WEB-BASED REAL-TIME MONITORING SYSTEM TO ENHANCE THE PARTICIPATION OF AN INDUSTRIAL POWER SYSTEM IN A RESTRUCTURED UTILITY INDUSTRY

by

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF TEXAS AT ARLINGTON

August 2006

In memory of my father

Ting-Chung Huang

ACKNOWLEDGEMENTS

Sincere appreciation is expressed to Drs. W. J. Lee, R. R. Shoults, W. E. Dillon, K. S. Yeung, and H. M. Chen for serving as members on the author’s graduate committee.

Special thanks are reserved to my graduate advisor, Dr. Lee, for his advice, encouragement, and support throughout the development of this dissertation and my academic program.

Appreciation is also extended to Dr. J. H. Chen and Mr. S. P. Wang who share their knowledge and suggestions with me.

Finally, I would like to express my deep appreciation to my wife, Fang-Yu Chou, and the rest of my family for their affections, trust, and support. They have meant very much to me. I could not have succeeded without them.

July 10, 2006

ABSTRACT

WEB-BASED REAL-TIME MONITORING SYSTEM TO ENHANCE THE PARTICIPATION OF AN INDUSTRIAL POWER SYSTEM IN A RESTRUCTURED UTILITY INDUSTRY

Publication No. ______

Shun-Hsien Huang, Ph.D.

The University of Texas at Arlington, 2006

Supervising Professor: Wei-Jen Lee

The opening of the Electric Reliability Council of Texas (ERCOT) grid to wholesale competition began in 1996 that initiated the first stage of deregulation in Texas. In order to relieve generation and transmission constraints, load reduction is considered as a form of available energy and spinning reserve. Afterward, power system becomes more dynamic and creates more opportunities for both electricity suppliers and consumers. Currently, both power supplier and demand consumer can participate in the energy and ancillary services (AS) markets to bid/offer for their energy, capacity, and demand in the ERCOT markets. In order to act as an effective market participant,

understanding the real time plant operation structure, load characteristics and market prices becomes key factor for industrial power plant to establish flexible and realistic bidding strategy in the power auction markets to maximize the profit, especially for those with in-house power generation and interruptible demand.

This dissertation develops a web-based real-time monitoring system to enhance the participation of an industrial power plant to a restructured electric market. This system has two main functions. One is dynamic performance monitoring system (DPMS) which performs the regular system operation monitoring, such as system power flow, frequency, tie-line flow oscillation, transformer temperature, and circuit breaker status. Event recording, database storage and report generation functions are also included. The other is dynamic cable rating system (DCRS) which monitors the overhead/underground cable temperature and estimates the system available ampacity by considering the cable loading, forecasting temperature, balancing energy market, and ancillary services markets prices. This newly developed DCRS is the first attempt to incorporate forecasting temperature information for cable rating estimation.

Unlike traditional power monitoring system, this system not only focuses on the system operation monitoring but also considers the economic factors, such as power market price and weather information to provide overall system information for market manager. Several distinct features, for instance, low cost GPS timestamp, web-based remote access, dynamic cable rating, available ampacity estimation, and real time power market prices information are taken into account to offer the convenience, accessibility and efficient operation strategies to the management system. Through this newly developed monitoring system, industrial power company is able to establish bidding strategy to maximize its profit in the restructured power markets without jeopardizing system operation.

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CHAPTER 1

INTRODUCTION

1.1 Background

Over the past ten years, the electric power utility industry in North America and other countries have experienced a strong drive towards deregulation. Based on the experience of the deregulation of the telecommunication, natural gas, and airline industries, people have considered the necessity of deregulating electric utilities to improve the operation efficiency and lower energy costs.

In 1992, Congress passed the Energy Policy Act [1], which allows utilities to compete with each other for customers, and to serve customers not located in their traditional service areas. In order to bring about this goal, the law requires that utilities transmit (or "wheel") power for other utilities over their lines under the same rates and conditions as they would transmit their own power, for themselves. It also requires that customers be permitted to choose their power provider from the market, rather than being held captive by their traditional local area provider.

The opening of the Electric Reliability Council of Texas (ERCOT) grid to wholesale competition began in 1996 that initiated the first stage of deregulation in Texas. The ERCOT market is primarily a “bilateral” market. In a bilateral market, market participants arrange to meet all of their anticipated electric energy needs through the use of bilateral contracts with suppliers. Market participants known as Qualified Scheduling Entities (QSEs) must schedule their energy obligations on a daily basis. Schedules are submitted a day in advance showing a balance between generation and load for each 15-minute interval for the following day. There is no large “pool” of resources from which retail entities can choose to assign a portion of their load responsibilities. However, markets for balancing energy and certain ancillary services do exist.

Wholesale electricity market prices depend upon the amount of loads being connected on the grid and the generation resources available to meet that demand. During periods of extreme peak demand, wholesale prices may reach many times of their off-peak levels. Even during milder weather when demand is moderate, premium prices are often paid for available resources because many generation plants were scheduled for maintenance.

The electric utility industry restructuring in the state of Texas has created opportunities and challenges to both electricity suppliers and consumers. In the ERCOT market, the ability to reduce load is considered as a form of available energy. Its value is equivalent to that of an increase in generation. Thus, during these periods, payments for load reductions are equal, dollar for dollar, to that which generating companies are paid for bringing additional power on line.

At present, both power supplier and demand consumer can participate in the energy and ancillary services (AS) markets to bid/offer for their energy, capacity, and demand in the ERCOT markets. Under the new restructured electric power market, optimizing bidding strategy based on available energy, capacity and demand to participate in various power markets becomes a very important issue for industrial plants with in-house generation facilities and interruptible demand. Understanding the currently system operation patterns and characteristics turns out to be key factors to establish flexible and realistic bidding strategies in the power auction markets to maximize the profit. For that reason, a well designed monitoring system is indispensable to realize this mission.

1.2 Motivation and Objectives

One cogeneration plant is located in Texas, which has two 138kV transmission lines tied to the system grid for power trade. There are three steam turbine units and seven gas turbine units with total 700MW generation capacity for the cogeneration. During normal operation, it could export or import power from the grid by responding to the market prices. Because of fast response time characteristics of gas turbine units, this cogeneration is able to participate into the real time balancing energy market to capture the good market prices periods. In addition, there are about 220MW interruptible loads in the plant, which create a good opportunity for this cogeneration to join the demand response programs in the ERCOT ancillary services markets. Hence, under the ERCOT operation structure, this cited cogeneration has maximum flexibility to participate into the ERCOT markets. In order to act as an effective market participant in the ERCOT markets, this cogeneration needs better understanding regarding the real time plant operation structure and load characteristics.

A dynamic performance monitoring system has been installed in this cogeneration since 1993 [2-3]. It has been a useful tool for both operators and plant managers. Due to the changes in the utility industry, and in-plant expansion, the original monitoring system is no longer adequate for the current power system structure.

One-day ERCOT balancing energy and ancillary services markets prices trends are shown in figure 1.1 and figure 1.2 [4-5]. Since the clearing prices of the auction markets have enormous fluctuation in one day, from the industrial power plant point of view, more profit may be made by capturing the good market price periods. Furthermore, if there are more available system resources during those good market price periods, extra profit could be earned. Unfortunately, the concerns of potential overloading of the underground cable inside the cogeneration, as shown in figure 1.3, has limited the capability of company's participation in the ERCOT's energy and ancillary services markets. The reasons for the limitation include:

1) During the installation of 69kV transmission line, #BG1, in the early times, part of #BG1was installed at an overhead 24 inches open tray and the rest part was installed in the underground 5 inched PE pipe with depth of 4 feet, which obviously limits the cable transfer capability.

2) Since #BG1 and #BG2 are connected in parallel in normal operation condition and their impedances are almost identical, the transfer capability of #BG2 is also limited.

3) The static cable ratings from manufactures, which is usually based on the conservative test environment, are applied as current operation criteria also limit the cable ampacity.

4) According to the system analysis of the cited cogeneration, the underground cable is the current bottleneck of the system to limit the system transfer capability to participate into the power auction markets.

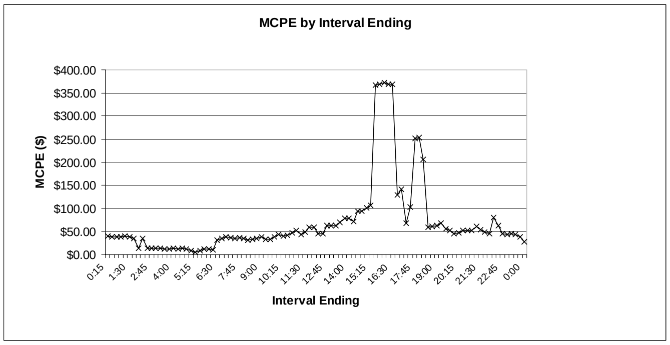


Figure 1.1 Balancing energy market clearing price

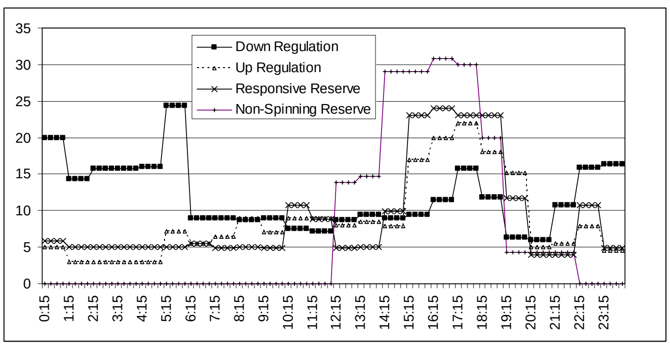


Figure 1.2 Ancillary services market clearing prices

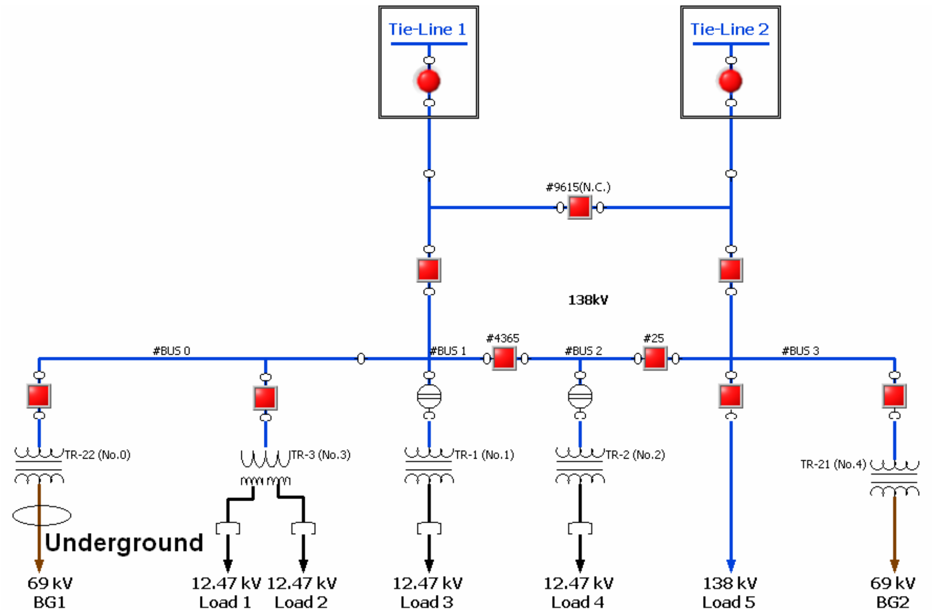


Fig. 1.3 The one-line diagram of the cogeneration plant

In order to upgrade the original inadequate monitoring system and to effective utilize the current facilities, such as underground cables and transformers, without jeopardizing the system, developing a newly web-based real-time power system monitoring system by merge the conventional monitoring function and auction market information to help both the operator to monitor the system operation and manager to establish good bidding strategies to participate into ERCOT power markets is the main objective of this dissertation.

This system has two main functions. One is dynamic performance monitoring system (DPMS) which monitors system operation condition to help the system operator and manager have better understanding of the system operation characteristics. The system information includes system power flow, frequency, tie-line flow oscillation, transformer temperature, voltage surge detection and circuit breaker status. Other functions, for instance, event alarm and record, database storage and report generation are also built-in. The other is dynamic cable rating system (DCRS) which detects the overhead/underground cable temperature and estimate the system available ampacity by considering the cable loading, forecasting temperature, balancing energy, and ancillary services markets prices. This newly developed monitoring system can provide the system manager the required real time system operation condition and system available capacity to establish a better bidding strategy to participate in the power markets.

1.3 Contributions

The contributions of this dissertation to the power system engineering are listed as follows:

1) Since the electric reliability council of Texas (ERCOT) applies the GPS timestamp, synchronized to Universal time (UTC), as standard timestamp. A simple, inexpensive, and highly precision absolute time, extracted from a low cost GPS receiver, is implemented to provide universal timestamp for this monitoring system.

2) In the conventional power monitoring system, the monitoring information is only accessible inside the control room. To extend the data accessibility and convenience, a web-based real-time monitoring function is developed for remote access. The real time system information can be obtained through intranet inside the office or internet around the world (with permit) to recognize the real time system operation condition.

3) Both the static and dynamic ratings of the system overhead/underground cables are implemented in this monitoring system to effective utilize the system facilities. The estimated cable ampacity based on constant temperature may be over-estimated or under-estimated. Therefore, in order to conform to the real operation, one specific

feature of this developed dynamic cable rating system is not only the current temperature but the forecasting temperatures are also considered to perform cable rating estimation for current and next several hours to avoid over/under cable rating estimation.

4) This developed monitoring system not only focuses on the system operation monitoring but also considers the economic factors, for instance, power market prices and weather information to provide practical system information for market manager to establish an optimal bidding strategy without compromising the reliability of the system facilities.

5) Through this newly developed monitoring system, the system engineer does have a better understanding about system operation characteristics. Currently, the cited cogeneration already makes remarkable profits by participating into the balancing energy market and the load acting as a resource in the responsive reserve service in the ancillary services markets, and they are seeking more opportunity to participate into other available demand response programs in the ERCOT markets.

1.4 Synopses of Chapters

The material in this dissertation is organized as follows:

Chapter 1 introduces the general background of the restructuring power market, illustrates the motivation and objective of this dissertation, and lists the contribution of this research work.

Chapter 2 discusses the demand response programs in the electric industry. Current electric industry and demand response programs in the United States are reviewed and two main types demand response programs are introduced. Since there is still no standard market structure in the electric industry, the demand response programs at several Independent System Operators (ISOs) are also discussed. Finally, summarize the existing demand response programs and future development in ISOs.

Chapter 3 describes the developed monitoring system. There are two main functions of the newly designed monitoring system, dynamic performance monitoring system (DPMS) and dynamic cable rating system (DCRS). The hardware configuration and designed functions are described. The specific features, such as GPS timestamp, remote access, dynamic cable ampacity estimation and other designed functions of this monitoring system would be discussed in detail. The integration of the whole system is presented.

Chapter 4 describes the installation of this monitoring system inside the cogeneration and presents the recording data of system events. Analyzing the recording data and from the industrial power plant point of view, investigate and recommend the opportunity for industrial plant to participate into various demand response programs.

Chapter 5 states the summary and conclusion of this dissertation and discusses the opportunity for further research.

CHAPTER 2

DEMAND RESPONSE PROGRAMS IN THE ELECTRIC INDUSTRY

2.1 Background

The system demand and supply must be continually balanced for both regulated and restructuring power system. In order to avoid system blackout and other disruptions, the system must have sufficient generation capacity to meet the highest demand. Building new power plants are essential to provide more generation capacity with the increasing system demand. Unfortunately, building new generation/ transmission facilities are not easy because of the social, economical, and environmental constraints. Therefore, system operators are facing a much more stressful operation condition with lower generation and transmission margins.

In the traditional electric wholesale market, the electricity price is primarily determined based on the generation cost without load participation. Some costly generation units have to be scheduled to provide extra generation capacity in order to satisfy the peak or extra-peak demand in hot season, which results in higher generation cost and consequently more payment for customers. The condition would become even worse in the restructuring power markets. Some price volatility may be caused just because of the lack of demand participation in the power market. The energy crisis in the west in the United States in 2000 and 2001, for example, is induced by market manipulation because of the absence of demand response of sharply higher energy prices [6]. Without the flexibility of system demand participation and difficulty of building new facilities, power system is already operated at a tight system margin, which may cause unexpected blackout or system disruption induced by some system disturbances.

By introducing the system demand response programs to the customers in the electric industry, the system operation will be more flexible. Customers can shift or reduce the demand consumption during the higher price periods. As a result, the system stress can be relieved, the system reliability can be maintained, extra generation capacity may not be required, and the overall cost would be reduced. During some system disturbances, blackout or further system disruption may also be possibly avoided by cooperating with the demand response program.

2.2 Electric Industry in the United States

Currently, the electricity industry of the US is consisted of ten regional markets, and their geographical locations are shown in figure 2.1 [7]. These ten regional markets are California, Midwest, New England, New York, Northwest, PJM, Southeast, Southwest, Southwest Power Pool, and Texas. Seven regional transmission organizations (RTOs), which are CAISO, MISO, ISO-NE, NYISO, PJM, SPP, and ERCOT, have been approved by the Federal Energy Regulatory Commission (FERC). Their geographical locations are shown in figure2.2.

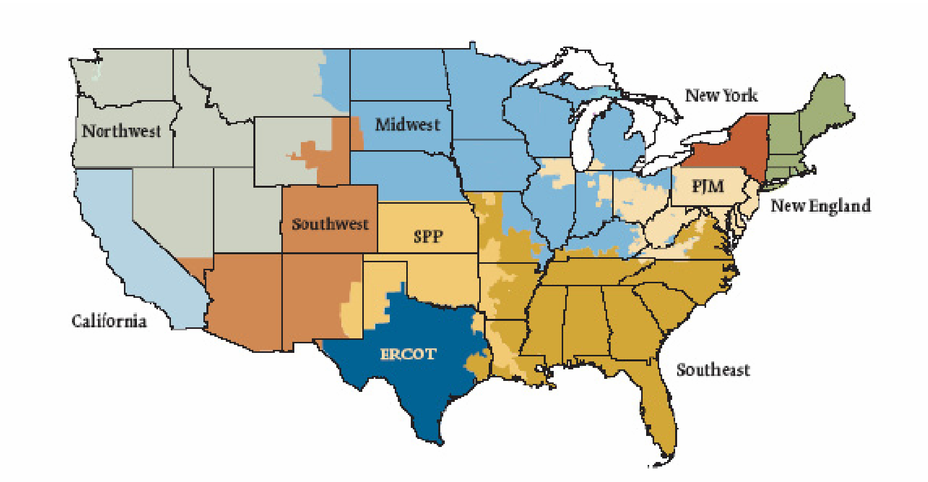


Figure 2.1 National overview of electric regions in the U.S.

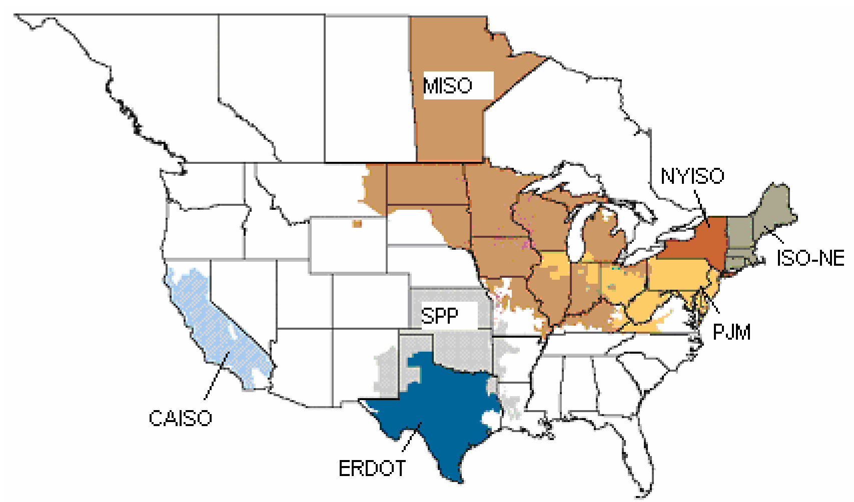


Figure 2.2 Regional transmission organizations in the U.S.

<u>2.3 Demand Response Programs in the United States</u>

According to the U.S. demand response coordinating council [8], demand response is defined as:

"Providing electricity customers in both retail and wholesale electricity markets with a choice whereby they can respond to dynamic or time-based prices or other types of incentives by reducing and/or shifting usage, particularly during peak periods, such that these demand modifications can address issues such as pricing, reliability, emergency response, and infrastructure planning, operation, and deferral."

The conventional vertically integrated electric industry is always a supply-side dominated market. With the stable low electricity price and high reliability power system, public do not have enough incentives to participate in the demand-side market. According to the Energy Policy Act in 1992, the legislation in the United States has opened wholesale electricity markets for economic reason. Since then, the vertically integrated structure of the electric industry has begun to change. In the beginning, the wholesale electricity market was still a supply-focused market, which has caused the possibility of market manipulation to affect the efficiency and electricity price of the markets. The main reason of this drawback of market manipulation is the absence of load customers to participate into the market to affect the demand decision [9]. The main benefit of the demand response of reducing sharply price spike can be explained by figure 2.3. The system demand would be higher at hot season (as L-Hot in the figure2.3) than normal days (L-Nor). If the demand is inelastic by responding to the electricity prices, the market price would be much higher (P-Hot) than regular market prices (P-Nor). However, the market price could be reduced to (P-Dem) by introducing the elastic demand (L-Dem) in the market. Therefore, the advantage of the demand response programs in the electric markets is the small reduction of the demand at extreme high demand periods could result in high reduction of market price to prevent the market price spikes [10-11].

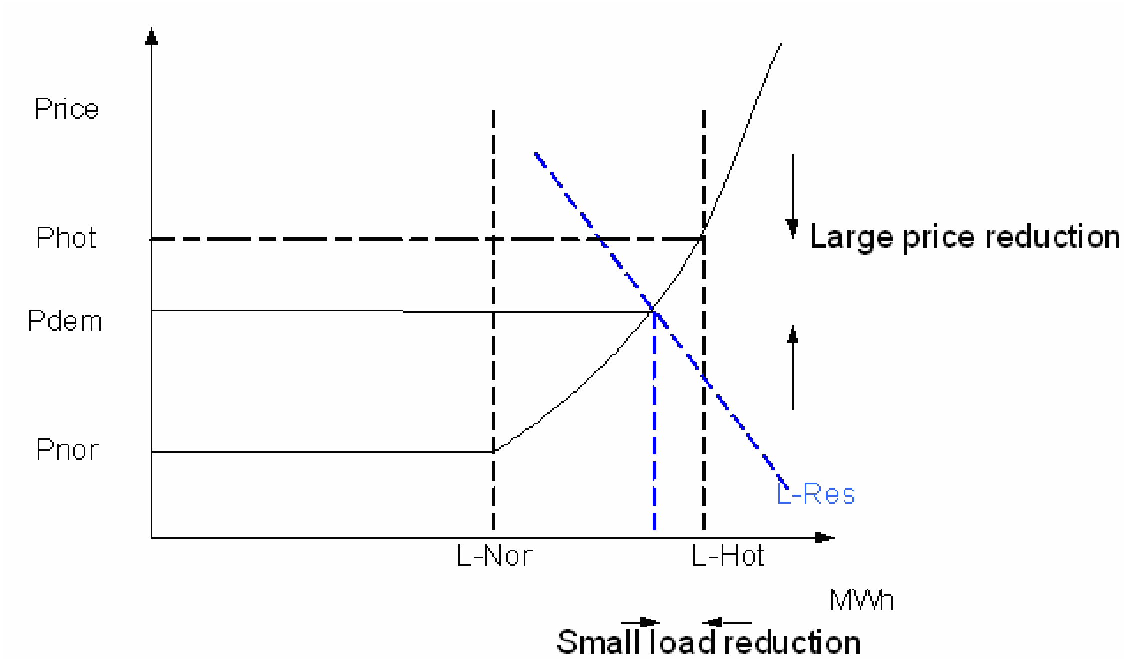


Figure 2.3 Electricity price with inelastic and price-responsive demand

In the United States, there are already several demand response programs sponsored by utilities and independent system operators (ISOs) [12-16]. In general, the demand response programs mainly can be categorized as two types: market-based pricing program (or economic program) and reliability-driven program (or emergency program) [17].

Market-based pricing program enables customers to adjust their demand in response to electricity prices. In particular, the customers would have higher incentives to reduce demand usage when the electricity price is extremely high. The market-based pricing program can be generally divided into three programs.

1) Time-of-use pricing program: the price is set by time blocks, such as peak, semi-peak and off-peak periods.

2) Real-time pricing program: the price is response to the real time electricity cost for each time interval, for instances, fifteen minutes or one hour.

3) Demand bidding program: allow customers to bid/offer their demand in the wholesale markets.

Reliability-driven program enables grid operator, such as independent system operator (ISO), to request customers reducing the demand consumption to maintain the system reliability. In general, there are also three programs in the emergency program.

1) Interruptible rates program: provides participants with a compensation or discount on the electricity prices when participants are called to interrupt the demand.

2) Direct demand control program: participants receive financially compensation to allow the utility or ISO to remotely interrupt their demand.

3) Voluntary program: participants with a certain amount demand to meet the utility or ISO's requirement can voluntarily join this program. Participants would reduce their demand voluntary or by the utility/ISO depending on the agreement or contract with utility/ISO.

2.4 Benefits, Drawbacks, Barriers and Issues [16-18]

Unlike traditional one-side electric market (supply side), the demand response program (demand side) brings the customer's effort into the electric market. This section discusses the benefits, drawbacks, and current existed barriers of the demand response programs in the United States.

2.4.1 Benefits

By introducing the demand response program to the electric industry, the power market becomes two-side structure, which creates several benefits in the electric markets. The main benefits of the demand response program in the electric industry can be concluded as follows:

1) Mitigate price volatility: in some wholesale markets, the periodic price spikes caused by some generation suppliers to manipulate the electricity price are observed, which is primarily due to the lack of demand response. By implementing the demand response in the power market, customers can reduce or shift their demand at high price periods, which can make the system demand become elastic in response to the market prices and consequently reduce the price spike.

2) Improve the energy efficiency: because customers can reduce or shift their usage at high price periods, power system would rely on more efficient and economical units without scheduling the high-cost generation units. Therefore, demand response in the electric market can improve energy efficiency and reduce overall electricity production cost.

3) Improve the system reliability: the researchers found that the load reduction could potential avoid rolling blackout during California's energy crisis of 2000 and 2001 [9]. Besides, in order to speed up the recovery of the system electricity service from the blackout event at August, 14, 2003, in northeast of America, the demand response participants are scheduled to interrupt their demand usage.

2.4.2 Drawbacks, Barriers, and Issues

Although there are many benefits for demand response in the electric market, some drawbacks, barriers and issues still do exist in the current market structure. Several important barriers, issues and drawbacks are discussed below.

1) Regulatory uncertainty: due to the lack of the standard market structure in the current electric market, and the indistinct responsibility between the FERC and states, as shown in figure 2.4, the coordination among federal, region, and state authorities is imperative for the demand response. In addition, some stakeholders' resistance to open the demand side market also become an obstacle for regulatory.

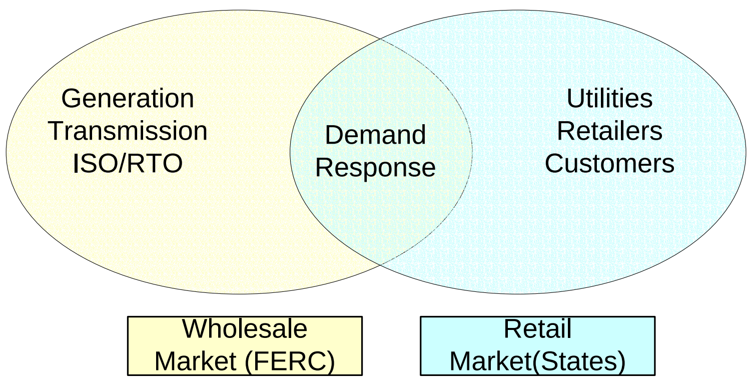


Figure 2.4 Fuzzy role of the demand response in the power market

2) Lacking of equipments at customers' (demand) side: currently, most customers are unable to participate in the demand response programs due to the lack of the necessary equipment, such as meters, communication devices, and billing tools. Although the technology for developing these equipments is mature, the production and installation cost of these equipment for retail customers are still significant for both the utilities and customers that have reduced the incentive for customers to participate in demand response programs.

3) Limited awareness and guidance for customers: despite the availability of demand response programs in many ISOs, some customers are still not aware that they are qualified to participate in these programs or what kind of benefit they can receive by joining those demand response programs. Furthermore, even though customers have the capabilities and incentives to participate into demand response programs, the various different demand response programs proposed by each ISO and the corresponding potential enormous violation penalty may confuse and impede the customers' incentives because of the absence of a guide for the customers to follow.

4) Lacking of incentives of customers: the reserve margins at some electric regions in the United States are about 20% or even higher. In other word, the requirement of system demand participation to relieve the system operation stress would not be tense. Besides, the low and stable electricity price in the market also impedes the customers to join the demand response programs because they may not able to get enough benefits if they reduce or increase their demand usages.

5) Some of the demand response programs may used infrequently but have to provide regular payments for participants to maintain the demand response requirement. These costly programs are difficult to justify during years when they are not needed.

6) The uncertainty of energy saving and load reduction measurement of demand response programs also diminish the incentives for ISO and utilities. For example, load interruptible programs may not function well because of the delay of manual operation. Besides, utilities or ISOs may have to estimate the energy saving or load reduction because of lacking meters and the validation may be difficult and time consuming.

2.5 Demand Response Programs at ISOs

The summary of the subscribed demand response programs at different ISOs in the United States in 2004 is shown in table 2.1 [7]. Since there are various different demand response programs proposed and encouraged by each ISO and different names of these programs, even some of them offer the same service. The demand response programs of each ISO, such as ERCOT, PJM, ISO-NE, and NYISO, are discussed below.

Table 2.1 Subscribed Demand Response Programs offered by ISOs in 2004

	Total Demand Response (MW)	Total Peak Demand (MW)	Ratio of DR to Peak Demand (%)
ISO-NE	368	25000	1.5
NYISO	1754	31000	5.7
PJM	3419	131300	2.6
ERCOT	1718	60475	2.8

2.5.1 ERCOT [14, 16, 19]

The mission of the Electric Reliability Council of Texas (ERCOT) is to direct and ensure reliable and cost-effective operation of the electric grid and to enable fair and efficient market-driven solutions to meet customers' electric service needs. ERCOT is primarily a bilateral market structure. In order to balance the supply and demand, ERCOT also administers the ancillary services and balancing energy markets. In the ERCOT market, market participants known as Qualified Scheduling Entities (QSEs) have the responsibility for matching load requirements and generation capabilities, and must schedule their energy obligations on a daily basis.

The purpose of the demand response programs, or called load reduction programs in ERCOT, is to provide the ERCOT market with valuable reliability, energy efficiency, and enhance the wholesale competition, mitigate the price spikes. These "demand-side resources," or loads, are encouraged to make their resources available by responding to wholesale price signals. Actual dollar values to be paid for these resources are established in the form of Market Clearing Prices, which are based on bid processes in various ERCOT-operated markets. The Market Clearing Price for Capacity (MCPC) expressed in dollars per megawatt-hour represents the price paid for making a capacity resource (load reduction or generation increase) available to the system. The Market Clearing Price for Energy (MCPE) expressed in dollars per megawatt-hour represents the price paid for actual deployment of a resource's energy (load reduction or generation increase). Table 2.2 shows the current demand-side resources allowed by ERCOT Protocols for loads to participate in the ERCOT administered markets as Voluntary Load, Balancing Up Load ("BUL"), or Load Acting as a Resource ("LaaR") [19].

Table 2.2 Demand-Side Resources in ERCOT

Resource Type	Resource or Service that can be Provided	Requirements
Voluntary Load Response	Curtailment or reduction in response to Market Price or other factors	Metering and/or curtailment technology defined in Retail Electricity Provider (REP) contract
Qualified Balancing Up Load (BUL)	Balancing-Up Load (associated with the Balancing Energy Market)	Interval Data Recorder (IDR) meter Qualification
Load Acting as a Resource (LaaR)	Various ERCOT Ancillary Services (AS)	IDR meter Telemetry Qualification

1) Voluntary Load Response: a customer may decide independently to reduce consumption from its scheduled or anticipated level in response to price signals or high

demand on the ERCOT system, without its being in the formal Load Acting as a Resource (LaaR) or Balancing Up Load (BUL) programs. Voluntary Loads stand to gain financially from the ERCOT markets—over and above the savings they may enjoy on their electric bills from reducing consumption when prices are high. Also like LaaRs and BULs, a Voluntary Load's ability to receive extra financial compensation depends entirely on its contractual relationship with its REP (and QSE). Loads (and their QSEs) are not penalized if they fail to follow their schedules unless Replacement Reserve Service is purchased by ERCOT.

2) Balancing Up Load: Loads that contract with a QSE to formally submit offers to ERCOT to provide balancing energy by reducing their electricity use are referred to as Balancing Up Loads (BULs). BULs are paid only if they actually deploy (reduce energy use) in response to selection by ERCOT, but if deployed they receive two separate forms of compensation, an energy payment for the actual load reduction delivered, based on the prevailing Market Clearing Price for Energy (MCPE) in the Balancing Energy Market and a capacity payment based on the Market Clearing Price for Capacity (MCPC) in the Non-Spinning Reserves market, which is an additional reward for BULs submitting bids into the balancing energy market, even though they are not actually providing non-spinning reserves.

3) Load Acting as a Resource (LaaR): Customers with interruptible loads that can meet various performance requirements can be qualified to provide operating reserves under the Load Acting as a Resource (LaaR) program. In the eligible day-ahead ancillary services ("AS") markets, the value of a LaaR's load reduction is equal to that of an

increase in generation by a generating plant (MWh times MCPE). Moreover, any provider of operating reserves selected through an ERCOT AS market is eligible for a capacity payment, regardless of whether the Resource is actually deployed (or curtailed, in the case of the LaaR). Currently, eight of twelve ancillary services programs in the ERCOT administered markets are available for demand participation.

In general, under the existing ERCOT administered markets, there are ten services are available for qualified loads. The detail of each service for demand participation is shown in table 2.3. According to ERCOT 2004 State of the Market Report [20], 67 resources totaling 1657 MW of capability were qualified as LaaRs to participate in the responsive reserves market, but never participated in the balancing energy or other available demand response programs. This phenomenon is reasonable because the value of curtailed load tends to be relatively high, and the probability of being deployed is relatively low in the responsive reserves service compared with other available ancillary services. Furthermore, the price in the balancing energy market is not high enough to attract load participants' incentives, and some other ancillary services may require technical abilities that some demand customers can not meet the requirement. As a result, the load participants would prefer to join the responsive reserves service than other services to increase their benefits.

Table 2.3 Demand-Side Participation in ERCOT

Service	Metering	Used by	Participation Basis for Payment	Markets Payment Determination	Time to Curtail/ Interrupt
Voluntary Load Response	Contractual with REP	REP	Actual deployment	Market-clearing balancing energy price	Contractual with REP
BUL	IDR settlement metering	ERCOT	Actual deployment	Market-clearing balancing energy price, plus prevailing price in Non-Spinning Reserve Market	Within 10 minutes for a full payment; within 70 minutes for a partial payment.
Responsive Reserves	Telemetry& IDR settlement metering	MP or ERCOT	Being available to be interrupted	Market clearing capacity price in Responsive Reserve Market and energy when deployed	Instantaneously or within 10 minutes if manually deployed
Non-Spinning Reserves	Telemetry& IDR settlement metering	MP or ERCOT	Being available to be interrupted	Market clearing capacity price in Non-Spinning Reserve Market and energy when deployed	30 minutes
Replace-ment Reserves	Telemetry& IDR settlement metering	MP or ERCOT	Being available to be interrupted	Market clearing capacity price in Replacement Market and energy when deployed	Must bid and respond in Balancing Energy Market
Regulation Up/Down	Telemetry& IDR settlement metering	ERCOT	Being available to be interrupted	Market clearing capacity price in Regulation Up and Down Markets and energy when deployed	Within moments to meet performance criteria
Balancing Energy Markets	Telemetry& IDR settlement metering	ERCOT	Actual deployment	Market-clearing balancing energy price	Within 10 minutes
OOMC	Telemetry	ERCOT	Being available to be interrupted	Compensation based on formulas for OOMC	Varies
OOME	Telemetry	ERCOT	Actual deployment	Compensation based on formulas for OOME	Varies

Note:

REP: Retail Electricity Provider

BUL: Balancing Up Load

IDR: Interval Data Recorder

MP: Market Participant

OOMC: Out of Merit Capacity

OOME: Out of Merit Energy

2.5.2 PJM [15, 16, 21, 22]

PJM Interconnection conducts three demand-response programs, active load management (ALM), emergency load response, and economic load response, that provide financial incentives for end-use customers to reduce their electricity use either during an emergency event or when Locational Marginal Prices (LMPs) are high on the PJM system.

1) Active Load Management: Retail customer's load that can be interrupted at the request of PJM. Such a PJM request is considered an emergency action and is implemented prior to a voltage reduction.

2) Emergency Load Response Program: This program provides compensation to end-use (retail) customers who voluntarily reduce their load during emergency conditions on the PJM grid. PJM pays the higher of the appropriate zonal Locational Marginal Price (LMP) or $500/MWh to the PJM Member that nominates the load. This program is designed to provide additional load reduction capability to supplement the ALM program.

3) The Economic Load Response Program: This program provides an incentive to customers or curtailment service providers to reduce electricity consumption when PJM LMPs are high. Participants in this program have the choice of day-ahead or real-time options. Participants who reduce load when LMP is less than $75/MWh will receive LMP, minus retail generation and transmission charges. When LMP is at or above $75/MWh, load reducers will receive LMP without having the retail generation and transmission charges subtracted. Two enrollment options, day-ahead and real-time, are

available in the economic load response program. The day-ahead option enables any qualified market participant to provide customers the opportunity to offer in advance of real-time operations to reduce the amount of electricity they will draw from the PJM system. They receive payments for actual load reductions based on the day-ahead LMP. The real-time option enables any qualified market participant to provide customers the opportunity to commit to reduce the amount of electricity they draw from the PJM system during times of high prices. They receive payments for the load reductions based on real-time LMPs.

At present, the economic load response program is still a pilot program and is going to set to expire at the end of 2007. There are several issues for the current economic load response program. First, the key issue of economic program is the supplement between the load participants and load service entities (LSE). The LSE has to pay the load participants at the market-clearing LMP, not the actual avoided generation cost, which may raise the LSE's concern when the LMP is higher than the avoided cost and results in the high payment of LSE. Second, both the day-ahead and real-time economic program participants receive the same payment creates another issue. Third, there is no demand response program offered in the PJM's ancillary service markets which also limits the market operation. Therefore, the PJM staffs are working on new programs for 2008 and beyond. Two demand response programs are under development, forward energy reserve market, and ancillary services market, and more issues are needed to be clarified. The trend of demand response participation in PJM in recent 5 years is shown in figure 2.5.

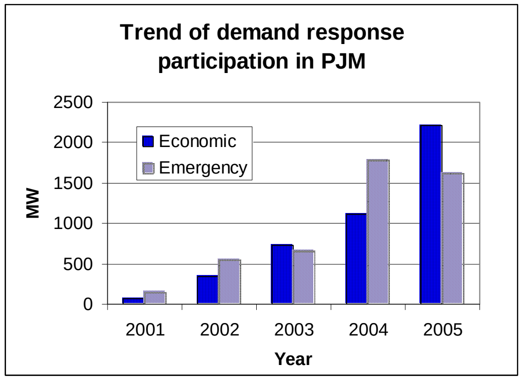


Figure 2.5 Trend of demand response participation in PJM

2.5.3 ISO-NE [12, 16, 23, 24]

Demand Response programs in ISO-NE compensate large electricity users for reducing consumption when market prices are high or demand is high and system reliability is at risk. Because the well designed demand response programs, over 13,000 MWh of electricity usage in 2004 is reduced. The demand response programs in ISO-NE include both the reliability programs and price programs. There are five demand response programs in the current in ISO-NE market services.

1) Reliability programs include the real-time 30 minute, real-time two hour demand response programs, and real-time profiled response program. The qualified real-time demand response participants must be able to curtail their consumption within 30 minutes or two hours after informed by ISO with equipped meter and communication capability and get paid at the higher of the real-time LMP or the floor price, which is $500/MWh in the 30 minutes program and $350/MWh in the two hour program, plus the ICAP (Installation Capacity) payment. The demand resources, which can be interrupted within 2 hours by following ISO instruction, can participate into the real-time profiled response program, which does not require metering capability.

2) Price programs includes the real-time price response program and day-ahead load response program. The real-time price response program allows customers to voluntarily reduce energy consumption during certain periods as determined by the ISO. The enrolling participant in the price response program only receives payments at the applicable real-time zonal price for the actual energy they curtail. For the real-time price response program, voluntary reductions will be allowed when the forecasted hourly appropriate zonal price produced by the day-ahead energy market, the resource adequacy or any update of the resource adequacy where the zonal price is greater than or equal to $100/MWh. The day-ahead load response program provides a day-ahead option to the real-time programs. The enrolling participant receives the greater of the offer price or the day-ahead hourly clearing price.

The summary of the demand response programs in the ISO-NE is shown in table 2.4. The demand response participants enrolled in the demand-response programs have been flat over the last few years and are not acknowledged by overall demand. Since the fluctuation of market prices is an important factor for a well-designed market, the ISO staff continues to improve the incentives for customers to participate in the demand-response programs and work with the states to remove any barriers to revealing efficient prices to retail customers.

Table 2.4 Summary of Demand Response Programs in 2005

Service	Metering	Used by	Participation Basis for Payment	Markets Payment Determination	Time to Curtail/ Interrupt
Real-Time 30 minutes Response	Metering & Communication	ISO-NE	Actual deployment	Greater of real-time price or floor price at $500/MWh, plus ICAP market price	Within 30 minutes of ISO request.
Real-Time 2 hours Response	Metering & Communication	ISO-NE	Actual deployment	Greater of real-time price or floor price at $350/MWh, plus ICAP market price	Within 2 hours of ISO request.
Real-Time Profiled Response	Communication	ISO-NE	Actual deployment	Guaranteed minimum payments is $100/MWh, plus ICAP market price	Within moments to meet performance criteria
Real-Time Price Response	Hourly data submitted	ISO-NE	Actual deployment	Greater of real time price or guaranteed minimum payments is $100/MWh	Voluntary to follow their offer
Day-Ahead Options	Hourly data submitted	ISO-NE	Actual deployment	Greater of offer price or the cleared hourly day-ahead market price	Specified by customers

2.5.4 NYISO [16, 25, 26, 27]

The demand response programs in NYISO also include both economic (price) and emergency (reliability) program. There are currently three demand response programs in the current NYISO market, two for emergency program and one for economic program.

1) Emergency Demand Response Program (EDRP): the NYISO notifies voluntary participants at least two hours in advance of when curtailments are needed to supplement conventional generation resources. Customers that curtail during the specified periods are paid either the locational-based marginal price (LBMP) or $500/MWH, whichever is higher.

2) Installed Capacity-Special Case Resource Program (ICAP/SCR): By utilizing load management capabilities to augment the supply of generation used by the NYISO as

standing reserves, the Installed Capacity Program/Special Case Resources program can be critically important in capacity-deficient regions of the State. Customers that qualify their load curtailment capability can sell their ICAP/SCR capacity. An ICAP/SCR participant receives an energy payment when they curtail, equal to the higher of the prevailing locational-based marginal price (LBMP) or the strike price (up to $500/MWh) it nominated upon enrollment.

3) Day-Ahead Demand Response Program (DADRP): to help ensure competitive bidding behavior, the Day-Ahead Demand Response Program allows load curtailment resources to compete directly against generation in the NYISO's day-ahead auction. Participants submit demand reduction bids that are treated as comparable to supply bids of generators. If scheduled, they receive market prices for load reductions that are scheduled for the next day.

The EDRP and SCR programs function very well in achieving actual load reductions during peak load periods, because the load participants would receive a better price that is close or exceed $500/MWh, which is close to the marginal values of consumption at peak load periods and creates the incentives for the load participation. The potential and load participation of DADRP are relatively low compare with EDRP and SCR. The reason for this issue may be caused by the fact that the load can also bid in other markets, such as price-capped load bidding.

The NYISO staff continues to seek improvement in the demand response programs. At present, demand response programs are only available in the day-ahead energy market. The possible demand response in the real-time and ancillary service markets are under study. Besides, the actual bids of the demand response in the current market structure are still modest, NYISO try to encourage the load participants to join the markets. With the growing of the distributed energy resources in the system, how to include these resources into the demand response programs is also an interest topic.

2.6 Summary

Table 2.5 compares the described four ISO demand response programs. ERCOT is the exception without any emergency demand response programs, but with most available demand response programs in the ancillary services markets. Currently, both PJM and ISO-NE are developing new demand response programs in the ancillary services markets. Once PJM implements the demand response programs in the ancillary services markets, PJM will have the broadest range to offer various demand response programs in the power market.

Table 2.5 Comparison of Demand Response Programs at ISOs

ISO	Economic Programs	Emergency	Others
ERCOT	Real-Time Energy Balancing Service		Ancillary Services and Balancing Up Service
PJM	Real-Time and Day-Ahead Options	Active Load Management and Emergency Load Response	
ISO-NE	Real-Time and Day-Ahead Options	Real-Time Load Response	
NYISO	Day-Ahead Energy Service	Emergency Demand Response	Installed Capacity-Special Case Resource

The well-designed demand response program would really improve the system efficiency and reliability. For example, over 13,000 MWh of electricity usage in 2004 is reduced in the ISO-NE. But the designed program may not work properly because the market structure or market operation conditions. In the ERCOT market, both the generation units and system load are allowed to participate in the responsive reserve service and up to fifty percent load participation are required to meet the responsive reserve service requirement. Both the generation units and load bid for their capacity and receive payment based on the market clearing price. Consider the possibility to be deployed and the benefits to be made in the responsive reserve market, however, the load participants have the advantage over the generation units because qualified load participants would receive the capacity payment when the load continue to work and once the load is deployed, they also receive another energy payment. This market rule creates a great incentive for load customers to participate into the responsive reserve service. Recently, some participants have bided their capacity for negative value in order to join the market because the payment is based on the clearing price which is usually set by the generation units.

At present, the demand response programs are under development at a very fast speed. Although there is still no standard demand response programs in the various markets, each ISO has made very impressive effort on developing the most effective demand response programs.

CHAPTER 3

WEB-BASED REAL-TIME MONITORING SYSTEM

3.1 System Description

Currently, the cited cogeneration monitors the system operation base on two systems; the original supervisory control and data acquisition (SCADA) system and dynamic performance monitor system (DPMS). Because of the expansion in recent years, it is difficult to access these two systems at two different buildings on once. Besides, the old dynamic performance monitor system can not meet the needs of current deregulated industry.

The advance in the microcomputer technology has enabled us to develop a low cost and easy maintenance web-based real-time monitoring system to replace the outdated DPMS. In order to act as an effect market participant in the power market, and fully understanding and utilizing current system operation facilities, a web-based real-time monitoring system is developed and installed to allow the plant manager and engineers to access the plant information remotely to enhance the capability of the cited cogeneration to participate in the restructuring electric industry. This newly developed monitoring system has two main functions. The first is dynamic performance monitoring system (DPMS) [28] which monitors overall system operation condition to provide the system operators and engineers with better understanding and information of the system operation characteristics. The monitoring information includes power flow, voltage, frequency, tie-line flow oscillation, transformer temperature, voltage surge detection, and circuit breaker status. In addition, the event alarm and recording, database storage, and report generation functions are also built-in. The other is dynamic cable rating system (DCRS) which is used to calculate the overhead/underground cable temperature and estimate the system available ampacity by considering the cable's loading, real time and forecasting temperature, real time energy market prices, and ancillary services markets prices. The integrated monitoring system can provide real time system operation condition and power market prices information for engineers to effectively participate in the power market. This chapter describes the designed functions and features of this integrated web-based real-time monitoring system.

3.2 Dynamic Performance Monitoring System (DPMS)

3.2.1 General System Description

The main purpose of the dynamic performance monitoring system (DPMS) is to monitor the real time system operation conditions. An overall structure of DPMS is shown in figure 3.1. The DPMS server is installed inside the substation to perform the monitoring functions, such as data collecting and event recording. One client computer is located in the control center, which is about two miles away from the substation, to provide the real-time monitoring information. A real time on-line website is also created for system engineer to access DPMS information through secure intranet inside the plant or internet around the world (with permit).

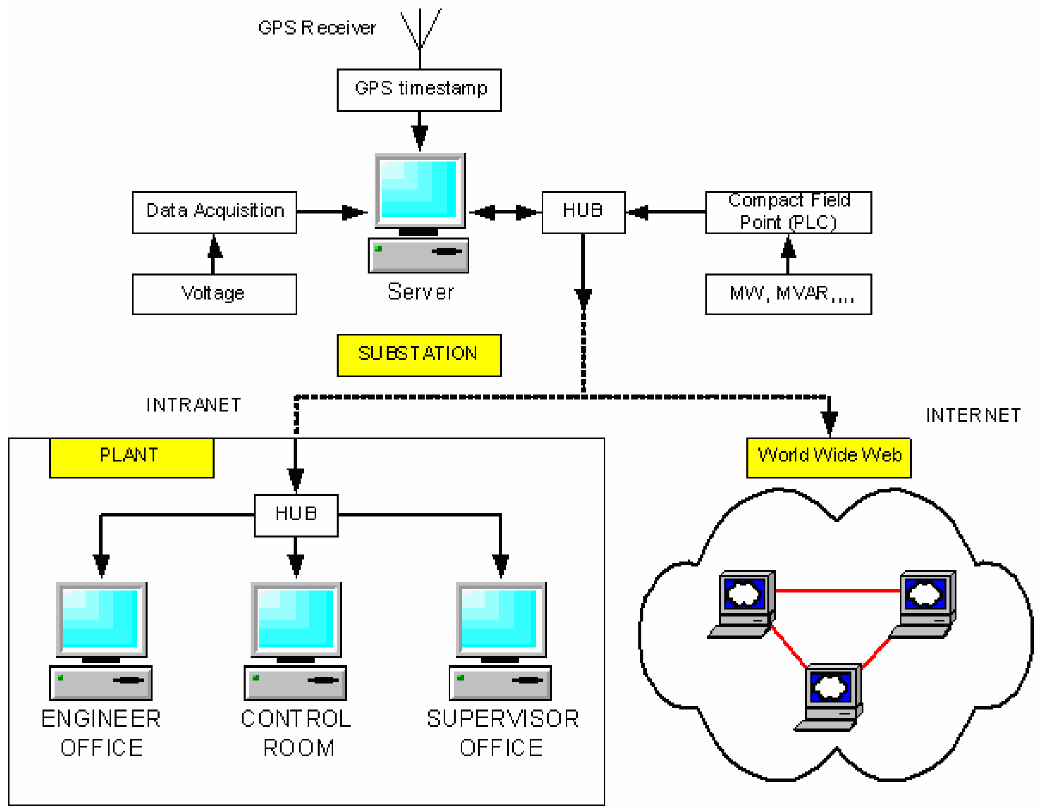


Figure 3.1 Overview structure of dynamic performance monitoring system

3.2.2 Hardware Configuration

Considering the usage and characteristics of required data, two different data sets as shown in table 3.1, are monitored in the DPMS. The high sampling rate is set at two kHz for sensitive signals, for instance, voltage, to capture the transient phenomena. The low sampling rate is set at 10 Hz for those signals with lower variation rates. DPMS detects and collects these analog data by capturing either actual waveforms or transducer outputs in the substation through data acquisition hardware. To provide the precise timestamp for the recorded data, GPS receivers are also installed in the substation to provide the universal timestamp.

Table 3.1 System Monitoring Points

	High	Low
Sampling Rate	32 Samples/Cycle	10 Samples/Second
Signal type	Voltage	Active & reactive power flow Transformer temperature Circuit Breaker status

There are many variable speed drivers in the cited cogeneration, and they are very sensitive to the voltage surge. These variable speed drivers have been tripped several times due to voltage surges. In general, the duration of surge could ranges from several microseconds to several cycles. In order to distinguish these surge issues and provide event recorded data, a hardware surge detection circuit is designed to detect the surge and DPMS would record the data and time information to confirm with the actual events. Due to the hardware limitation, it is possible that the actual surge waveform may not be captured by DPMS because the sampling rate of voltage is 2 kHz.

The block diagram of the designed surge detection circuit is shown in figure 3.2. There are three main functions of this surge detection circuit. The first is voltage limiter, which is to protect the analog circuit from unexpected high level switching or lightning surges. Second, voltage comparator compares the input voltage with the user selectable threshold voltage level. Whenever the voltage is higher than the threshold setting, a detection signal will be generated. As mention earlier, the surge probably lasts only several microseconds which is shorter than one scanning cycle of DPMS and the detection signal of voltage comparator may not be captured by DPMS. Therefore, the third function with mono-stable pulse generator would generate a digit pulse with longer duration for DPMS to be able to recognize the surge event.

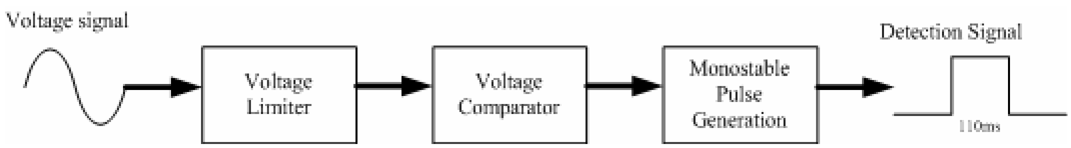


Figure 3.2 Voltage surge detection circuit function block scheme

The hardware configuration of the DPMS can be expressed in figure 3.3. All the monitoring signals are sampling by data acquisition card (DAQ) and Programmable Logic Controller (PLC). All the monitor data is associated with the universal timestamp, which can be very useful when comparing DPMS data with other monitoring data or ERCOT information.

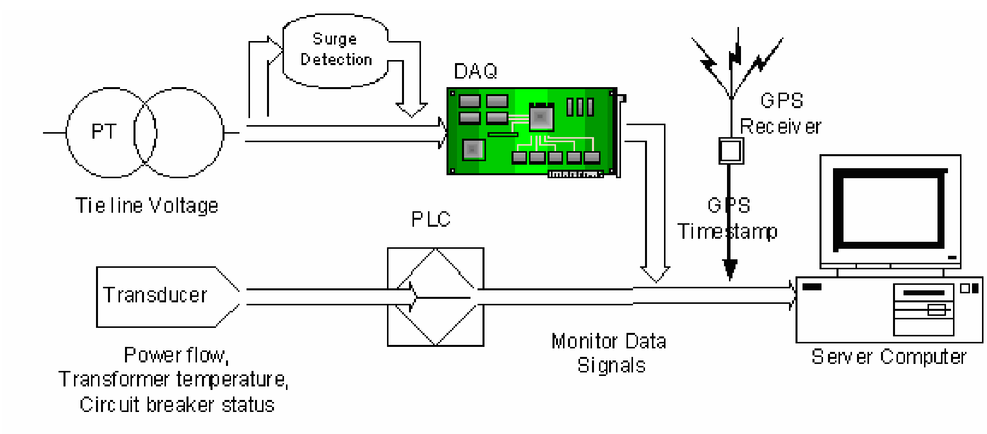


Figure 3.3 Hardware configuration of server computer

3.2.3 System Design Function

The designed functions and features of DPMS are described in below.

3.2.3.1 Universal Timestamp

Based on today’s technology, three options, Internet Time Server, Atomic Clock, and Global Position System (GPS), are available to provide the universal timestamp for the development. Though it is less expensive to use Atomic Clock as timestamp, the regular update rate is one hour which is lower than GPS. In addition, the cited cogeneration belongs to an international company, there are other plants located outside the United States. Using the Atomic Clock as timestamp will limit the possible DPMS implementation at other oversea plants. To match the timestamp with the Electric Reliability Council of Texas (ERCOT), the GPS universal timestamp is adopted in DPMS. With any commercial GPS receiver, one can extract the timestamp information from the NEMA (National Electrical Manufacturers Association) sentence sending out by the GPS satellites [29-33].Because the high cost of the commercial GPS timestamp package, a low cost GPS timestamp is implemented by extracting the GPS receiver's NEMA sentence. The extracted GPS timestamp is updated every one second and the error is less than 1ms.

In order to prevent the failure of GPS receiver due to severe weather or other unforeseeable factors, the internet time server option is also included in DPMS as back up function. There are eight internet time server addresses built in DPMS. Under normal operating condition, GPS is the default timestamp of DPMS. If DPMS losses the GPS signal, DPMS will automatically switch to the internet time server option to connect to one of the eight available time servers, such as Colorado time server, to obtain the available universal timestamp. At the same time, DPMS will inform the system engineer to check the GPS receivers.

3.2.3.2 Event Trig Mechanism and Record Function

One of DPMS' features is the event trigger and record function. Several event triggering mechanisms are designed in DPMS to examine the system operation conditions and record the event information for further analysis. These event triggering mechanisms include

1) Over/Under Voltage**:** based on the following two triggering criteria, voltage triggering mechanism will be activated.

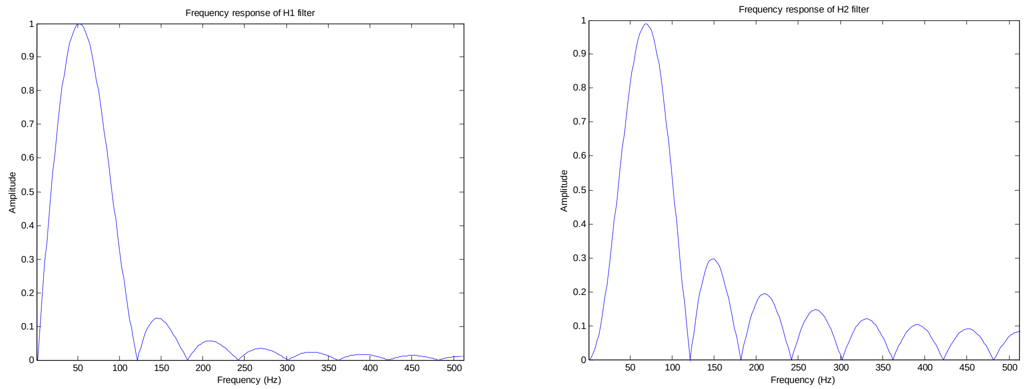
- 10% > |Vdev| > 6% and the situation lasts more than three (3) cycles
- |Vdev| > 10% and the situation lasts more than one (1) cycle.

The rated line-to-line voltage of the tie line is 138kV. Any voltage deviation exceeds triggering point, both the tie line voltage/frequency raw data and cycle RMS data will be recorded. The record duration is two seconds before disturbance and five seconds after the system is recovered and $|V_{dev}|$ is less than 5.0%. One special operation mode of DPMS is the dead bus mode. If voltage is under 0.65p.u and lasts for more than five seconds, DPMS will switch to dead bus operation mode. In this particular mode, DPMS will only perform the monitoring function without any event trigger and record function. Once the voltage is recovered back to above 0.65p.u., DPMS will automatically switch back to normal operation mode to perform all the designed functions.

2) Over/Under Frequency**:** The cited cogeneration plant is qualified to participate in several demand response programs in the ERCOT power markets. One of the special demand response programs, Load Acting as a Resource (LaaR), allows participants to

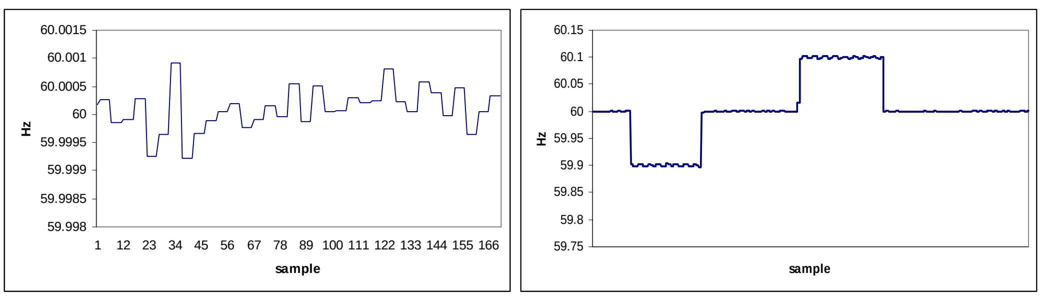
bid their demand into the ERCOT power markets. For example, currently, the required amount of responsive reserve service in ERCOT is 2300MW and LaaR is limited to fifty percent on high-set under-frequency relays at 59.7 Hz. The Under Frequency Relay (UFR) opens the load feeder breaker immediately on automatic detection of an under frequency condition. However, the response time of the transducer for SCADA is around 400ms, which is not fast enough to reflect with the actual situation.

Two frequency measurement methods are developed to measure accurate and real time system frequency. The first one is to apply the signal process technology [34-36]. Two discrete non-recursive finite-impulse-response (FIR) filters are designed to eliminate the DC and higher order harmonic components of the voltage signals to avoid the signal waveform distortion. The frequency responses of these two filters are shown in figure 3.4. The test results of an ideal 60 Hz voltage signal and variable frequency signals are shown in figure 3.5. Since the estimated error in all the tests is less than 0.1%, which is ±0.06 Hz, DPMS can provide reliable and accurate frequency estimation. The advantage of this method is easily implemented in the software analysis. However, the main disadvantage is the high sensitivity of the sampling signals. Once the sampling signal are not well sampled, for instance, with time delay or not exactly equally sampled at specific rate, the significant estimation error would be induced. Therefore, another method with traditional frequency measurement by using high speed counter is also developed. One 80MHz counter is applied to perform the frequency measurement from the voltage signal. The sinusoidal voltage signal would be converted to the square waveform to count the period for each raising interval of the square waveform and the reciprocal of the counted interval is the measured frequency.



(a) (b)

Figure 3.4 Frequency responses of the digital filters (a) Sine; (b) Cosine



(a) (b)

Figure 3.5 Frequency estimation test results (a) 60 Hz; (b) Variable frequency

In order to match the operation of the high setting under frequency relay, DPMS frequency triggering mechanism will be activated based on the following triggering criteria.

- $|\Delta f| > 0.2$ Hz and the situation lasts more than three (3) cycles.

Once the frequency fluctuation is higher than the predefined quantity, both the tie line voltage/frequency raw data and cycle RMS data would be recorded for further analysis. The record duration will be 2 seconds before disturbance, and five seconds after system is recovered and the $|\Delta f| \leq 0.05$ Hz.

3) Low Frequency Oscillation: DPMS would monitor the active and reactive power on the tie-line. The low frequency oscillation monitoring mechanism will be activated when any of the following situations happens.

- Normal: P<=5 MW and Q<=10 MVAR
- Record: 5<P<=10 MW and 10<Q<=20 MVAR
- Record and alarm: 10<P<=20 MW and 20<Q<=30 MVAR
- Record and trip: P>20 MW and Q>30 MVAR

Once any of the above mentioned low frequency oscillation is detected by DPMS, the tie line P, Q raw data and corresponding oscillation magnitude will be recorded for further analysis. The total recording duration will be 30 seconds which includes 2 seconds data before disturbance.

4) Transformer Over-Temperature: In order to utilize the transformer capacity effectively without damaging the facilities, transformer over-temperature triggering mechanism will be activated when the transformer temperature is greater than 100 degree C. Since the temperature variation of the transformer is slow, only the time duration of over temperature would be recorded.

5) Circuit Breaker Operation: DPMS will detect and record the time and location of any circuit breaker operation within the plant.

6) Surge Detection: An analog surge detection circuit is designed to detect the voltage surge. It provides triggering signal for DPMS to record voltage data for further analysis. Since the duration of surge could range from several microseconds to several cycles, it is possible that surge is detected by the hardware but not captured by the DPMS

because the sampling rate of tie-line voltage is two kHz. Though DPMS may not be able to catch the voltage surge raw data, the timestamp can be used to confirm with the real event.

3.2.3.3 Report Generation and Print Function

Report generation is a basic but important function for regular monitoring system. Four reports generated from DPMS are discussed as follows:

1) Fifteen Minutes Demand Trend Data: One second average of each monitored real and reactive power flow will be calculated and recorded for 15 minutes period power demand trend. This trend data can help the system engineer understanding the operation characteristics at each period.

2) Daily Fifteen-Minute and Hourly Demand Report: The fifteen-minute and hourly demand average of each bus and total exchange power flow to the system grid will be calculated and recorded.

3) Daily Summary and Monthly Report: the daily summary report includes three data, the maximum, minimum power demand in one day, total power energy consumption/generation of each bus in one day, and the daily system alarm information, which includes the detected events information. Similar to the daily summary report, the monthly report also includes three data in one month. System operator and engineer can very easy have an overview of the overall system operation static data.

3.2.3.4 Remote Access

Since the DPMS server is located in the substation, which is around two mile away from the control room, one of the distinct features of this newly developed DPMS is the remote access function. One client computer is installed in the control room to access server computer through network to obtain the monitoring information. System engineers and managers can also access the DPMS through intranet inside the plant or internet around the world (with permit). This function improves the accessibility of the information and provides convenience for plant personnel to retrieve the monitoring information.

3.2.3.5 Data Storage and Management

Another important function of DPMS is the data management of the designed DPMS. Two data formats, file based and database, are included to store the DPMS information. With the designed database, engineer can easily retrieve the desired historical information for further analysis.

3.3 Dynamic Cable Rating System (DCRS) [37-41]

3.3.1 General System Description

The import/export bottleneck of the cited cogeneration is the ampacity of the underground cables. In general, the thermal limit of electric power cable is defined by using the manufacture’s specifications, which is relative conservative under worst case scenario. In order to improve the flexibility of the cited cogeneration to actively participate in the ERCOT’s auction markets and avoid potential permanent damage to the equipment, an on-line dynamic cable rating system (DCRS) for overhead/underground cables is developed. The main purpose of DCRS is to help the system engineer to maximize asset utilization without jeopardizing system facilities and/or compromising the cable reliability. DCRS can perform both the steady state measurement and dynamic estimation of cable rating based on the real time cable loading, cable's surface temperature, ambient temperature, and forecasting temperature.

DCRS can be used in both off-line simulation and on-line operation. As for off-line simulation, DCRS is a useful planning tool to help the system engineer understand the steady state and dynamic characteristics of overhead/underground cables for the feasibility study of possible system infrastructure improvement. For on-line operation, DCRS can provide real time system information, such as cable loading, cable temperature, forecasting temperature, system available ampacity, and real time market prices. In order to prevent the potential damage to other system facilities by raising the flow of cables, transformer temperature is also monitored. Based on the operating condition, DCRS can estimate the steady state and short-duration available ampacity.

Traditionally, dynamic cable rating is usually calculated based on the constant ambient temperature, which may result in over or under estimation. The overestimated ampacity may cause some potential equipment damage, and the underestimated ampacity may limit the utilization of cable transfer capability. In order to confirm with the real operation condition, one specific feature of DCRS takes both current cable temperature and forecasting temperatures into consideration to perform the short-duration ampacity estimation.

The overall structure of DCRS is expressed in figure 3.6. DCRS will extract the real time forecasting temperature from an available weather station website and update regularly. In addition, DCRS will also connect to the ERCOT website to extract the real time balancing and ancillary service market prices. Through the temperature sensor signals feed into data acquisition equipment (DAQ), DCRS monitors the real time underground cable's temperature. The real time cable and transformer loading and transformer temperature also can be extracted from the dynamic performance monitoring system (DPMS). After collecting all the required information, DCRS provide the real time cable rating estimation and available ampacity for the system engineer to establish good bidding strategies. All the DCRS information will be saved into database, and all the DCRS information can also be accessed on line through a secure connection

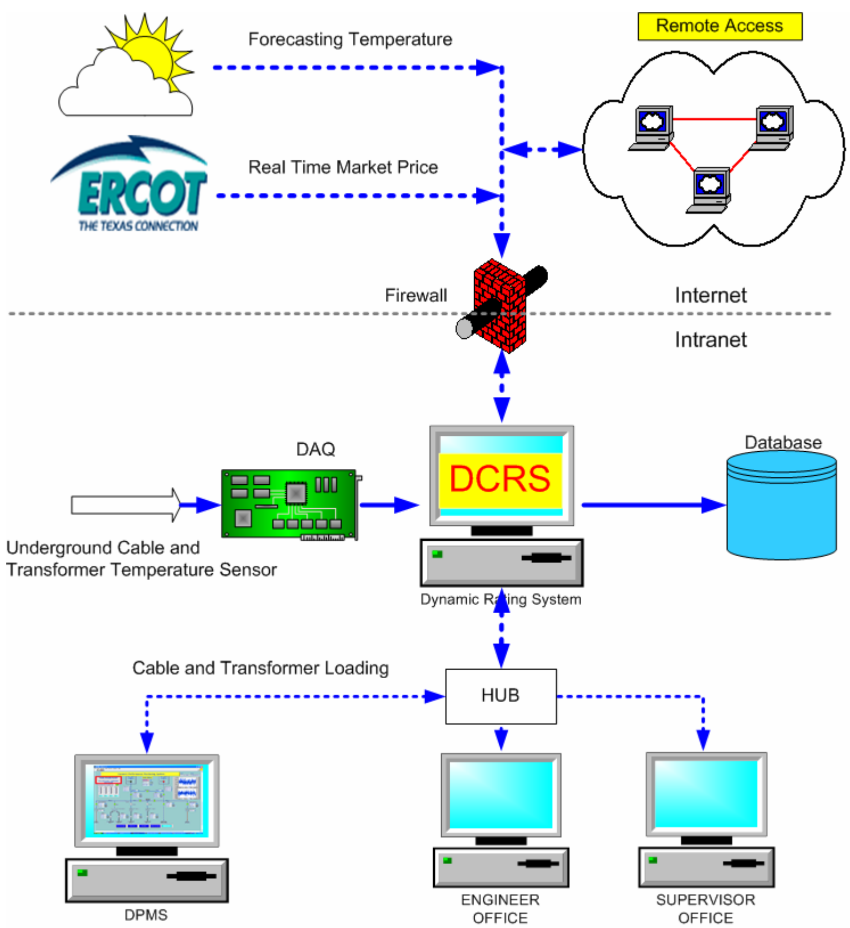


Figure 3.6 Overall structure of dynamic cable rating system

3.3.2 *Cable Thermal Model Description*

DCRS will monitor and estimate both the underground and overhead cable ratings of the cited cogeneration. Based on the cable specification data provided by the manufactures, the cable thermal model can be constructed to perform the steady state and dynamic cable rating estimation [42-44]. An example of the cross section of a typical 69kV single-core XLPE cable is shown in figure 3.7 and the cable technical data is listed in table 3.2.

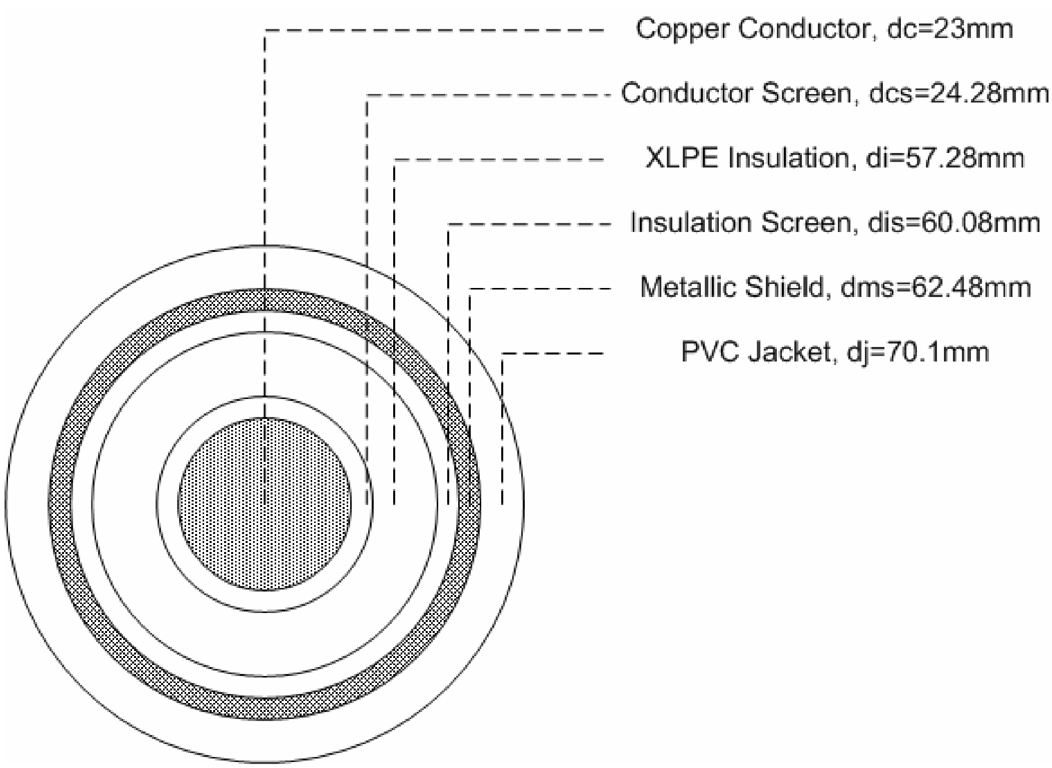


Figure 3.7 Cross section of a 69kV XLPE cable

Table 3.2 An Example of 69kV XLPE Cable Technical Data

Cable Parameters	Unit	Value
Conductor resistance; d.c. 20 ^oC , R	ohm/m	0.0473×10^{-3}
Conductor resistance; a.c. 90 ^oC , R_o	ohm/m	0.0624×10^{-3}
Dielectric loss, W_d	W/m	0.88
Sheath loss factor, λ_1	$--$	0.1772
Armor loss factor, λ_2	$--$	0
Thermal resistance between conductor and sheath, T_1	$^oC.m/W$	0.59
Thermal resistance between sheath and armor, T_2	$^oC.m/W$	0
Thermal resistance of external serving, T_3	$^oC.m/W$	0.115
Thermal resistance of the surrounding of a cable in air, T_4	$^oC.m/W$	0.669(at 45 ^oC)
Thermal capacitance of the conductor, Q_c	$J/^oC.m$	317.4
Thermal capacitance of the insulation, Q_i	$J/^oC.m$	5806.8
Thermal capacitance of the sheath, Q_s	$J/^oC.m$	554.45
Thermal capacitance of the jacket, Q_j	$J/^oC.m$	1348.88
Number of core, n	$--$	1
Maximum operating temperature	^oC	90

3.3.2.1 Steady State Thermal Circuit Model

Because the fundamental similarity between the heat flow due to the temperature difference between the conductor and its surrounding medium and the flow of electric current due to the voltage difference and electric elements, Ohm's law can be analogous to Fourier's law in the thermal calculations. Electric current corresponds to heat flow, voltage potential corresponds to temperature and electrical resistance corresponds to thermal resistance. According to IEC 287-2-1 and 287-1-1, the steady state thermal network of a single-core cable can be shown in figure 3.8. Where T_1, T_2, T_3, and T_4 represent the thermal resistances. T_1 is the thermal resistance between conductor and sheath, T_2 is the thermal resistance between sheath and armor, T_3 is the thermal resistance of external serving, and T_4 is the thermal resistance of the air surrounding the cable. W_d, W_c, W_s and W_a represent dielectric, conductor, sheath, and armor losses, and W_s and W_a can be expressed in W_c by multiplied the sheath and armor loss factor.

$$W_s = \lambda_1 W_c \tag{3.1}$$

$$W_a = \lambda_2 W_c \tag{3.2}$$

$$W_c = I^2 R \tag{3.3}$$

where

λ_1 : sheath loss factor

λ_2 : armor loss factor

I : current carrying capacity (A)

R : a.c. resistance of the conductor at maximum operating temperature (ohm/m)

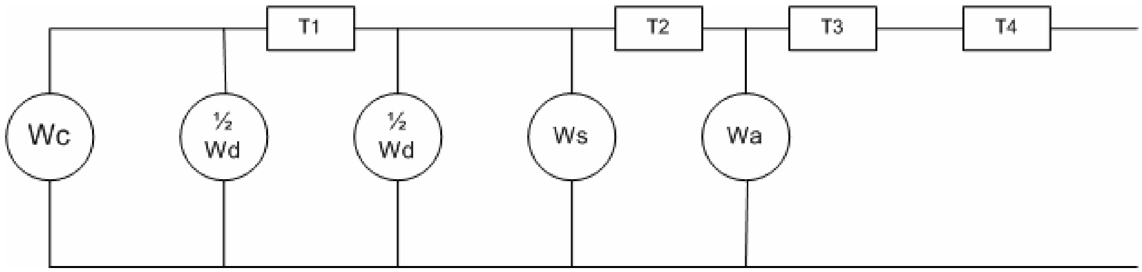


Figure 3.8 Steady state thermal circuit of a 69kV cable

The conductor temperature rise above the ambient temperature, which is defined as $\Delta\theta$, can be calculated by solving the thermal network in figure 3.8.

$$\begin{aligned}\Delta\theta &= (W_c + \frac{1}{2}W_d)T_1 + (W_c + W_d + W_s)T_2 + (W_c + W_d + W_s + W_a)(T_3 + T_4) \\ &= (W_c + \frac{1}{2}W_d)T_1 + [W_c(1+\lambda_1) + W_d]T_2 + [W_c(1+\lambda_1+\lambda_2) + W_d](T_3 + T_4)\end{aligned} \tag{3.4}$$

The permissible current rating can be obtained from equation (3.4).

$$I = [\frac{\Delta\theta - W_d[0.5T_1 + (T_2 + T_3 + T_4)]}{RT_1 + R(1+\lambda_1)T_2 + R(1+\lambda_1+\lambda_2)(T_3 + T_4)}]^{0.5} \tag{3.5}$$

For multiple conductors, the current rating can be modified as follows:

$$I = [\frac{\Delta\theta - W_d[0.5T_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3 + T_4)}]^{0.5} \tag{3.6}$$

where

n: number of conductors in the cable

There are two important objectives for the steady state cable ampacity computation. The first is to determine the cable conductor temperature under certain cable loading, and the second to determine the cable maximum ampacity rating by giving conductor temperature. By applying the technical data in table3.2 to equation (3.5), for example, and assume T_4 is the ambient temperature, the current carrying capacity of the typical 69kV XLPE cable at the ambient temperature 45^oC and 37^oC is 683.1 and 742.53 Ampere. Therefore, higher cable current rating is usually possible using actual load and temperature, which would allow more transfer capability.

$$I = [\frac{(90-45)-0.0088[0.5\times 59+(0+11.5+66.9)]}{0.0624\times 10^{-5}\times 59+0.0624\times 10^{-5}\times (1+0.1772)\times (11.5+66.9)}]^{0.5}$$
$$= 683.1 Amp$$

$$I = [\frac{(90-37)-0.0088[0.5\times 59+(0+11.5+66.9)]}{0.0624\times 10^{-5}\times 59+0.0624\times 10^{-5}\times (1+0.1772)\times (11.5+66.9)}]^{0.5}$$
$$= 742.53 Amp$$

Since there are sensors installed on the surface of the underground cables, the cable surface temperature is available and the steady state current rating of the underground table can be calculated based on the same equation as the overhead cable without using T_4.

3.3.2.2 Thermal Dynamic Model of the Cable

There are two main issues for the dynamic cable ratings that are most concerned by the system engineer. First, under current cable loading condition, how much load can be increased and maintained for a specified period of time without exceeding the temperature limit. Second, under current cable loading condition, how long can the cable operate without exceeding the conductor temperature limit by increasing a certain amount of cable loading.

In general, the conductor temperature rise is contributed by the current inside the internal part of cable and ambient conditions from external part of cable. In order to find the conductor temperature rise of the internal part of cable, a lumped capacitance method is applied to solve the combination of thermal resistances and capacitances of the thermal circuit. A typical short-duration transient lumped capacitance thermal network of a 69kV single core XLPE overhead cable is shown in figure 3.9. d_x is the virtual diameter of the insulation with equal thermal resistances to represent the short-duration transients.

$$d_x = \sqrt{d_c d_i} \tag{3.7}$$

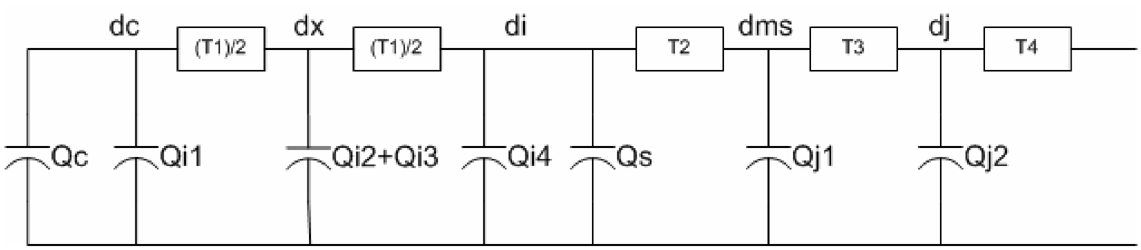


Figure 3.9 Typical short-duration transient thermal network of a 69kV cable

Q_c is the thermal capacitance of the conductor, $Q_{i1} \sim Q_{i4}$ are the insulation thermal capacitances for short-duration transient model and the sum of $Q_{i1} \sim Q_{i4}$ is equal to the total insulation thermal capacitance Q_i. Q_{j1} and Q_{j2} are thermal capacitances of jacket and their sum is equal to the total jacket thermal capacitance Q_j. Q_s is the thermal capacitances of sheath. Q_{j1} and Q_{j2} can be calculated by multiplying the Van Wormer coefficient.

$$Q_j = \frac{\pi}{4}(d_j{}^2 - d_{ms}{}^2) \cdot c \tag{3.8}$$

$$Q_{j1} = pQ_j \tag{3.9}$$

$$Q_{j2} = (1-p)Q_j \tag{3.10}$$

$$p = \frac{1}{2\ln(\frac{d_j}{d_{ms}})} - \frac{1}{(\frac{d_j}{d_{ms}})^2 - 1} \quad (3.11)$$

where

p : Van Wormer coefficient

c : specific heat of the material ($J/^{o}C \cdot m^3$)

Similar to Q_j, $Q_{i1} \sim Q_{i4}$ can also be calculated by multiplying the Van Wormer coefficients.

$$Q_{iA} = \frac{\pi}{4}(d_x^{\ 2} - d_c^{\ 2}) \cdot c\ ,\ Q_{iB} = \frac{\pi}{4}(d_i^{\ 2} - d_x^{\ 2}) \cdot c \quad (3.12)$$

$$p_A = \frac{1}{2\ln(\frac{d_x}{d_c})} - \frac{1}{(\frac{d_x}{d_c})^2 - 1}\ ,\ p_B = \frac{1}{2\ln(\frac{d_i}{d_x})} - \frac{1}{(\frac{d_i}{d_x})^2 - 1} \quad (3.13)$$

$$Q_{i1} = p_A Q_{iA}\ ,\ Q_{i2} = (1 - p_A) Q_{iA} \quad (3.14)$$

$$Q_{i3} = p_B Q_{iB}\ ,\ Q_{i4} = (1 - p_B) Q_{iB} \quad (3.15)$$

Because the cable surface temperature is available through the sensors for the underground cable, figure 3.9 can be modified to represent the short-duration transient thermal circuit of the underground cable, which is shown in figure 3.10.

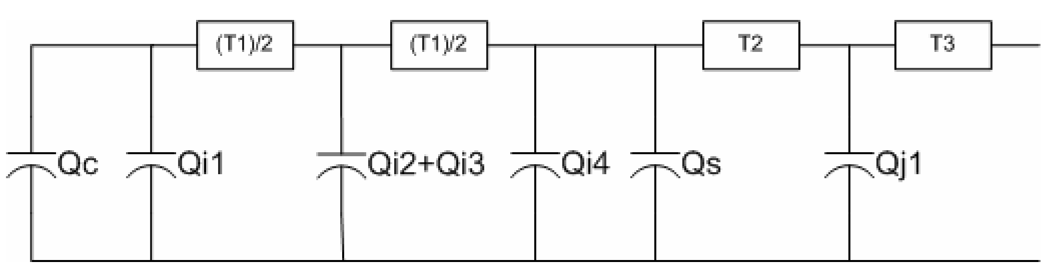


Figure 3.10 Typical short-duration transient thermal network of a 69kV underground cable

The conductor temperature can be obtained by solving the transient thermal network. Since the in-plant demand of the cited cogeneration is very stable, it is sufficient to assume that the thermal network is in the steady state before increase or decrease the cable loading. Traditionally, the two port equivalent network is applied to perform the analytical computation to obtain the conductor temperature response with respect to the heat source. Although the simplified two port equivalent circuit can be used to estimate the conductor temperature, the disadvantage of this two port equivalent network is the other components' temperatures, such like insulation's temperature and jacket's temperature, are unable to be calculated from the simplified two port network.

In order to compute the temperatures of every component for the short-duration transient thermal circuit, the Runge Kutta 4th method is used in DCRS to solve the ordinary differential equations for the transient thermal network. Two conditions are required for the solution process, the input heat source and the initial condition of the thermal capacitance, to solve the ordinary differential equations. The initial condition of the thermal capacitor can be calculated from the steady state response of the thermal network. For the short-duration transient simulation, the final temperature of each thermal capacitance becomes the initial condition for the next transient simulation. The conductor loss W_c is taken as the input heat source to solve the transient network. In order to include the sheath and armor loss in the circuit, the thermal resistances $T_2 \sim T_4$ must be multiplied by the sheath and armor losses factors λ_1 and λ_2. Similar to the thermal resistance, the thermal capacitances Q_s and Q_j must be divided by the sheath and armor losses factors λ_1 and λ_2. The modified network is shown in figure

3.11. To add all parallel thermal capacitors at the same node, the conductor and other components' temperatures can be calculated by solving the equivalent circuit as shown in figure 3.12. Base on KCL theorem, the ordinary differential equations for the transient circuit in figure 3.12 can be expressed in equation (3.16).

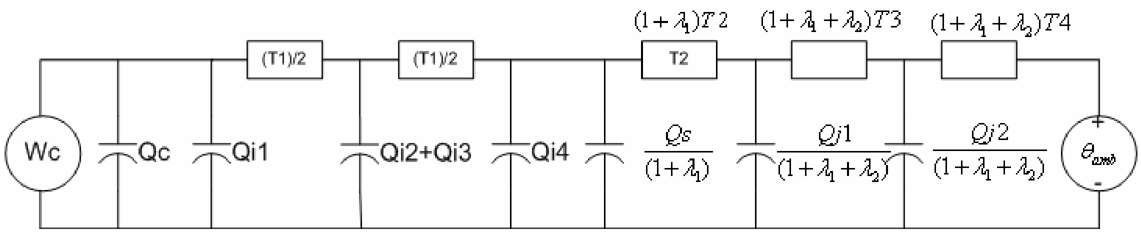


Figure 3.11 Short-duration transient thermal circuit of a 69kV cable

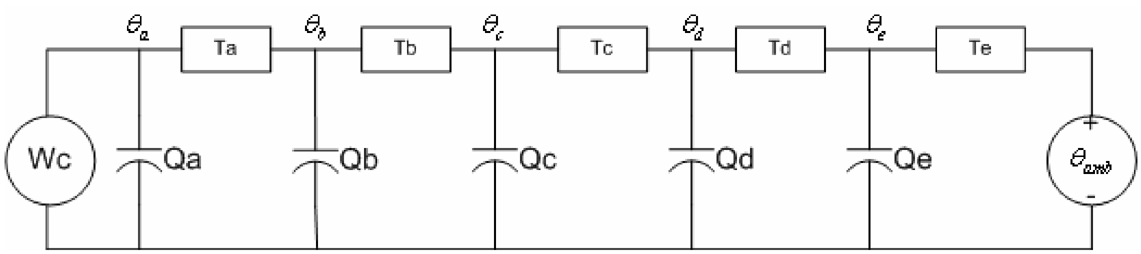


Figure 3.12 Simplified short-duration transient thermal circuit of a 69kV cable

$$
\begin{aligned}
Q_a \frac{d\theta_a}{dt} &= W_c + \frac{\theta_b - \theta_a}{T_a} \\
Q_b \frac{d\theta_b}{dt} &= \frac{\theta_a - \theta_b}{T_a} + \frac{\theta_c - \theta_b}{T_a} \\
Q_c \frac{d\theta_c}{dt} &= \frac{\theta_b - \theta_c}{T_b} + \frac{\theta_d - \theta_c}{T_c} \\
Q_d \frac{d\theta_d}{dt} &= \frac{\theta_c - \theta_d}{T_c} + \frac{\theta_e - \theta_d}{T_d} \\
Q_e \frac{d\theta_e}{dt} &= \frac{\theta_d - \theta_e}{T_d} - \frac{\theta_e - \theta_{amb}}{T_e}
\end{aligned}
\qquad (3.16)
$$

The equation can be expressed in matrix form as shown in equation (3.17).

$$\begin{bmatrix} \frac{d\theta_a}{dt} \\ \frac{d\theta_b}{dt} \\ \frac{d\theta_c}{dt} \\ \frac{d\theta_d}{dt} \\ \frac{d\theta_e}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-1}{Q_aT_a} & \frac{1}{Q_aT_a} & 0 & 0 & 0 \\ \frac{1}{Q_bT_a} & \frac{-1}{Q_aT_a}+\frac{-1}{Q_bT_a} & \frac{1}{Q_bT_a} & 0 & 0 \\ 0 & \frac{1}{Q_cT_b} & \frac{-1}{Q_cT_b}+\frac{-1}{Q_cT_c} & \frac{1}{Q_cT_c} & 0 \\ 0 & 0 & \frac{1}{Q_dT_c} & \frac{-1}{Q_dT_c}+\frac{-1}{Q_dT_d} & \frac{1}{Q_dT_d} \\ 0 & 0 & 0 & \frac{1}{Q_eT_d} & \frac{-1}{Q_eT_d}+\frac{-1}{Q_eT_e} \end{bmatrix} \begin{bmatrix} \theta_a \\ \theta_b \\ \theta_c \\ \theta_d \\ \theta_e \end{bmatrix} + \begin{bmatrix} \frac{W_c}{Q_a} \\ 0 \\ 0 \\ 0 \\ \frac{\theta_{amb}}{Q_eT_e} \end{bmatrix} \text{ where } \begin{bmatrix} \theta_a(0) \\ \theta_b(0) \\ \theta_c(0) \\ \theta_d(0) \\ \theta_e(0) \end{bmatrix} = \begin{bmatrix} \theta_a(t^-) \\ \theta_b(t^-) \\ \theta_c(t^-) \\ \theta_d(t^-) \\ \theta_e(t^-) \end{bmatrix} \quad (3.17)$$

A 69kV XLPE overhead cable is taken as an example to illustrate the short-duration dynamic cable rating estimation. According to the technical data in table 3.2 and figure 3.9, the short-duration transient thermal circuit parameters of a typical 69kV XLPE overhead cable can be calculated as follows and the network is shown in figure 3.13. Because the thermal resistance of the surrounding of a cable in air, T_4, is a function of temperature, T_4 is required to be updated to reflect the ambient temperature changes.

$$p = \frac{1}{2\ln(\frac{70.1}{62.48})} - \frac{1}{(\frac{70.1}{62.48})^2 - 1} = 0.481$$

$$Q_{j1} = pQ_j = 0.481 \times 1348.88 = 648.81$$

$$Q_{j2} = (1-p)Q_j = 700.07$$

$$Q_{iA} = 1607.56, \quad Q_{iB} = 4200$$

$$p_A = \frac{1}{2\ln(\frac{37.17}{23})} - \frac{1}{(\frac{37.17}{23})^2 - 1} = 0.42,$$

$$p_B = \frac{1}{2\ln(\frac{60.08}{37.17})} - \frac{1}{(\frac{60.08}{37.17})^2 - 1} = 0.34$$

$Q_{i1} = p_A Q_{iA} = 675.18$, $Q_{i2} = (1 - p_A) Q_{iA} = 932.38$

$Q_{i3} = p_B Q_{iB} = 1428$, $Q_{i4} = (1 - p_B) Q_{iB} = 2772$

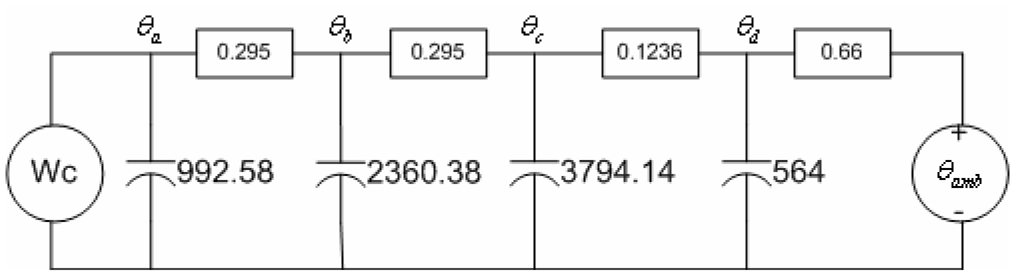


Figure 3.13 Equivalent short-duration transient circuit of a 69kV overhead cable

Assume the cable has been operated at 500A continuously at the ambient temperature 20^oC and the cable loading is going to be increased to 600A. Then the final steady state temperature can be calculated from figure 3.13 without considering the thermal capacitances. If the cable loading is increased to 600A, the dynamic response of the temperature is shown in figure 3.14. According to the simulation result of figure 3.14, the components' temperatures would reach to another steady state level if the current remains at 600A for an extended time.

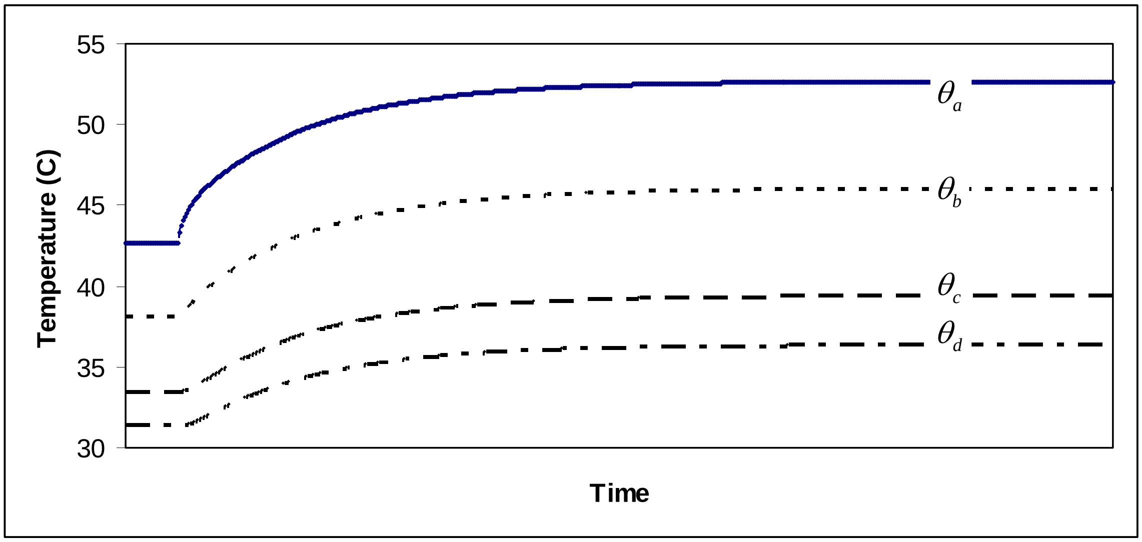


Figure 3.14 Temperature response of the 69kV overhead cable loading increasing from 500A to 600A

For the overhead cable, it is unnecessary to find the temperature rise response of the external parts of cable and only the surrounding thermal resistance is required to update with respect to the surrounding temperature. As for the underground cable, the cable's surface temperature response, defined as θ_e, of the external parts of underground cable can be calculated by solving the heat transfer equation and the solution can be expressed as:

$$\theta_e(t) = W_t \frac{\rho_s}{4\pi}[-E_i(-\frac{d_j^{\ 2}}{16\delta \cdot t}) + E_i(-\frac{L^2}{\delta \cdot t})] \tag{3.18}$$

$$W_t = \frac{\theta_{sen} - \theta_{amb}}{T_4^{'}} \tag{3.19}$$

where:

W_t : heat source of the external parts of cable (J/m)

ρ_s : soil thermal resistivity ($^oC.m/W$)

δ : soil thermal diffusivity, 0.5×10^{-6} (m^2/s)

t : time of seconds

L : depth of burial of the cable, m

$-E_i(-x)$: the exponential integral, $= \int_x^\infty \frac{e^{-v}}{v}dv$

θ_{amb} : ambient temperature

θ_{sen} : cable surface sensor temperature

$T_4^{'}$: thermal resistance between underground cable and earth ground

The short-duration transient thermal network of the underground cable can be expressed in figure 3.15. The estimated cable surface temperature is the estimated θ_{sen} for the next transient simulation. And the total temperature response can be obtained by solving the ordinary differential equations of figure 3.15.

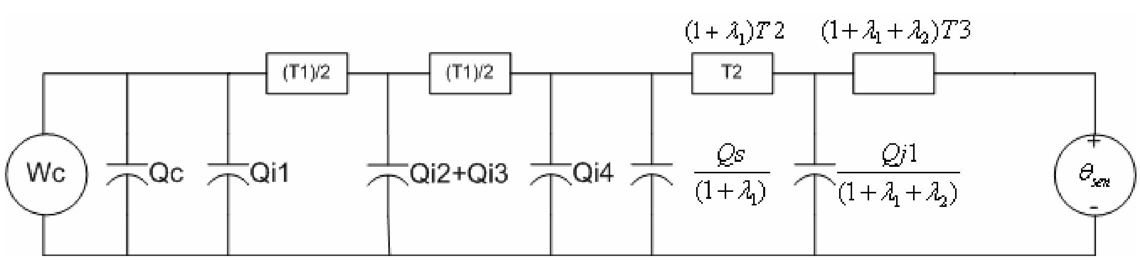


Figure 3.15 Short-duration transient thermal circuit of a 69kV underground cable

3.3.2.3 Dynamic Cable Capacity Estimation

The flowchart in figure 3.16 illustrates the procedure of DCRS to estimate the overhead cable available capacity. First, DCRS reads the system information, such as the real time ambient temperature, real time cable loading, and the forecasting temperature. Based on the real time temperature, the steady state thermal model of the cable will be constructed to calculate the cable conductor static rating and other components' temperatures. The second step is to update the conductor's resistance with respect to the calculated conductor temperature and the thermal resistance of the air, T_4, with respect to the ambient and forecasting temperature. Construct the cable short-duration transient network and perform the dynamic analysis to estimate cable conductor temperature. Increase the cable loading until the estimated conductor temperature exceeds the conductor limit temperature or the transformer's transfer capability. The underground cable available capacity estimation flowchart can be shown in figure 3.17. The steady state and dynamic thermal circuits of the underground cable are similar to the overhead cable but including the external heat source.

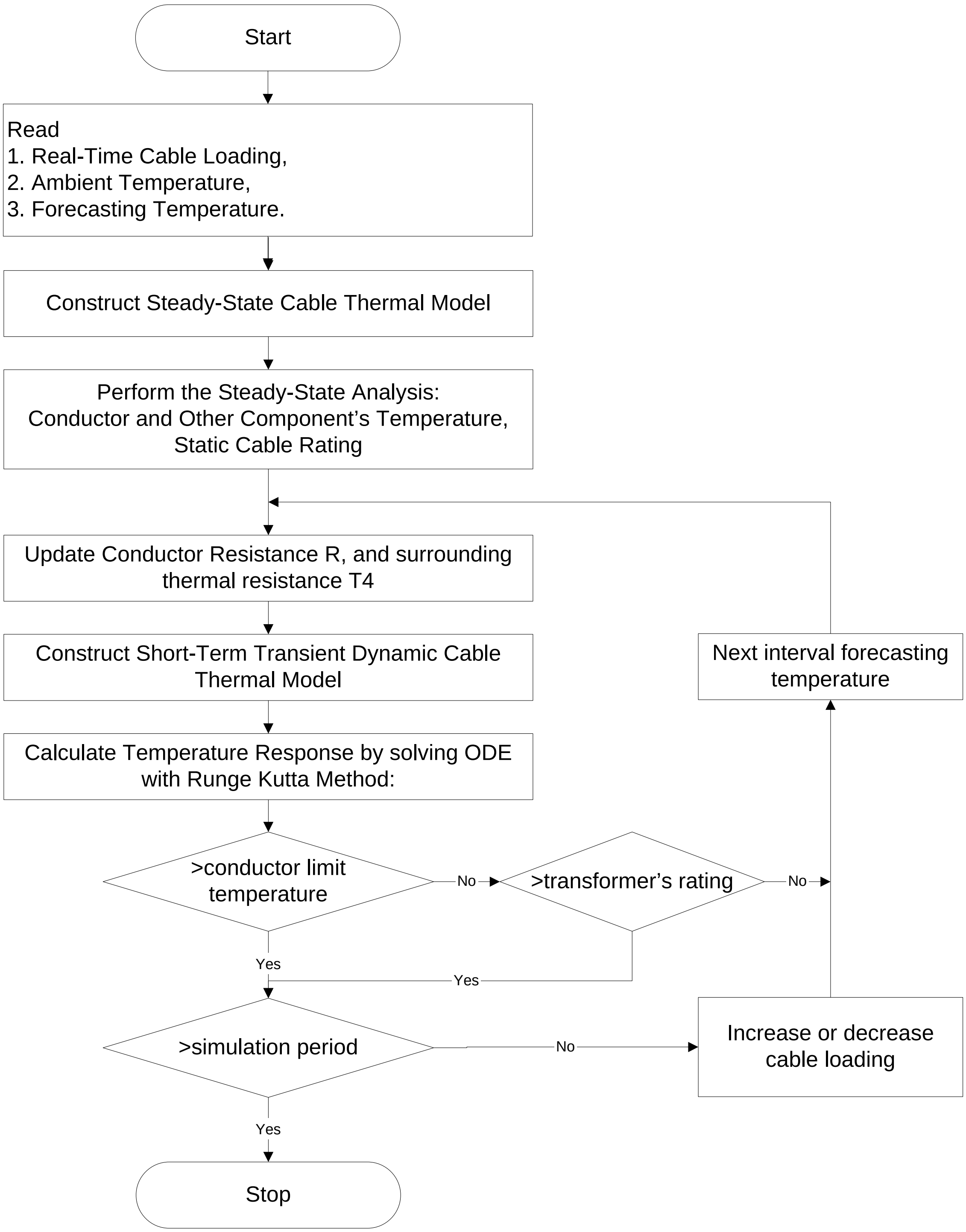


Figure 3.16 Flowchart of the overhead cable dynamic cable rating estimation

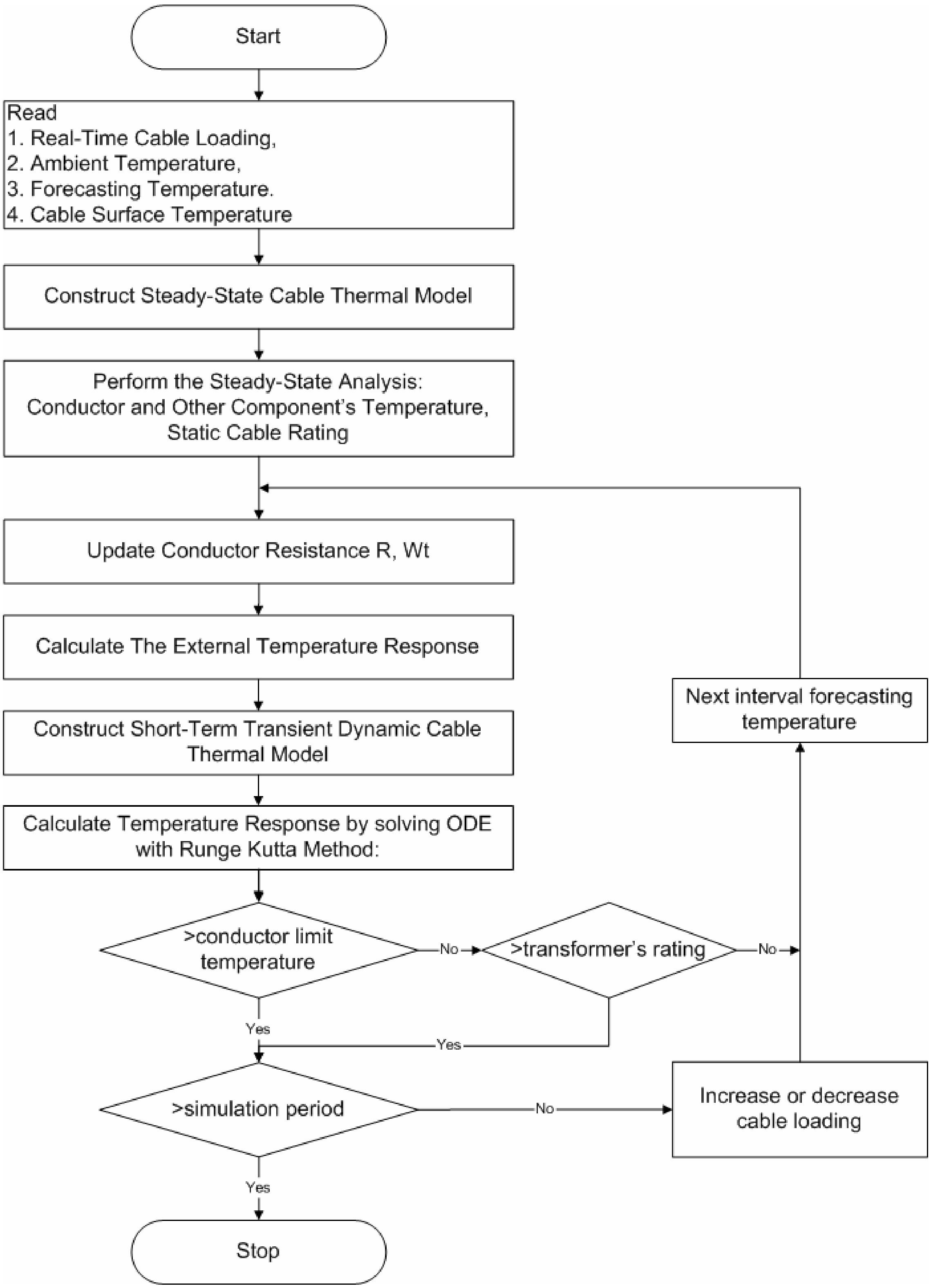


Figure 3.17 Flowchart of the underground cable dynamic cable rating estimation

3.3.3 *Integration of DCRS and Real Time Pricing for Market Participation*

3.3.3.1 Real Time Steady State Measurement and Dynamic Rating Estimation

The conductor temperature is the key factor that determines the transmission capability of a cable. In order to perform the system available transfer capacity estimation, temperature sensors will be installed to obtain the surface temperature of the underground cable. Three temperature sensors will be installed at the front, middle and end of the underground cable to identify the hottest spot of the underground cable. DCRS will use the information to perform steady state and dynamic rating calculation.

In order to confirm with the real operation condition, DCRS includes real time and forecasted temperatures in the short-duration dynamic rating estimation to prevent under or over estimation. DCRS will connect to the available weather station website to extract the forecasting temperature information and update regularly for the dynamic rating calculation. According to the simulation results as shown in figure 3.18, the system is usually having higher cable ampacity than the manufacture's static rating by including the real time temperature information. The short-duration cable conductor temperature estimation with and without considering the forecasting temperature is shown in Figure 3.19. In figure 3.19, the conductor temperature may be over-estimated (yellow area) or under-estimated (light blue area) compare to the constant temperature assumption. Therefore, it is necessary to include the temperature information for better cable ampacity estimation.

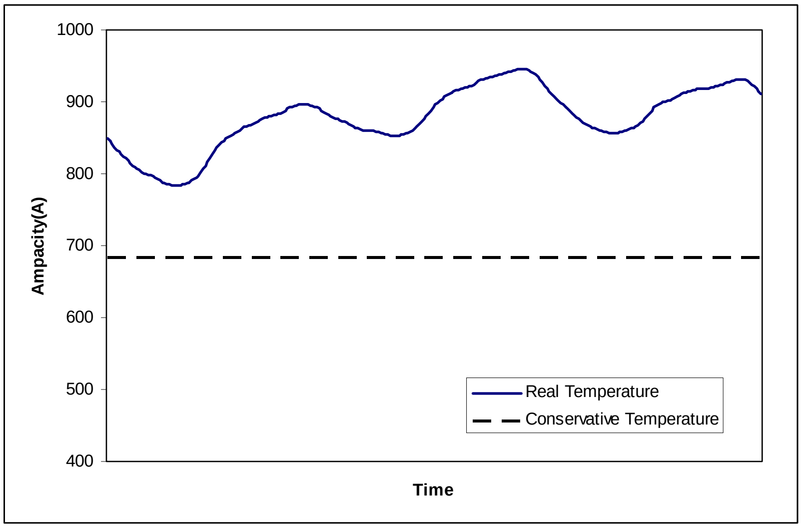


Figure 3.18 Steady state cable rating for real time and conservative temperature

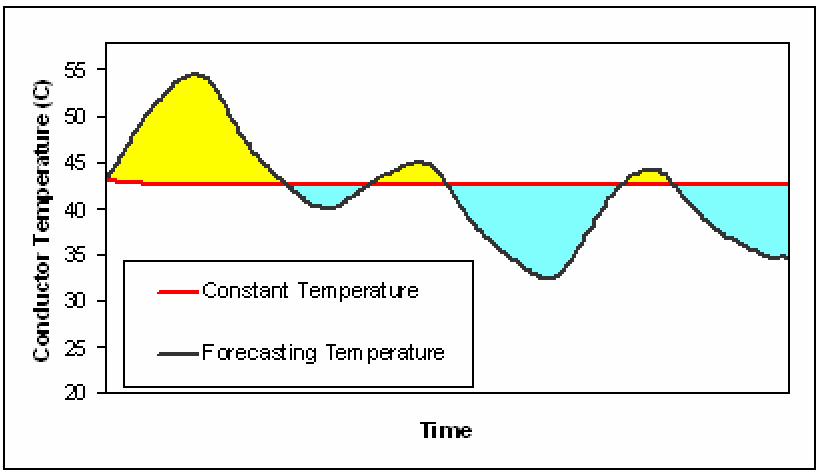


Figure 3.19 Cable ampacity forecasting for constant and forecasting temperature

3.3.3.2 Real Time Market Prices Information

Market price is very important information to establish bidding strategy. DCRS will extract both the real time balancing and ancillary services markets prices from ERCOT. Based on the real time system operation condition from DPMS and the system available capacity and real time markets prices information from DCRS, system engineers will be able to adjust or establish optimal bidding strategies to utilize the plant resource in a more effective manner. In the real time balancing market, the price would be published every 15 minutes in advance to the current operating time. The ancillary services markets are day-ahead market and the prices are determined by previous day-ahead bidding results. Figure 3.20 shows an example of the extracted ERCOT market prices information provided by DCRS. The price fluctuation for the ERCOT power markets really increase the incentive of the cited cogeneration to maximize the asset utilization, especially when the market price is attractive.

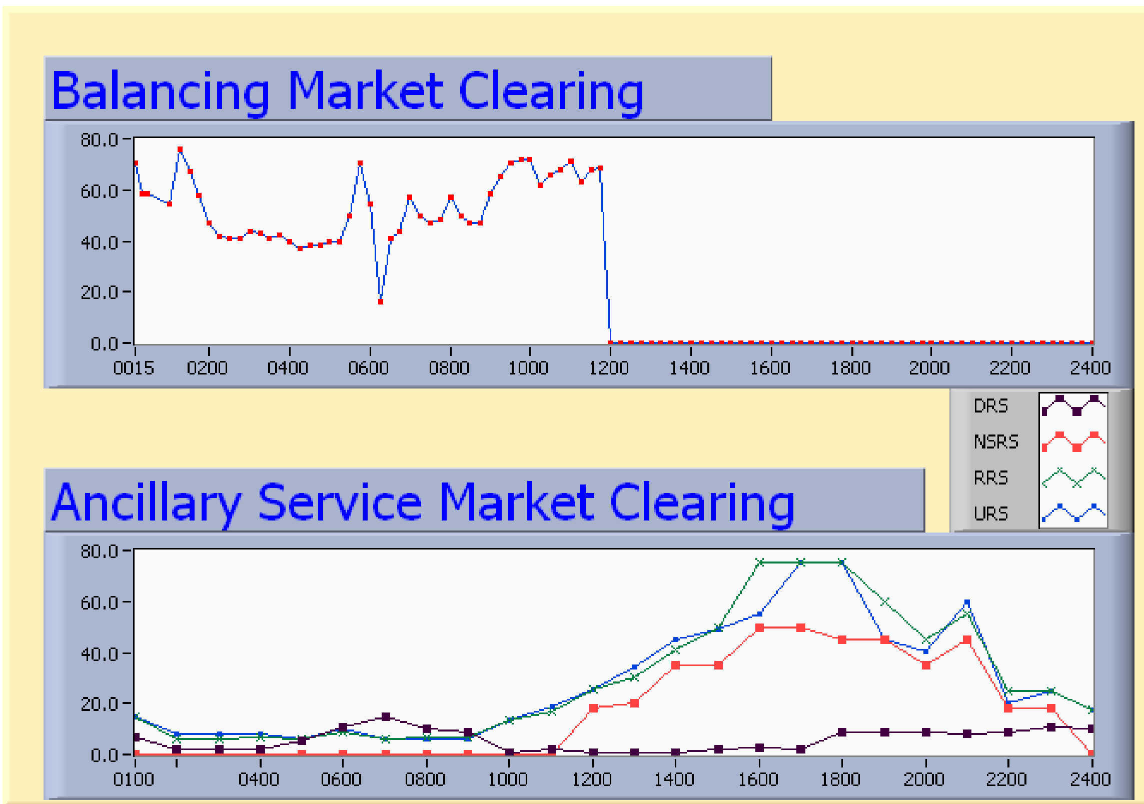


Figure 3.20 ERCOT's balancing and ancillary services markets prices

3.4 Real Time Monitoring System Integration

The overall real time monitoring system includes the dynamic performance monitoring system (DPMS) and the dynamic cable rating system (DCRS). DPMS is responsible for monitoring the real time system operation condition and DCRS is responsible for monitoring and estimating the cable temperature and finding out the system available capacity. The overall structure of the integrated real time monitoring system is shown in figure 3.21.

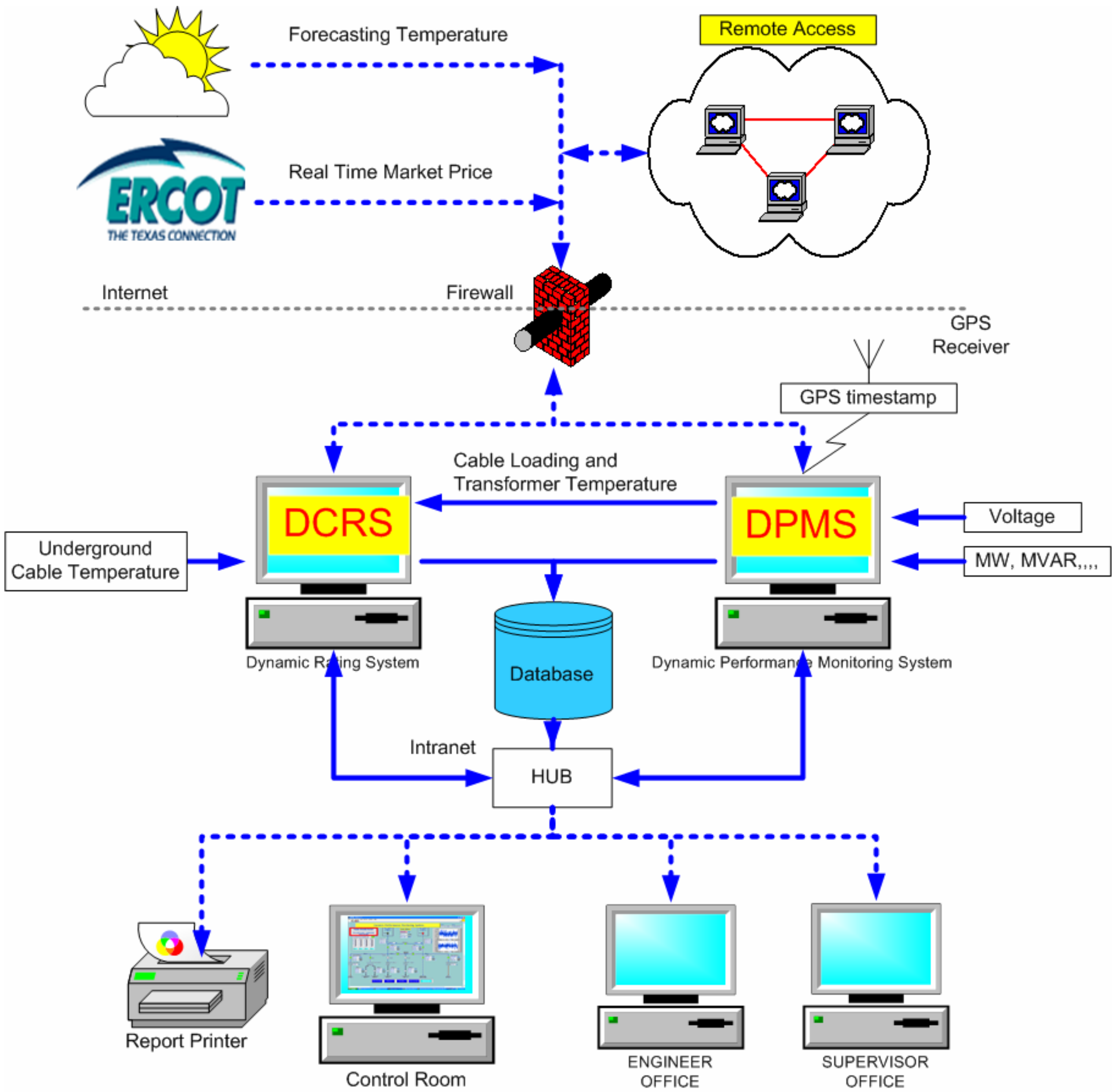


Figure 3.21 Overall structure of the web-based real-time monitoring system

CHAPTER 4

OPERATION RESULTS AND DATA ANALYSIS

This newly developed web-base real-time monitoring system has been installed in the substation of the cited cogeneration power plant. This chapter describes the system installation and implementation. The experiment results and field recorded events will also be analyzed and discussed. Two main programs of the ERCOT's markets are recommended for the cited cogeneration plant while in view of the economic benefit and facilities reliability.

4.1 System Installation

4.1.1 Hardware Functions

The developed web-base real-time monitoring system is installed in the substation and the connection of the input signals are shown in figure 4.1. and figure 4.2. The specification of the data acquisition hardware and server computer is listed in table 4.1 and table 4.2 respectively. As shown in figure 4.1, the front panel provides a graphical user interface for engineer to access and maintain the monitoring system. The server computer is responsible for performing the designed functions. An uninterruptible power supply (UPS) is also installed to provide reliable power source for the monitoring system. A surge detection circuit is designed to detect and record the voltage surge. In figure 4.2, the voltage signal is extracted from potential transformer (PT), and other signals are provided by transducers.

Figure 4.1 Installation of the monitoring system

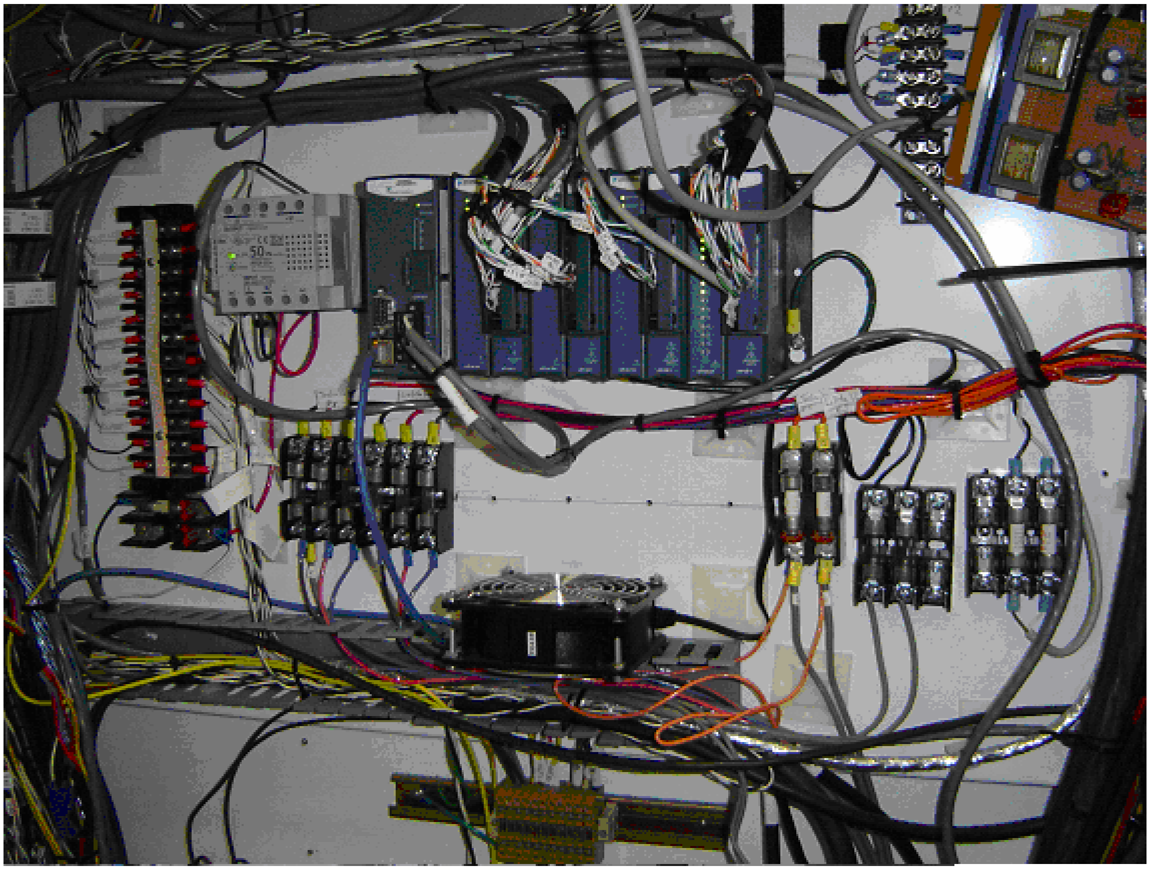


Figure 4.2 Signals connection of the monitoring system

Table 4.1 Data Acquisition Hardware Specification

	DAQ Card	Compact Field Point
Sampling Rate	32 Samples/Cycle	10 Samples/Second
Signal Type	Voltage Surge Detection Signal	Active & reactive power flow Transformer temperature Breaker status Cable Temperature
A/D Converter	0 to 10V analog input 12 bits	±20mA/±30V analog input 12 bits 18 to 30V digital input
Computer Link	Peripheral Component Interconnect (PCI)	Two RS-232 Serial Ports One Ethernet Port

Table 4.2 Server Computer Specification

Module	Description
CPU	Inter P4, 3GHz 512MB Memory 160GB Hard Driver
Monitor	17” Monitor
UPS	1500VA

4.1.2 Graphic User Interface

A well designed graphic user interface (GUI) is important for system operator and engineer to maintain and access this monitoring system. These designed front panels include:

1) **DPMS one-line diagram panel**: As shown in figure 4.3, this front panel is to display the overall system information, such as active, reactive power flow, transformer temperature, and circuit breaker status. Audio and visual alarm will be activated if any abnormal condition is detected. In addition, five most recent recorded events and the current daily statistical operation data are also accessible from the front panel. Operator and engineer can understand the real time system operation condition easily and be aware of any abnormal event by glancing through this panel.

2). **DPMS voltage-frequency panel**: As shown in figure 4.4, this panel displays the trend of the tie line voltage and system frequency. Since the cited power plant is participated in the LaaR programs in the ERCOT ancillary services market, an alarm would be issued and this event would be recorded once the frequency reaches the 59.8 Hz.

3). **DCRS information panel**: As shown in figure 4.5, this panel displays the steady-state and short-term dynamic rating of each 69kV transmission line. Figure 4.6 shows the overall system bottleneck of the system and the corresponding short-term dynamic rating analysis result. The market balancing energy and ancillary service clearing prices and forecasting temperature information are shown in figure 4.7. DCRS would perform both the steady-state and short term dynamic cable rating estimation based on the real time cable loading, temperature measurement, and forecasting temperature information. The steady-state analysis would calculate the real time cable conductor temperature, which is the main limiting factor of the cable ampacity. Also the permitted static ampacity under the real time operation condition would be calculated. The short-term dynamic cable rating estimation would estimate the possible cable temperature raise based on the increased cable loading and forecasting temperature. The permitted operation period at different cable loading would be estimated. Finally, the portion with the lowest available ampacity of the cables will be considered as the system bottleneck and will be used by the engineer to modify or establish the bidding strategy.

4). **Daily historical information**: As shown in figure 4.8, this panel is used to retrieve the historical daily information from database to provide daily operation information, which includes the overall active and reactive power transaction trend, market cleaning price, cable loading and available ampacity information. Engineer can analyze the system performance through this information to adjust or modify the system operation pattern and bidding strategy to maximize the profit without compromising the reliability of the system facilities.

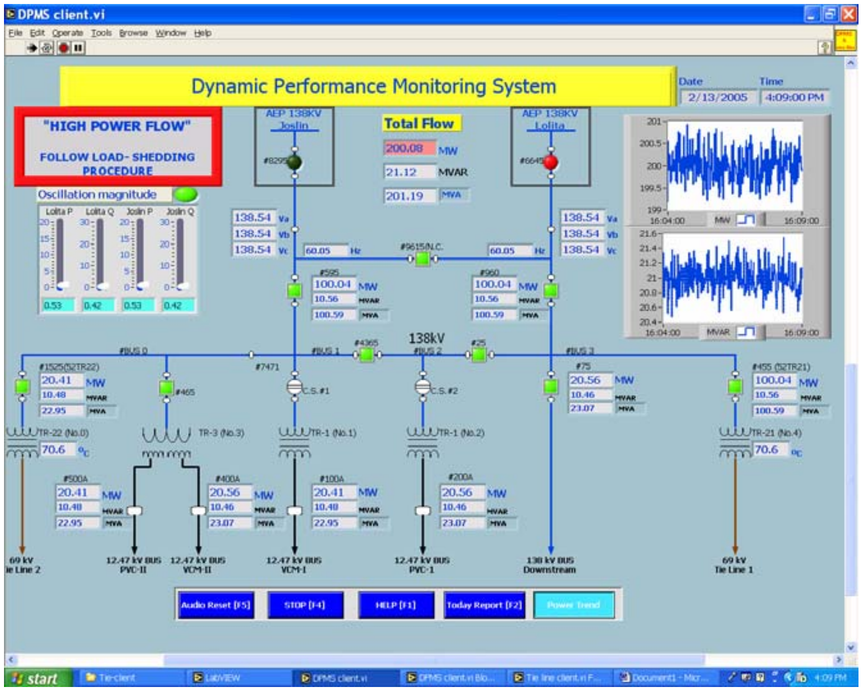


Figure 4.3 DPMS one-line diagram front panel

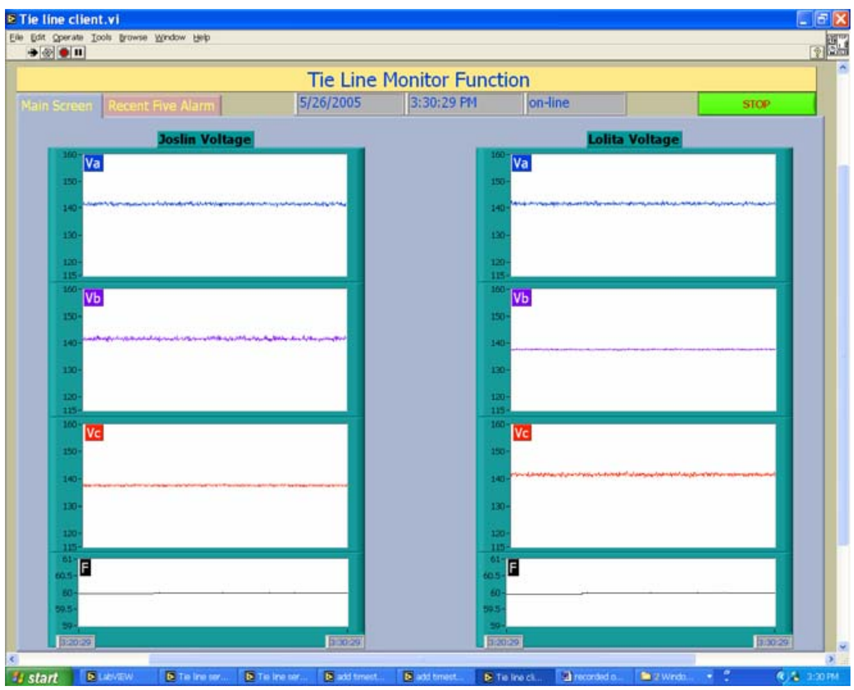


Figure 4.4 The voltage-frequency trend front panel

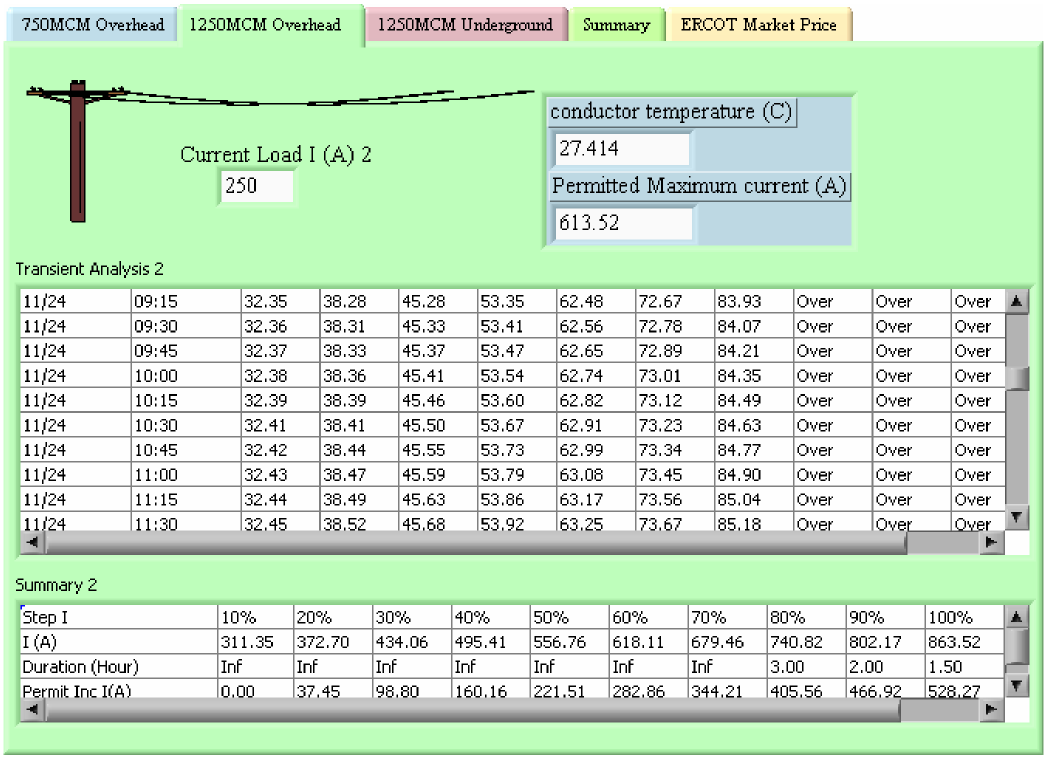


Figure 4.5 The short-term dynamic analysis of each 69kV cable

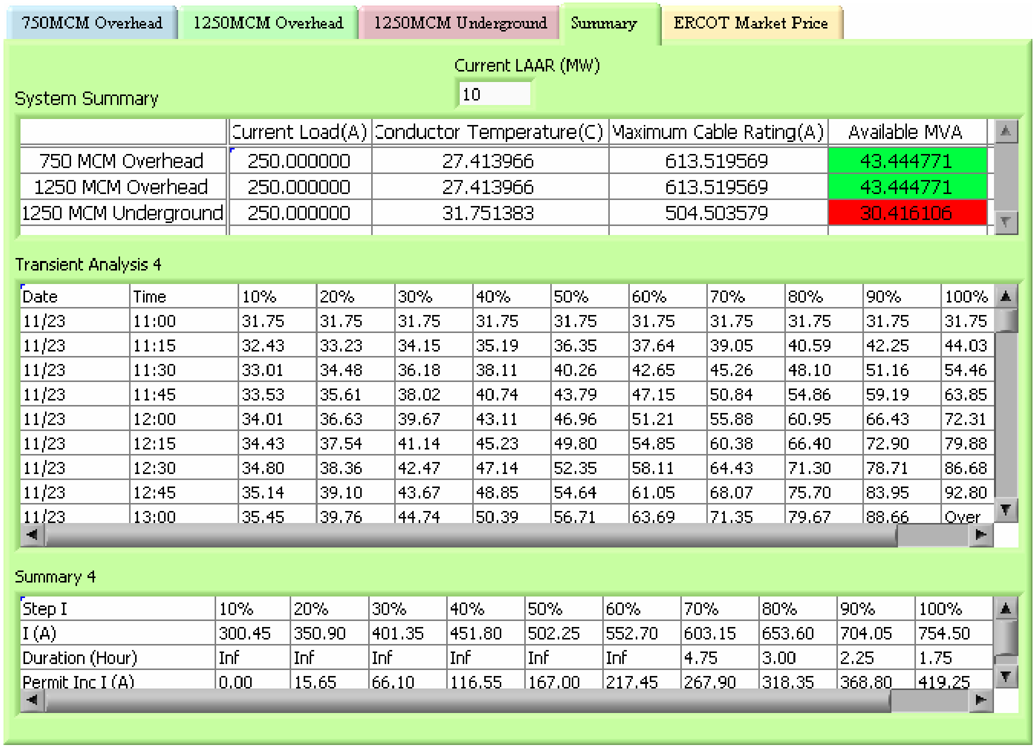


Figure 4.6 The system bottleneck and the corresponding short-term dynamic analysis

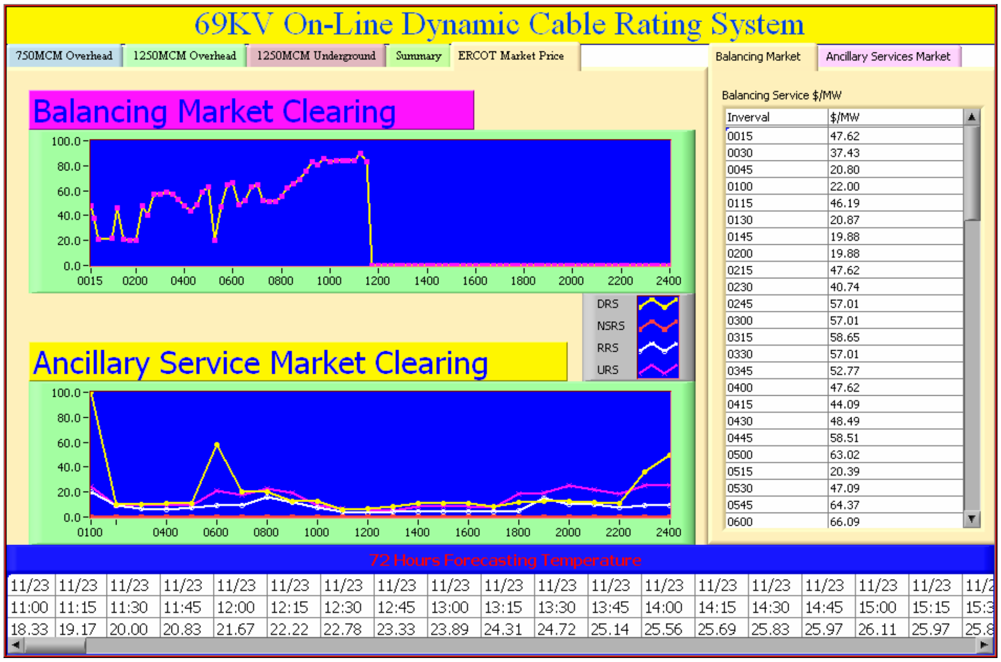


Figure 4.7 The ERCOT market prices and forecasting temperature information

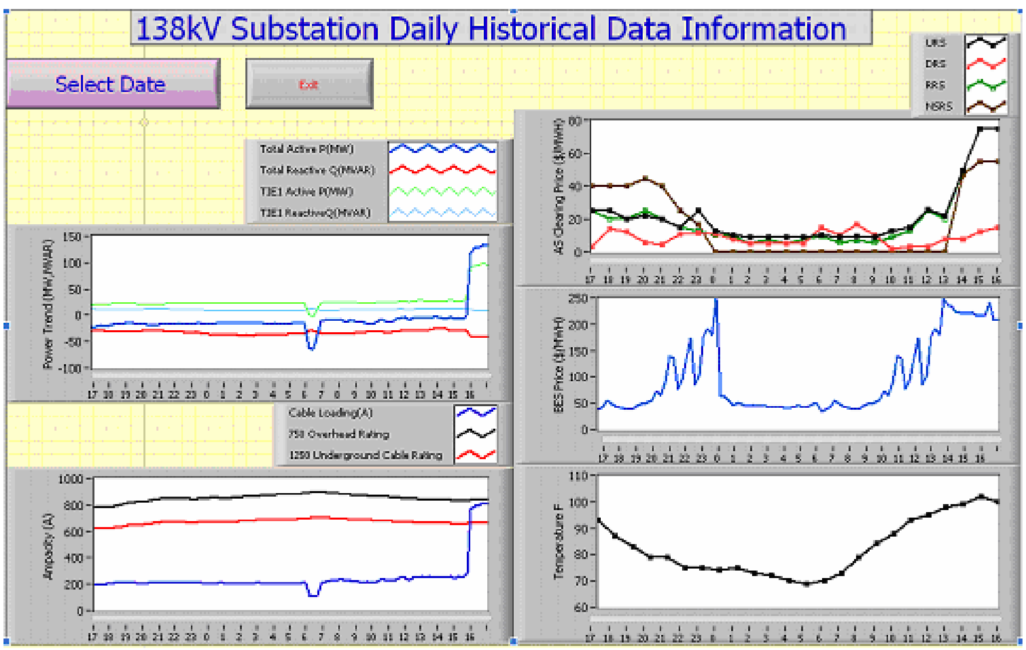


Figure 4.8 Daily historical information

4.2 Opportunities of the Cogeneration Plant

The cited cogeneration is located in the ERCOT grid. During normal operation, it could export or import power from the grid according to the market prices. In addition to 220MW interruptible loads in the plant, the fast response time characteristics of gas turbine units have enable the cogeneration plant to join the demand response programs, especially for the LaaR programs, in the ERCOT ancillary services markets. Under the ERCOT operation rules, the cited cogeneration plant has maximum flexibility to participate into the ERCOT markets.

Consider the potential economic benefit and existing operation characteristics, two main programs of the ERCOT's power markets are recommended for the cited cogeneration. The first one is the LaaR program in the responsive reserve service. By participating into the responsive reserve service, the cited cogeneration will receive the market clearing price for capacity (MCPC) payment plus the market clearing price for energy (MCPE) if the resource is actually curtailed. The other one is the balancing energy market. Because of the fast response time characteristics of gas turbine units, once the MCPE is attractive, the cogeneration could exercise the in-plant generation units to import or export the energy to the grid. With the help of the designed monitoring system, the cogeneration would have enough information to establish or modify their bidding strategy to successful participate into these two recommended programs in the ERCOT's market.

4.3 Operation Record and Case Study

Figure 4.9 shows one day balancing energy market MCPE and figure 4.10 shows the corresponding operation record of the cogeneration. According to the operation record, the cited cogeneration could adjust their in-plant generation units to sell or purchase power from the grid. In general, the MCPE is higher in the afternoon while the temperature is high and the cogeneration would participate into the energy market to sell power for benefit, which can be observed in figure 4.9 and figure 4.10.

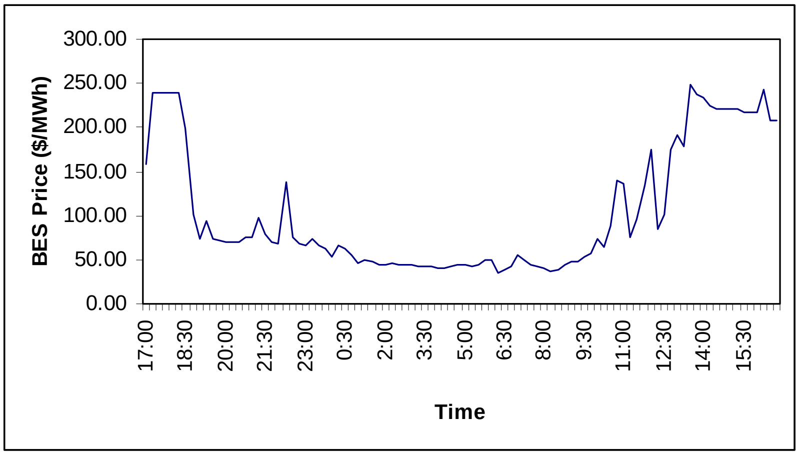


Figure 4.9 One day balancing energy market clearing prices for energy

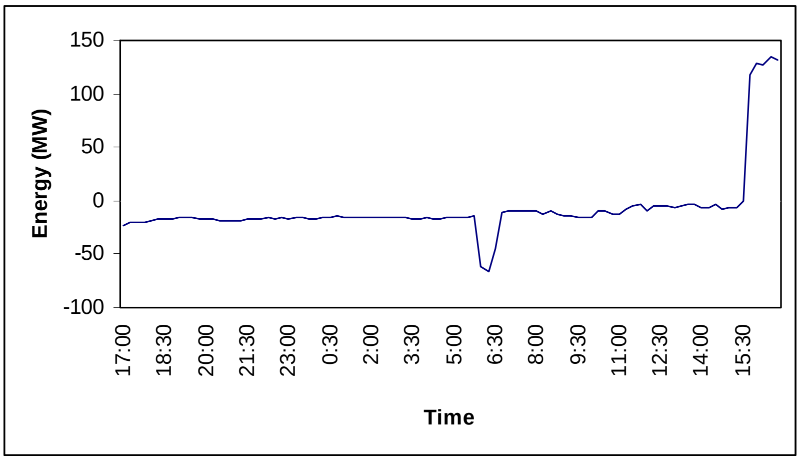


Figure 4.10 One day recorded operation record for the cited cogeneration

Figure 4.11 shows the temperature trend at the cited power plant for three days began at April 16, 2006. Compound with the unusual seasonally high temperature and some unexpected generation outages, the margin of the ERCOT system was running short. Figure 4.12 shows the frequency event recorded by DPMS at April 17, 2006. The system frequency has dropped to 59.8 Hz. In order to cover the unexpected increasing demand and generation shortage, ERCOT has requested the cited power plant facility to trip the demand that is participated in the LaaR's program. Figure 4.13 shows the recorded three days operation record and the estimated ampacity of the 69kV transmission lines of the cited cogeneration began at April 16, 2006. The cited plant has participated in both LaaR program and the balancing energy market. Because the tripping of the demand, the extra power was sent to the grid through two 69kV transmission lines that has pushed the cable loading to 820 Ampere. The short-term dynamic ratings of these two 69kV lines are simulated and the result is shown in table 4.3. According to the operation record, the temperature information, and the dynamic rating analysis by DCRS in table 4.3, only one and half hour is allowed for the overloading condition at 820 Ampere to prevent the over-temperature of the conductor. Unfortunately, due to the lack of the DCRS information at that moment, the cited plant continued to participate into the balancing energy market for four hours. This may have caused some damages on the underground cables. If DCRS were available at that time, this undesired operation scenario should have been avoided.

Therefore, with the information and analysis provided by the designed monitoring system, the cited cogeneration power plant will be able to participate into those two recommended market services effectively without compromising the facilities reliability.

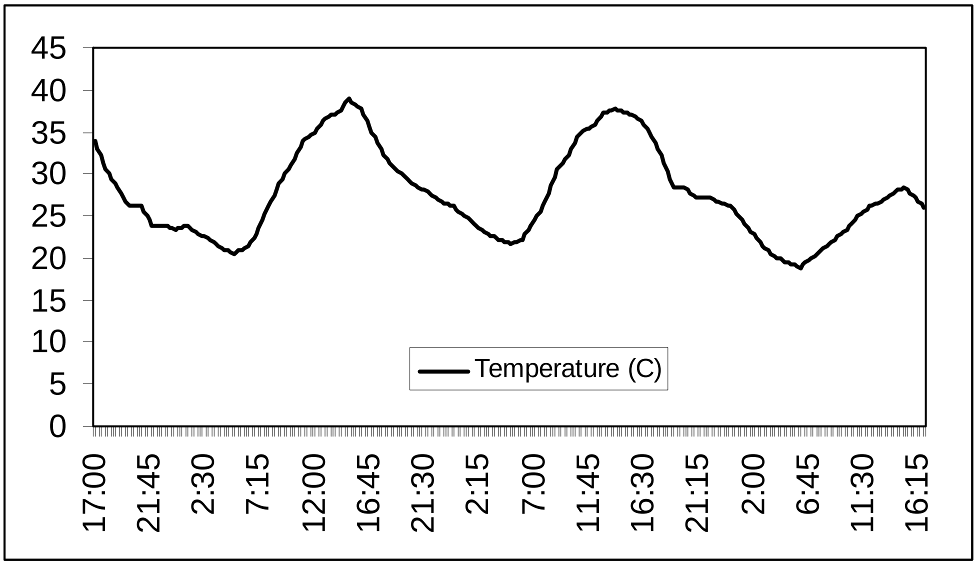


Figure 4.11 Three days' temperature trend began at April 16, 2006

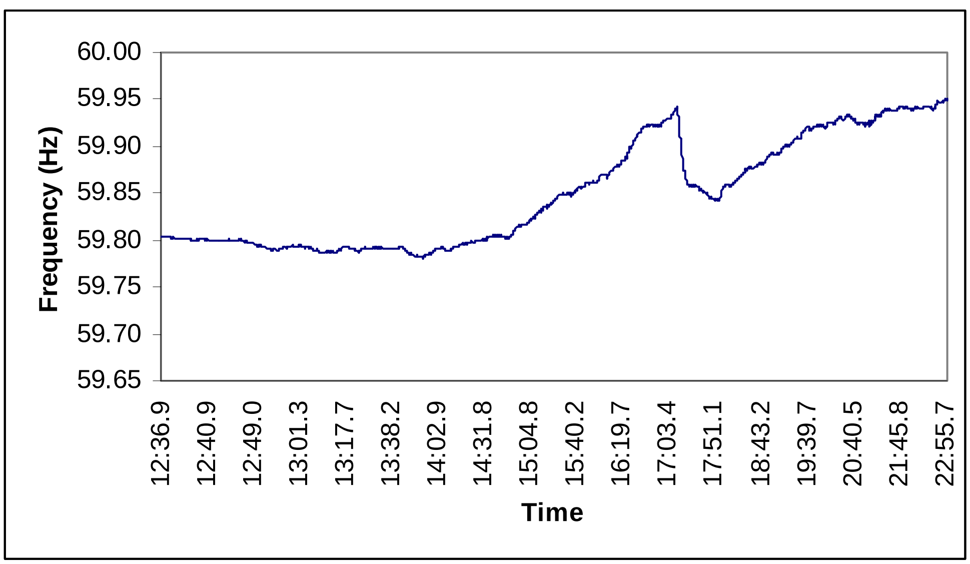


Figure 4.12 Recorded frequency event at April 17, 2006

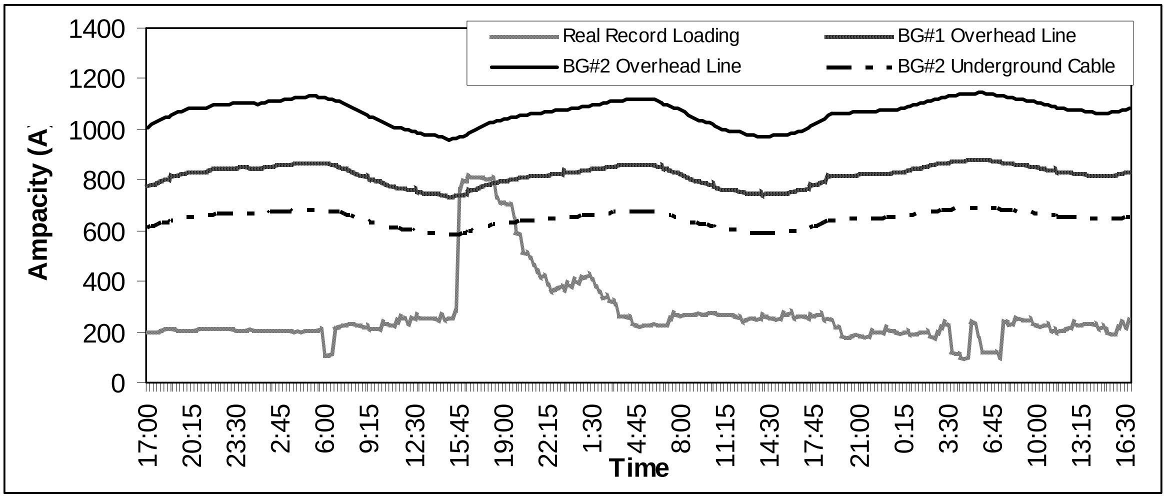


Figure 4.13 Comparison of record cable loading and estimated cable rating

Table 4.3 Short-term Dynamic Cable Rating Analysis of the Underground Cable

Cable Loading (A)	<=800	820	870	920	970	1020
Permit Duration (Hour)	Steady State	1.5	1	0.75	0.5	0.5

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 Summary and Conclusion

The electric utility industry restructuring in the state of Texas has created opportunities and challenges to both electricity suppliers and customers. At present, both power supplier and demand consumer can participate in the balancing energy and ancillary services (AS) markets to bid/offer for their energy, capacity, and demand in the ERCOT markets. Understanding the currently system operation patterns and characteristics turns out to be the key factor to establish flexible and realistic bidding strategies in the power auction markets to maximize the profit.

In order to effective utilize the existing power instruments in an industrial power company, a web-based real-time dynamic performance monitoring system is developed and installed in the substation of the cited cogeneration to provide the system engineer with better understanding of their system operation characteristics. With the designed remote access capability, system engineer can either access the monitoring information through intranet or security access the website of the monitoring system at remote location. With successfully extracted the GPS timestamp, the monitoring and recorded data have universal timestamp which is synchronized with the ISO data timestamp.

In addition to the market information, available energy and capacity to participate in the market are also the essential information to be an effective market participant. The development of an on-line dynamic cable rating system (DCRS) to help system engineer maximizing asset utilization without jeopardizing system facilities and/or compromising the reliability of the cables. DCRS can provide the static and dynamic rating of the overhead and underground cables for a cogeneration facility. Though the cable dynamic rating has been studied by several researchers, this newly developed DCRS is the first attempt to incorporate forecasting temperature information for cable rating estimation. DCRS has extracted and updated the temperature forecasting information from the website of an available weather station for the dynamic rating calculation. This will yield more realistic results than the traditional approaches that were based on constant temperature. This monitoring system provides technical, weather, and marketing information for responsible personnel to establish or adjust the system schedule and the bidding strategy in time to maximize the profit without compromising the reliability and security of the facilities.

Take both the potential economic benefit and existing operation characteristics of the cited cogeneration into consideration, balancing energy and responsive reserve service ancillary service markets in the ERCOT markets are recommended for the cited cogeneration. With the assistance of the designed monitoring system, the undesired operation scenario as mentioned in chapter 4 could be prevented from potential damaging the facilities.

5.2 Recommendation for Further Research

The monitoring system in this dissertation could be extended to include the optimal dispatch for the in-plant generation units. Currently, due to the lack of each in-plant generation unit's efficiency information, the adjustment of the in-plant generation is equally shared by each on-line unit. Therefore, it is recommended that an optimal scheduling between each unit could be made based on their efficiency to reduce the production cost.

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