand knowledge.
- The market economy is likely to force power systems to operate much closer to their stability limits. Operation decisions will have to be based on accurate on-line real time information rather than relying on offline simulations with assumed system operating conditions.
- The stability of these oscillations is of vital concern for secure system. The characteristics of those dynamics and the factors influencing them are not fully understood. The frequency information may be used to verify the assumptions and to verify the simulated results.
- The real time frequency is very useful in post-mortem analysis. It may help answer questions like what happened, why it is happened, and how to avoid it in future operations.
- When a large blackout started, real time frequency information may be used to track down the point(s) of origination of the blackout.
- Some power system protection and control applications, e.g. frequency relay for load shedding, load-frequency controller, require accurate and fast estimation of the frequency.
- As a very important parameter of power quality, on-line frequency information can be used to verify the power quality.
- Power system loads is sensitive to frequency, data captured after disturbance indicates that their aggregated initial change is in the same direction as the frequency changes, on-line real time frequency information can be the reference for correct automatic generation control (AGC).

B.3 FNET Architecture

This section describes a real time GPS synchronized wide area frequency monitoring network (FNET) via Internet. FNET system is a practical way to quickly deploy a cost-effective real-time wide-area synchronized measurement system. One of the key elements that make this initiative practical is to measure frequency at 110V single-phase outlets to avoid costly substation installations. FNET also uses the Internet as the communication infrastructure to allow wide area data transmission and gathering.

A wide area communications network associated with accurate frequency recorders and powerful center processing system is the key for an effective FNET system design. Figure B.1 shows the framework of the FNET system. The FNET system consists of two major components. One is the FRU (Frequency Record Unit) which performs GPS synchronized frequency data measurement, network interface and data transmission. Another part is the information management system (IMS) server, which performs data management, analysis, and user interface. Internet provides the integrated wide area communication media between FRU and IMS server.

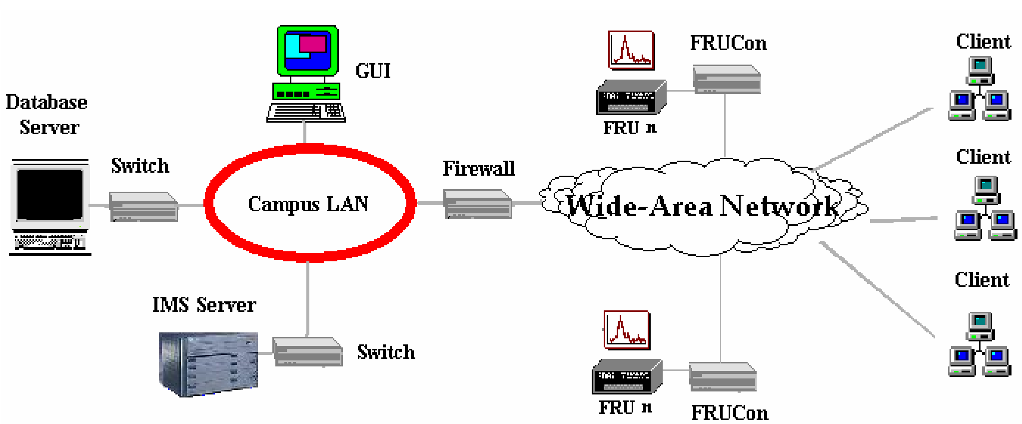


Figure B.1 FNET System Architecture

B.4 Frequency Measurement Algorithms and Devices

As shown in Figure B.2, the FRU consists of voltage transducer; low pass filter; A/D converter; GPS receiver board; Central processor unit; and the network communication module. Voltage transducer takes analog voltage data off the 110V wall outlets, filters and converts the analog voltage data into digital data. In the processor, frequency information, including the rate of frequency change, voltage and relative voltage angle, are computed using Phasor techniques, time tagged, and transferred to the main server via Internet. The low-pass filter eliminates high frequency noise and acts as an anti-aliasing filter. The filter also performs FFT (Fast Fourier Transforms) to extract the fundamental of the voltage waveform, which may experience high distortion at the 110V-level.

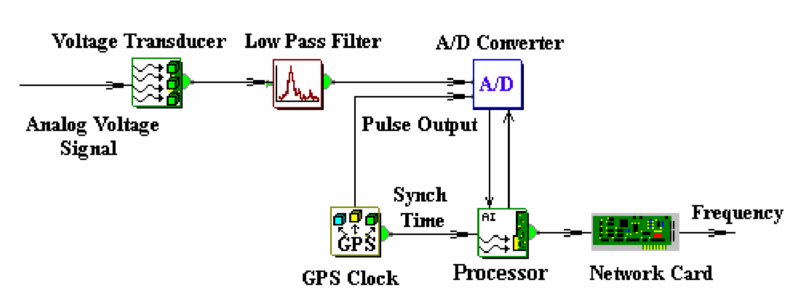


Figure B.2 Data Acquisition and Transmission System

A GPS clock, which provides universal sample triggering pulses, will be integrated into the FRU platform. GPS synchronization permits precise comparison of data taken any where in the system. The clock uses a small antenna to track multiple satellites simultaneously. The signal received from the GPS satellite is processed to produce a synchronous pulse once a second accurate to within 200 nanoseconds. In the hardware design, the GPS clock generated sampling pulses will drive the A/D converter input channel to ensure synchronized data acquisition and supply accurate time for the frequency data. The proposed FRU will have a sampling rate of 1.44 kHz (24 points/cycle), dynamic frequency accuracy within ±0.001 Hz, and synchronization within 1μs. The required accuracy of synchronization can be determined so that at 60Hz, a sampling error of 1 μs corresponds to an angular error of 0.0216 degrees (0.018 for 50 Hz system).

B.5 Information Management Server

IMS server plays a vital role in the FNET system. It is developed base on the multi-tier client/server architecture that models, coordinates, and integrates the frequency acquisition, processing and display functions. As shown in Figure B.3, IMS server supports four roles: Internet client service, FRU communication function, Database operation and Web services. The frequency data is transmitted to the IMS server through WAN (Wide Area Network) in real time. IMS Server receives and processes the data, logs the data to the database server and publishes the data to the web. Java-based GUI (Graphical User Interface) integrates the frequency display, monitoring and historical data retrieval into a common easily accessible user interface. The IMS Server is written entirely in Java and does not require any native code. A Java interpreter is required to parse the bytecode each time the IMS Server program runs.

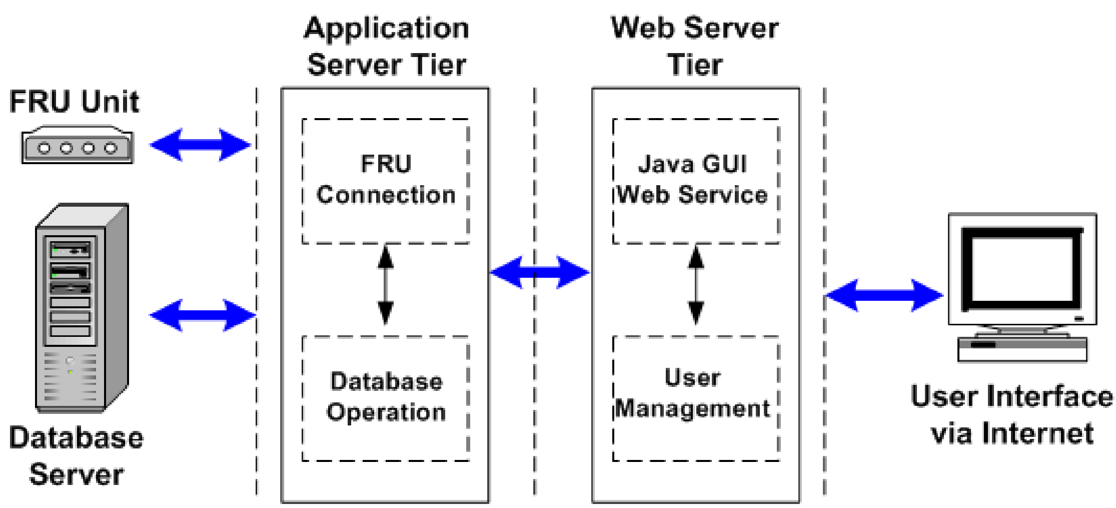


Figure B.3 Multi-tier IMS System Structure

B.5.1 Data Communication Service

FNET system is a two-way communication link between IMS server and FRU running via Internet. FRU collects the real-time frequency from the remote location, transmits the data to the IMS server. FRUCon, which stands for FRU connectivity to IMS server, acts as a data communication bridge between the IMS server and FRU unit. In the actual FNET system, FRUCon is embedded in the FRU Unit, and multi-threading is used to process concurrent FRUCon processes. When a FRU tries a connection to the IMS server, a thread will be set up to process the data transmission from the FRU. In some places, due to the lack of network, wireless communication could be an alternate choice for data transmission. In this case, FRU will make use of wireless modem to set up the connection to the IMS server.

B.5.2 Database Operation Service

Backend database is dedicated to data and file service that can be optimized without using any proprietary database languages. It provides a convenient data accessing mechanism. The historical storage consists of logged data, frequency disturbance events and real time frequency data. Access to the database is provided through a series of interface modules that read and write data to the database tables. In the IMS system, JDBC and OLE DB (object-linking and embedding database) are used for database manipulation. The data management component ensures that the frequency data is consistent throughout the distributed environment through the use of features such as data locking, consistency, and replication.

B.5.3 Java-based Graphical User Interface

Java-based GUI (JGUI) provides a means for utility engineers, planners and common users to access the system frequency data. The functionality of the JGUI, is only limited to viewing the overall frequency information. Two kinds of GUIs are supported by the IMS system. One is the Java-based Interface client display. It has the same graphical user interface as that of the server site for the real time update of the frequency data. Another is the ASP (Active Server Pages) based system frequency search engine where the user can type in the area, time, and frequency value, the corresponding information will be displayed in tabular display using HTML format.

B.5.4 Security Management

When the user accesses the IMS Server, a security mechanism will be triggered to allow only the authorized user to access the real time frequency information. Passwords are set at multiple levels to allow users accessing different levels of Information.

B.5.5 FRU Location Selection

Power system oscillation is a complex phenomenon. Oscillations associated with a single plant are local modes, normally having frequencies in the range of 0.7 to 2.0 Hz. Oscillations associated with groups of plants are inter-area modes, have frequencies in the range of 0.1 to 0.8 Hz. The FRUs will be placed according to the modes of oscillations of interest. The locations should effectively reflect the different frequency clusters of inter-area oscillations; cover as broad an area as possible in order to capture dynamic behavior of larger system disturbance. RFU location should represent the system frequency, effectively describe the behavior of major inter-connected systems, and provide information on the large area load behavior. In future FNET system, more FRUs can be located near large generation centers and in load concentrated areas for local modes frequency oscillation study.

B.6 Laboratory Implementation

In the preliminary work of the FNET initiative, an Internet based frequency monitoring simulator is being developed at Virginia Tech. The simulator was used as a small-scale information management system (IMS) to process artificially generated oscillation and disturbance data. The frequency data is transmitted to the server, displayed, processed, and stored in a database. The real time frequency data can be viewed virtually anywhere in the world via Internet. Figure B.4 illustrates the implementation of this small-scale real time frequency monitoring test system at Virginia Tech.

The simulator consists of four components running on the several computers as show in Figure B.4. The first module is the FRU simulator that simulates the real-time FRU. FRU runs on 20 UNIX machines. The FRU simulator will generate oscillation and disturbance data to simulate the real power system operation. Every machine runs five FRU data acquisition programs. Each program will send out data in 10 packages / second rate. 20 UNIX Workstations can simulate 100 FRU units and generate 200 kbps Bytes / second. Second module is the IMS Server program. Internet Information Server is employed to support Web publishing and gateway access function. Campus firewall is used to prevent the hackers from attacking the system. The third module is the commercial RBDMS (Relational Database Management System. The fourth module is a standard Internet browser, which runs on several client PCs. All the machines are linked to the campus network backbone through high speed Ethernet.

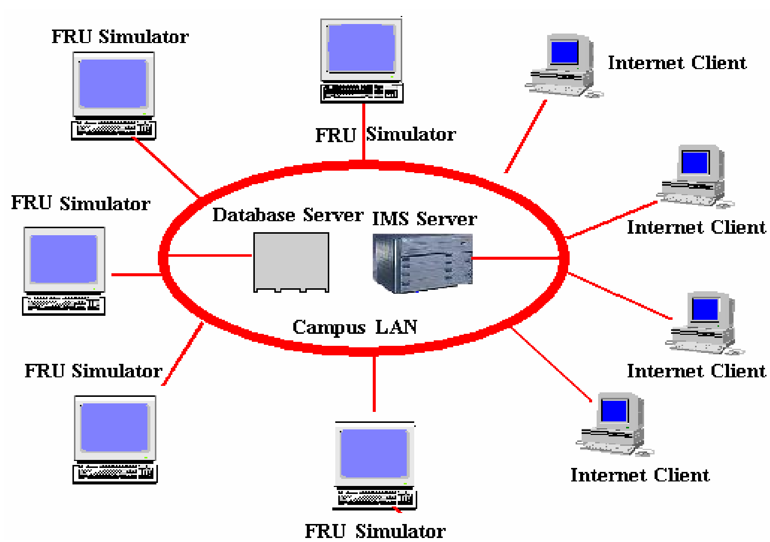
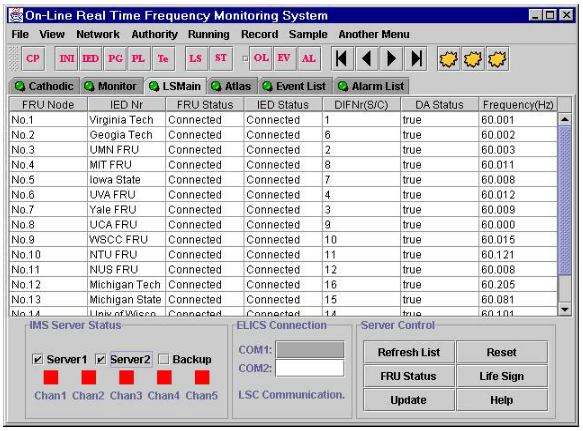


Figure B.4 FNET Simulation System

The frequency information management system (IMS) server is set up at Virginia Tech with the following system configurations:

Hardware: For reliable data transmission, processing and web service, a powerful dual server (clustering system) with RAID (Redundant Array of Inexpensive Disks) system is employed. In the dual server structure, two identical servers communicate with each other through the private cluster connection. The two servers run separately and backup the public data (including the system data and the application data) in the Shared Disk. One server acts as hot standby server and can take over main server's functionality if the main server fails.



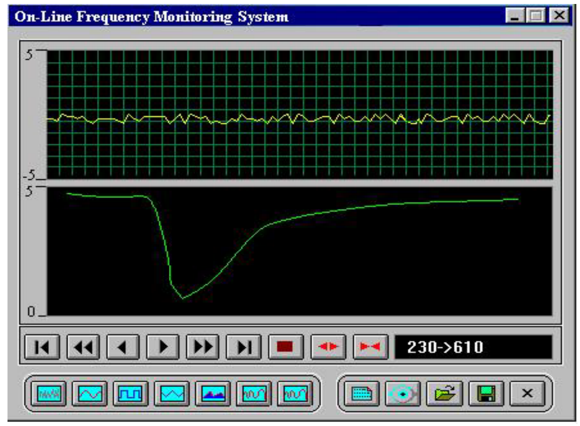


Figure B.5 IMS Server Interface

Figure B.6 Main MMI Interface

Software: Windows server 2000 is installed at the IMS server as the main operation system. Commercial RBDMS is installed at the database server machine as the backend database. C++ is employed for some parts of the server communication. Java is used for the MMI design. Data acquisition simulator program is based on socket communication. Standard Internet browser such as IE (Internet Explorer) or Netscape can be employed as the network browser for the Internet user to access the frequency data.

Figure B.5 shows the GUI at the server site, it displays the different FRU locations, their communication status, and real time frequency data. Communication failure, abnormal statues, and frequency data will be written to the event list display as well as logged to the database. Figure B.6 illustrates the real time frequency data waveform displayed on the Internet client site.

B.7 Conclusion

Continuous synchronized quasi real-time wide area frequency information can be very valuable in many different ways. Information from FNET will be able to provide system operators with real time system states, to detect system disturbance, to perform post disturbance scenario reconstruction, to verify system models and parameters used in simulations, to gather power quality information, to track the sequence of events leading to an emergency; to supply references for AGC and FACT control actions. The real implementation of the system can be realized by connecting the existing FACT devices through IED (Intelligent Electrical Devices), the real time information data can be exchanged using the LAN (Local Area Network), gateway can be set as the protocol interpreter among the different IEDs. With increase Internet speed and reliability, the future real time wide area frequency information might be used to perform control and protection functions such as load shedding and emergency area separation. Just like the early days of Internet, some of the potential applications of FNET are still beyond our imagination.

Appendix C Real Time Frequency Data Visualization

When analyzing power system steady state or dynamic state characteristics, we always confront large amount of data. Most of the data interpretations currently used are still rely on text-based display which is tedious and time consuming. As the analyses and computation become more and more accurate, the data amount also grows exponentially. Therefore, finding a good approach for large amount data visualization is of practical important. Efficient generation of data rendering is required to understand and interpret data. With the rapid development of computer hardware and software, especially the innovative advances in computer graphic technology, great improvement can be achieved to develop efficient GUI (Graphical User Interface) for data visualization. In this section, we will present a new approach to render the power system frequency variation data.

Computer graphics have been widely used for data visualization. One typical example is the temperature map. In the thermal based weather map. Areas with red color signify higher temperature region while areas with more blue color specify cooler temperature. By using smooth and continuum data animation, people can quickly get a feeling of how the dynamic temperature varies. Same concept can also be implemented in the power system for dynamic data rendering.

Power system data visualization is related to two major issues: data allocation and data magnitude rendering. In frequency data visualization system, we use 3-D (dimensional) space to interpret the dynamic data information. 2-D singular space x and y are used to specify the measuring point location. Z space specifies the data magnitude. RGB (Red-Green-Blue) color system is also be used to convert 3D animation into 2D visualization.

The frequency dynamic data visualization contains three steps: frequency variation area tessellation; frequency data interpolated shading; data rendering and animation.

C.2 Frequency Variation Area Tessellation

2-D space specifies the location of the frequency measuring points. In the frequency visualization system, we divided the frequency variation area into hundreds of interconnected triangles. The reason of choosing triangles instead of other polygon such as squares is that they are not flat in 3-dimensional space. Therefore, the color distribution will not be smooth. The decomposition of the terrain into triangles can guarantee any three points in space will be coplanar.

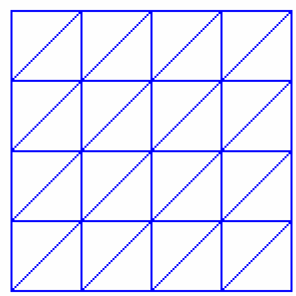


Figure C.1 Coplanar Space Tessellation

In the frequency visualization case, we take the USA map as the rendering space and divided the USA map into 128 x 128 squares with two triangles in each grid.

C.3 Frequency Data Interpretation and Interpolated Shading

Frequency data magnitude can be signified using two approaches: Z dimension magnitude and color intensity (Color or gray-scale). Two approaches can be easily exchanged by using different color intensity to represent different magnitude. In this section, both methods are used for frequency data rendering.

To render the frequency data using 3D space, X and Y represent the measuring point location and Z axis value represents the frequency magnitude. The maximum frequency will be filtered from raw data and set as the unit value. Z axis value of other point is set proportional to this unit value.

To rendering the frequency data using color, RGB color system [133] is used. RGB is the scheme that is being used most often when dealing with colors on a computer. Three primary colors: Red, Green, Blue are defined. The values for red, green, and blue are specified in a scale from 0-255. Other colors can be represented using different value of RGB, like yellow can be set as RGB (255, 255, 0). The “True color" has the color spectrum of 16M colors (256x256x256).

The color is of continuity in natural, therefore, in order to keep the smooth color rendering for the frequency allocation map, gouraud approach [132][133] is used for color shading. Gouraud shading is a method for linearly interpolating a color or shade across a polygon Gouraud shading computes a color for each vertex of each triangle and then smoothly interpolate between these vertex colors within the triangle.

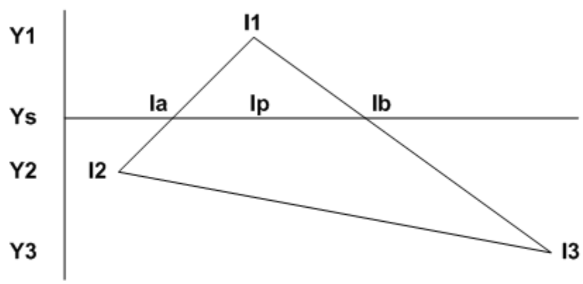


Figure C.2 Gouraud Shaded

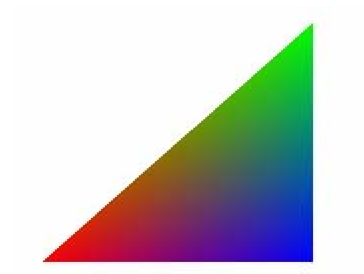


Figure C.3 Gouraud Shaded Triangle

In Figure C.2, we can determine the color of I1, I2, I3, then color of Ia, Ib and Ip can be calculated by:

$$Ia=I1-(I1-I2)(y1-ys)(y1-y2)$$

$$Ib=I1-(I1-I3)(y1-ys)(y1-y3)$$

$$Ib=Ib-(I1-I3)(yb-yp)(yb-ya)$$

Figure C.3 illustrates a gourauded shaded triangle if we set the I1 to be green, I2 to be red and I3 to be blue.

C.3 Data Visualization API

In frequency data visualization system, OpenGL (Open Graphics Library) [132][133] is adopted for generating high-quality 3D or 2D graphics objects. OpenGL is a low-level graphics library specification. OpenGL provides a small set of geometric primitives - points, lines, polygons, images, and bitmaps and a set of commands that allow the specification of geometric objects in two or three dimensions. The OpenGL API was designed for use with the different languages such as C and C++ programming and is supported on a number of graphics hardware platforms.

In this section, we have used MESA/OpenGL library [134] with windows 2000 operating system and visual C++ for frequency data rendering software development.

C.4 Frequency Data Rendering

Dynamic frequency data was generated by simulation program in different contingency cases. As mentioned in section C.1, the frequency allocation map is divided into 128 x 128 squares with two connected triangles in each square. Two kinds of frequency rendering points are defined. One is called measuring point. Its data are calculated by power system simulation software and therefore are known. Another kind of point is called rendering point. Its frequency data will be calculated based on its original frequency data (normally assumed to be 60 Hz) and the traveling wave effect from the measuring points. Each measuring point is put on one corner of the grid according to its geographic location. The measuring point frequency will be read in from raw data file and then converted into RGB color. More red signifies higher frequency while more blue represents lower frequency. The color of the point with maximum frequency will be set as RGB (255, 0, 0). The color of the point with minimum frequency will be set as RGB (0, 0, 255). The color of the point with fundamental frequency 60 Hz will be set as RGB (0, 255, 0). The RGB values of rendering points are calculated proportional to the frequency value.

RedOffset = (MaxFrequency)/frequency

GreenOffset = (MaxFrequency)/ frequency if frequency is greater than 60 Hz

GreenOffset = (-MinFrequency)/ frequency if frequency is less than 60 Hz

BlueOffset = (MinZ)/ frequency

When animation starts, the measuring points are changing with time according to the simulation data. The changes of frequency of the measuring points will also propagate to all the rendering points. Points that are close to the changing pointer have severer effect than those are farther away. Figure C.4 to Figure C.9 show some snapshots of one simulation case for USA nation wide frequency variation.

C.4 Summary

As the power system steady state and dynamic state study becomes more and more efficient and accurate. It is essential to generate high quality graphic user interface for efficient data visualization. This section introduced an implementation of computer graphic application in the power system frequency data rendering. OpenGL technology is used for frequency data interpretation.

The result shows that by using computer graphics technology, it is feasible and easy to improve the large amount data visualization. Computer graphics technology supports a useful aid to large amount power system data rendering and interpretation.

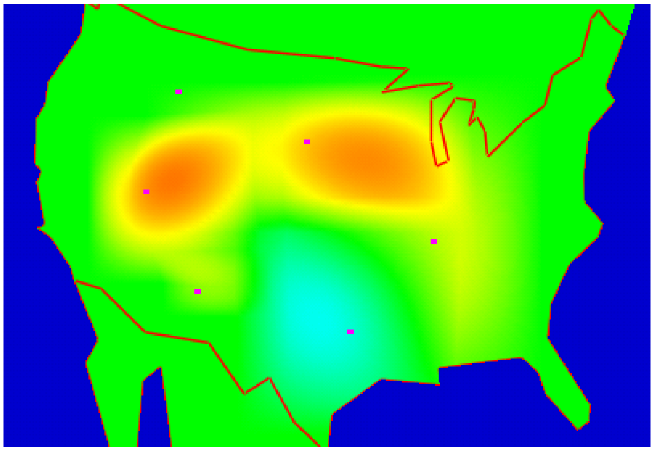


Figure C.4 USA Frequency Data Visualization Snapshot 1

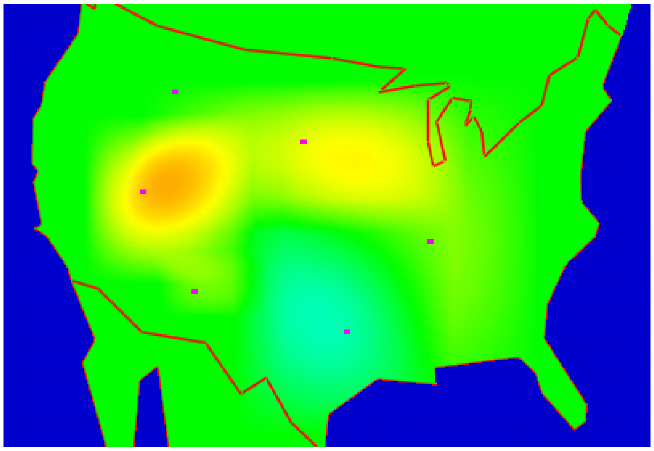


Figure C.5 USA Frequency Data Visualization Snapshot 2

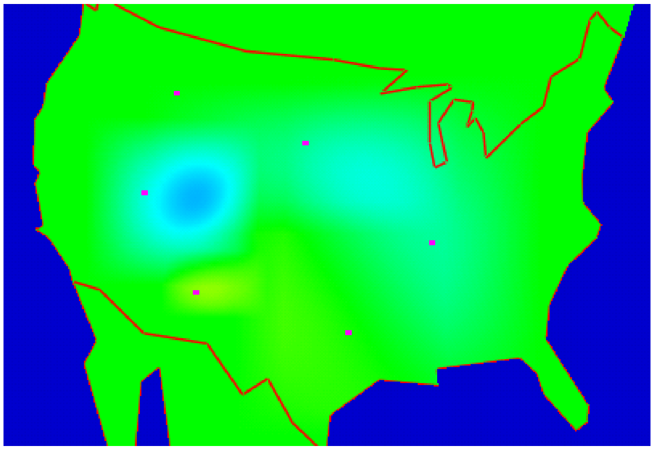


Figure C.6 USA Frequency Data Visualization Snapshot 3

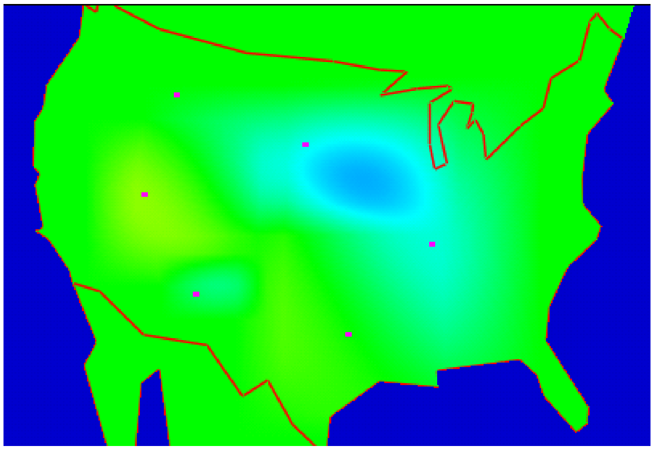


Figure C.7 USA Frequency Data Visualization Snapshot 4

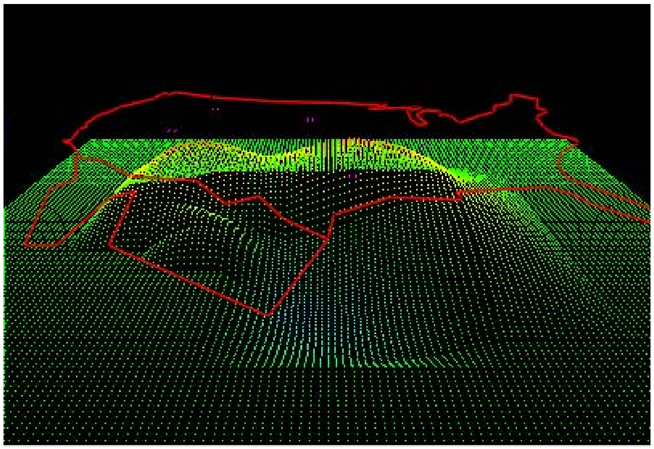


Figure C.8 USA Frequency Data Visualization Snapshot 5

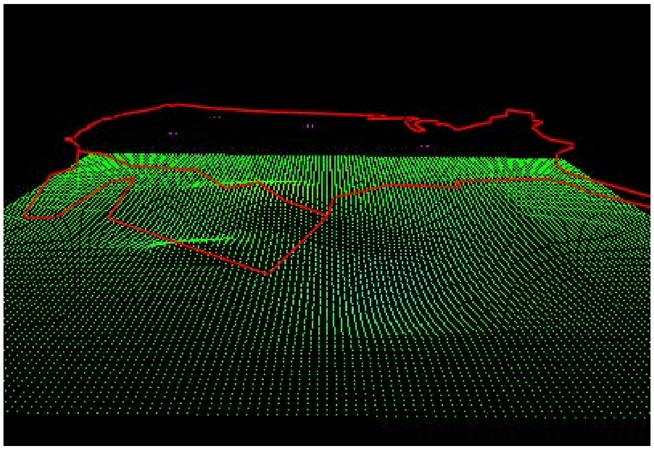


Figure C.9 USA Frequency Data Visualization Snapshot 6

Appendix D PDNet Information Management System

D.1 The Need for Transformer PD Monitoring

Power transformers are the most critical and costly component in transmission and distribution systems, especially those of large capacity such as generator step-up transformers and system tie auto-transformers. Catastrophic failures of power transformers can occur without warning, resulting in serious oil spills, fires, and extensive damage to adjacent equipment, and major disruption of service. EHV power transformer has unacceptable failure rates of more than 3% per year per device. Dielectric breakdown is a major cause of EHV transformer failures. A informal survey indicated that over 75% of large, EHV transformer failures are caused by dielectric problems [135]. Partial discharges are involved in any transformer insulation failure. These discharges can degrade electrical insulation and eventually lead to failure and loss of the transformer. It is important that the partial discharge activity of important transformers being monitored to detect incipient insulation problems, to prevent catastrophic failures, and to prevent extensive cost.

In most cases, partial discharges in power transformers start well before the structure fails. An exception is the static electrification related discharge. Static electrification often causes partial discharges because of the combination of normal AC and accumulated DC voltages, particularly during transformer startup [135]. The partial discharge typically happen at regular time intervals ranging from seconds to hours apart. The more frequently they occur, the more severe their activity. Once there is partial discharge activity, failure can occur at any moment. If an incipient insulation failure is recognized before it leads to an internal fault, then the transformer may be repaired or replaced in a controlled fashion. The monitoring of partial discharge is necessary and fast reaction to monitoring information is mandatory.

D.2 Acoustic PD Detection for Power Transformers

Optical fiber sensors are used to detect the partial discharge of power transformers. They are installed in the transformer at locations near the possible PD sites. The direct acoustic waves generated by the PD can be captured before being corrupted by other signals from indirect paths. Since high frequency acoustic waves are heavily attenuated by transformer oil, the sensors response frequency can be designed to be higher than that of piezoelectric sensors to avoid ambient mechanical noise resulted from rain, snow, wind, etc [135]. Such sensors are also insensitive to low frequency mechanical noise such as Backhausen noise. Since the simplest location technique is based on the fact that the signal will be the largest when close to the source, PD location will be easier using the high frequency optical fiber sensors. Optical fiber sensors have some advantages for the transformer partial discharge detection. Optical fiber sensors are chemically inert, and electrically non-conducting so that they do not affect the integrity of insulation system, hence they provide a suitable means to monitor the condition of high voltage (HV) equipment. Another obvious advantage of fiber-optic sensors is their immunity to electromagnetic interference (EMI). They are very useful in hostile environments, such as those often encountered during HV power equipment testing and condition monitoring, where EMI can make the measurement impossible.

D.3 PDNet Information Management System Design

PDNet information management system plays a role for the PD data collection, post-fault analysis, database operation and communication management. As illustrated in Figure D.1, PDNet system contains two parts: data acquisition unit and data processing unit.

D.3.1 Data Acquisition and Transmission Unit

The frequency range of the PD acoustic signal that has been considered is from 70kHz up to 350kHz since most of the energy is contained within this range. The medium that acoustic wave will propagate could be the transformer oil and other solid materials, such as copper coils. In most of the cases, the PD pulse duration is usually within 100us, and the pulse duration is determined mainly by the PD current response itself instead of the bandwidth of the monitoring system. According to these data, The DA (Data Acquisition) Board sampling rate is set at 1MHz and the sampling duration is 200 us (100 us data before event and 100 us data after event). Therefore, each event will generate 600 points of data (1MHz x 200 us x 3 sensors).

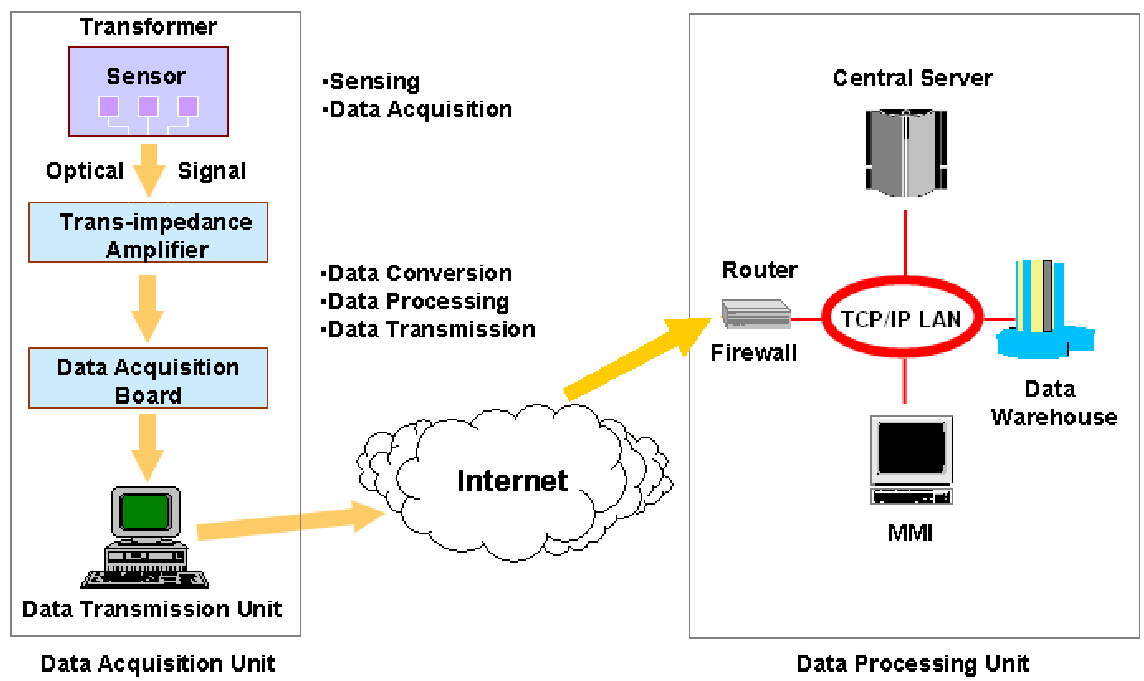


Figure D.1 PDNet System Architecture

When PD occurs, the ultrasonic signal will propagate in the oil-filled power transformer. Optical sensor will pick up these pressure waves, convert the pressure signal into optical signal, and transmit to the Trans-impedance amplifier. There, the optical signal will be converted into electrical analog data. DA board will digitize the analog signal and transmit the transient data to the center server for further analysis through public network.

D.3.1 PDNet Information Management Unit

PDNet information management unit is used to manage the PD real time information centrally. It plays important roles in three aspects: manages the communication channel with PD client sites; processes the PD real time information; manipulates the database for data storage and retrieval.

When PDNet server starts, server socket will be set up waiting for the connection from PD data source client. When transformer partial discharge occurs, PDNet client will initialize the connection to the server. After the authentication, PDNet server will create a thread to process the data communication with the PDNet client. Real time fault data will be saved to the database for further analysis.

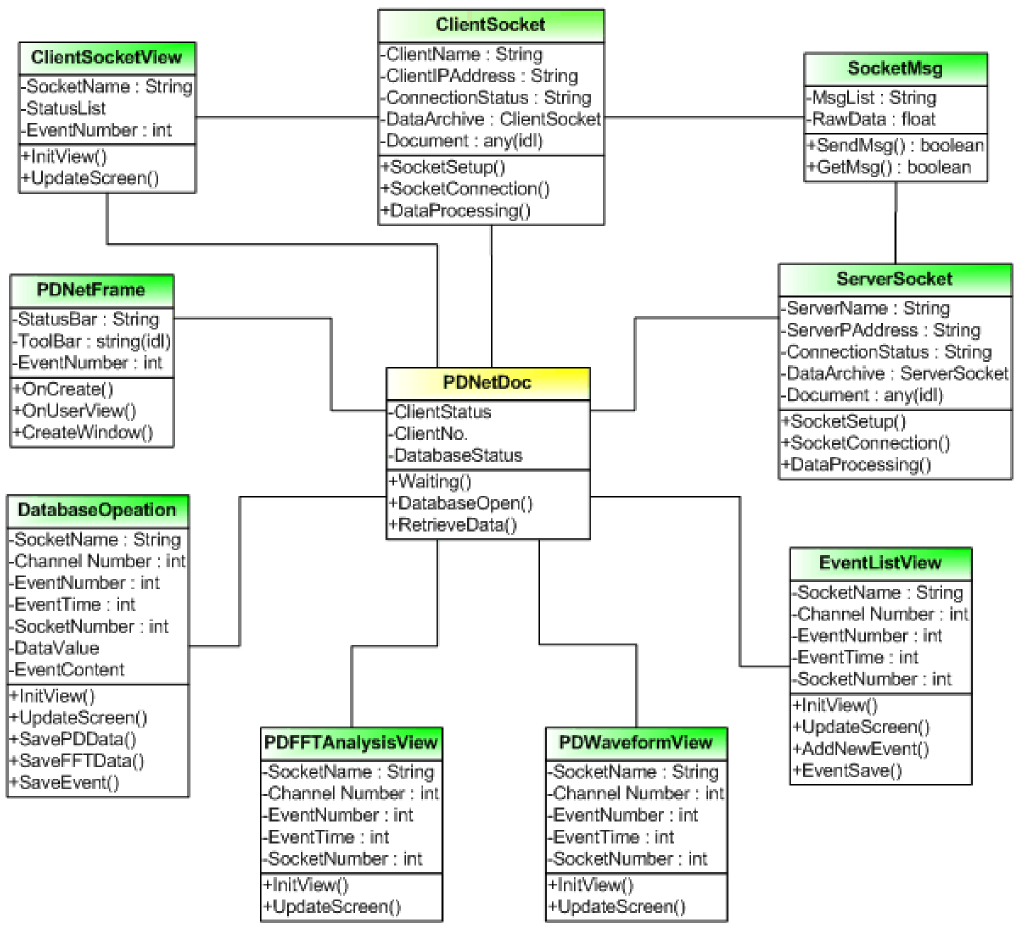


Figure D.2 PDNet Information Management System Class Diagram

Figure D.2 illustrates the class diagram of PDNet information management system. Following lists the major class modules of PDNet information management system.

- PDNetDoc: Processes the system initialization; manages the global parameters and variables.
- PDNetFrame: Defines and displays main GUI frame for PNDet; manages the menu and system message processing.
- PDWaveformView: Shows the transformer partial discharge waveform. Different channel data can be selected when multiple channel data are transmitted concurrently.
- PDFFTWaveformView: Displays the transformer partial discharge FFT (Fast Furrier Transform) waveform.
- EventListView: Displays system event and alarm information.
- DatabaseOpeartion: Connects to the database for data storage and retrieval.
- ClientSocketView: Displays client communication status.
- ServerSocket: Initializes the socket on the server side listening for the connection from PD data source client.
- ClientSocket: Processes the actual data communication with client socket when the connection request from client is accepted.
- SocketMsg: Stores the format and regulation for the data exchange.

Figure D.3 to Figure D.6shows the main interface of the PDNet information management system.

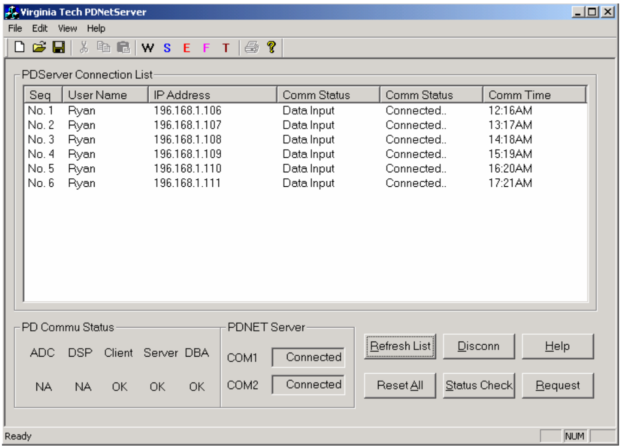


Figure D.3 Client Socket Status

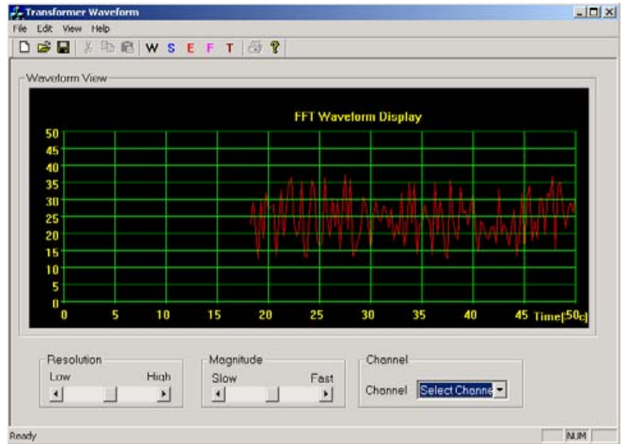


Figure D.4 PD Waveform

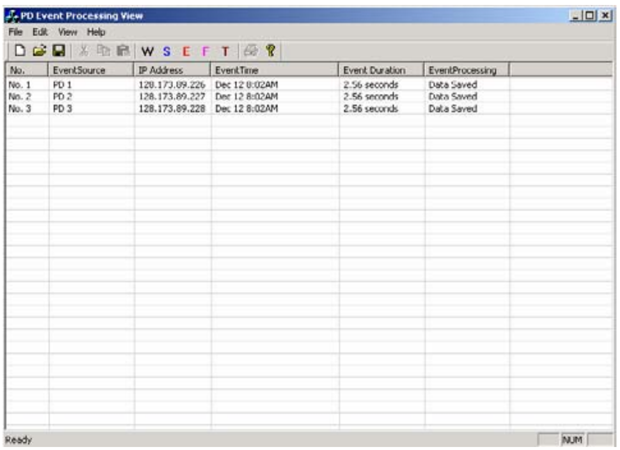


Figure D.5 Data Storage View

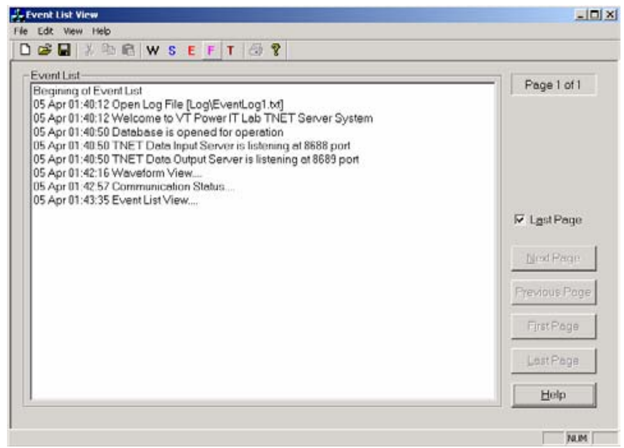


Figure D.6 System Event List View

D.3.1 PDNet Information Management Unit Configuration

The PDNet information management unit prototype is set up at Virginia Tech on a high performance PC. Windows 2000 is chosen as the main operating system. SQL Server is selected as the backend database. All the database communication is through Campus high-speed Ethernet network.

List of Publication since Joining Virginia Tech

[1] B. Qiu, Young Sun Ong, Hoay Beng Gooi, Yilu Liu, "Managing Metadata over the WWW using eXtensible Markup Language (XML)", IEEE Power Engineering Society Winter Meeting, Vol. 1, 2002, pp 678 – 683.
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