An Expert-based Approach for Demand Curtailment Allocation Subject to Communications and Cyber Security Limitations

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ABSTRACT

A smart grid is different from a traditional power system in that it allows incorporation of intelligent features and functions, e.g., meter reading, adaptive demand response, integration of distributed energy sources, substation automation, etc. All these intelligent features and functions are achieved by choosing appropriate communication technologies and network structures for the smart grid appropriately.

The objective of this dissertation is to develop an AHP (analytic hierarchy process) - based strategy for demand curtailment allocation that is subject to communications and cyber security limitations. Specifically, it: (1) proposes an electrical demand curtailment allocation strategy to keep the balance between supply and demand in case of the sudden supply shortage; (2) simulates the operation of the proposed demand curtailment allocation strategy considering the impact from communication network limitations and simultaneous operations of multiple smart grid applications sharing the same communication network; and (3) analyzes the performance of the proposed demand curtailment allocation strategy when selected cyber security technologies are implemented. These are explained in more details below.

An AHP-based approach to electrical demand curtailment allocation management is proposed, which determines load reduction amounts at various segments of the network to maintain the balance between generation and demand. Appropriate communication technologies and the network topology are used to implement these load reduction amounts down to the end-user. In this proposed strategy, demand curtailment allocation is quantified taking into account the demand response potential and the load curtailment priority of each distribution substation. The proposed strategy helps allocate demand curtailment (MW) among distribution substations or feeders in an electric utility service area based on requirements of the central load dispatch center.

To determine how rapidly the proposed demand curtailment strategy can be implemented, the capability of the communication network supporting the demand curtailment implementation needs to be evaluated. To evaluate the capability of different communication technologies, selected communication technologies are compared in terms of their latency, throughput, reliability, power consumption and implementation costs. Since a number of smart grid applications share the same communication network, the performance of this communication

network is also evaluated considering simultaneous operation of popular smart grid applications.

Lastly, limitations of using several cyber security technologies based on different encryption methods - 3EDS (Triple Data Encryption Standard), AES (Advanced Encryption Standard), Blowfish, etc. - in deploying the proposed demand curtailment allocation strategy are analyzed.

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GENERAL AUDIENCE ABSTRACT

With the rapid development of smart grid, the penetration of renewable energy resources is higher than ever and keeps growing. However, the output of such variable resources usually contains sudden and unpredictable changes. Therefore, maintaining grid operations has become a challenging task, especially with high percentage of renewable energy penetration.

A smart grid is different from a traditional power system in that it allows incorporation of intelligent features and functions, e.g., meter reading, adaptive demand response, integration of distributed energy sources, substation automation, etc. On the other hand, the proper operation of smart grid requires many different smart grid applications functioning in an organized manner. Functions of all these smart grid applications are made possible by two-way communication technologies and networks. Any uncertainty or failure of the communication system will affect the operation of the power system. To analyze electric power grid operations, it is necessary to take into account the integrated communication system.

To protect end-use customers' privacy, a reliable and secure communication network is necessary. Applying cyber security technologies, such as encryption methods, to prevent adversary attacks can protect customers' privacy and allow the smart grid to operate reliably. Nonetheless, implementing encryption methods require extra software and hardware which increase complexity of the system. In addition, the processing of encryption/decrption also extends the system latency. Especially, by using strict cyber security standards, the operation of smart grid application may be negated. However, some smart grid applications have strict demands on fast operation speed. Therefore, it is necessary to analyze the limitation of using encryption methods on the smart grid operation.

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1. INTRODUCTION

1.1 Background

According to the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability [1], a smart grid generally refers to a class of technology people are using to bring utility electricity delivery systems into the 21st century, using computer-based remote control and automation. These systems are made possible by two-way communication technologies and computer processing that have been used for decades in other industries.

With the penetration of renewable energy sources, distributed energy resources and the introduction of plug-in electric vehicles, many methods are being deployed to help electric utilities to keep the balance between electrical supply and demand. To reduce peak electricity demand, many electric utilities in the U.S. have introduced various types of demand response (DR) programs -- both time-based DR programs and incentive-based DR programs. Time-based DR programs are achieved in response to electricity prices, which are usually announced one day ahead. Incentive-based DR programs offer payments for customers to reduce their electricity usage during periods of system stress conditions. One popular incentive-based DR program, known as an emergency demand response program (EDRP), can alleviate power system stress conditions by reducing load at customer premises. EDRP usually needs an advance notice of at least two hours.

In an event where there is a sharp decrease of available generation, causing a significant drop in power system frequency, under frequency load shedding (UFLS) will be activated to curtail part of system load fast enough to recover the system frequency back to its nominal value. UFLS is typically used as the last resort to minimize the risk of a further uncontrolled system separation, loss of generation, and blackouts. Usually, its response time is within a fraction of a second. Despite the fact that UFLS can curtail the large amount of loads within a very short period of time, it comes at the cost of large load lost.

In the current practice, DR is first implemented to alleviate power system stress conditions when time is sufficient. With the increasing penetration of renewable energy sources, however, the sudden loss of renewable energy output may lead to insufficient generation to keep up with the demand for electricity in certain periods. Since DR program requires at least two hours for customer notification, DR implementation is not a suitable means to mitigate fluctuation in renewable energy sources. Neither should UFLS be used, which causes large-scale load drop. This calls for a novel demand curtailment approach that has the ability to respond faster than DR programs and avoid UFLS operation. This approach should also take into account the DR potential and the load curtailment priority of each group of customers.

These factors can be determined by using the information on power consumption measured at customer premises. This novel demand curtailment application needs to collect information from end-use customers, performs its decision making process, distributes demand curtailment decisions quickly enough to curtail necessary loads, and brings back the balance between supply and demand before the system frequency goes down below the UFLS operation threshold, for example, the frequency is lower than 59 Hz for more than 0.1 second. The transmission of both from customer measurements and control center decisions must rely on a fast and reliable communication network. Since smart grid networks are typically shared with many other smart grid applications, operations of other smart grid applications may impact the speed at which the proposed demand curtailment approach can take action. Therefore, it is necessary to evaluate the capability of communication technologies supporting such operations. Since the proposed smart grid application involves wide area network (WAN), neighborhood area network (NAN) and premises area network (PAN), all three levels of the network are evaluated by taking into account latency, data error ratio, implementation cost considering different communication technologies.

As mentioned, the proper operation of the novel demand curtailment approach requires information from end-use customers. In order to protect end-use customers' privacy and keep the smart grid operation more reliable, cyber security technologies based on different encryption methods on smart grid applications are necessary. Nonetheless, applying encryption methods increases system operation complexity and latency. Especially, strict cyber security standards may negate the effective deployment of curtailment allocations. On the other hand, the proposed demand curtailment allocation approach is strict with operation speed. Thus, it is important to analyze the limitation of applying different encryption methods to secure successful operation of the proposed demand curtailment allocation approach.

1.2 Objectives and Scope of the Dissertation

To address the issue of sudden loss of generation -- which may come from generator trips, transmission lines failures, or sudden decrease in renewable energy outputs - this dissertation proposes an expert-based demand curtailment allocation approach which can curtail end-use loads faster than traditional DR programs and prevent UFLS operation. Specifically, it is an approach to manage the electrical demand using inputs from experts and information about DR potential and load curtailment priority level. The proposed approach can allocate demand curtailment amounts from a transmission substation to distribution substations, and subsequently to feeders or end-use customers.

To determine how quickly the proposed demand curtailment strategy can be implemented, the capability of the communication network supporting the proposed demand curtailment application needs to be evaluated. Since a number of smart grid applications share the same communication network, the capability of this network must be evaluated considering operation of other popular smart grid applications.

To protect customer privacy and to keep smart grid from being attacked, many cyber security technologies can be implemented in smart grid's communication networks. On the other hand, additional processing time and encryption bytes added to smart grid data decrease the efficiency of demand curtailment allocation strategy. As a result, it is necessary to analyze the limitation of some commonly used and easily implemented encryption methods onto the proposed demand curtailment allocation strategy.

Specifically, the proposed work includes the following objectives:

Objective 1: Propose a demand curtailment allocation method to keep the balance between supply and demand in case of temporary supply shortage (e.g., sudden loss of renewables) and avoid the operation of UFLS. The proposed approach allocates demand curtailments (MW) among distribution substations (DS) or feeders in an electric utility service area based on requirements of the central load dispatch center. Demand curtailment allocation is quantified taking into account DR potential and load curtailment priority of each DS, which can be determined using DS loading level, capacity of each DS, customer types and load categories (deployable, interruptible or critical). Analytical Hierarchy Process (AHP) is used to model a complex decision-making process according to both expert inputs and objective parameters. And then, proper communication technologies and the network topology are used to implement these reductions down to the end-user.

Objective 2: Evaluate the capability of communication technologies and networks for the demand curtailment approach which is proposed in objective 1. This is to prove that the operation of the proposed approach can function quickly enough to avoid the operation of UFLS. Goals include:

Goal 2.1: from the control center to end-use customers:

Develop a communication network model in OPNET to support the proposed demand curtailment application between the control center and end-use customers (within wide area network and neighborhood area network). Popular communication technologies are evaluated to understand their latency, throughput, reliability, power consumption and implementation costs.

Evaluate the capability of the proposed demand curtailment approach considering the background traffic generated based on popular smart grid applications that share the same network. These applications include distribution automation, pricing application, metering application and electric vehicle application. Characteristics of each smart grid application such as data packet size, data sampling frequency, latency and reliability requirements are considered when modeling the application.

Goal 2.2: within a smart home:

Develop a communication network model in OPNET to support the proposed demand curtailment application between the home management system and smart appliances. Common communication technologies are evaluated to understand their latency, throughput, reliability, power consumption and implementation costs. Evaluate the capability of the proposed demand curtailment approach within a smart home/building.

Objective 3: Analyze the limitations of using several different encryption methods on the proposed demand curtailment allocation approach.

Goal 3.1: without encryption method

A small-scale power system is simulated with a sudden loss of renewable energy sources. The simulation shows the frequency change of the system with and without the implementation of the proposed novel demand curtailment application. Case study results verify that the proposed demand curtailment approach can keep system's frequency within its allowable operating range, and its operation is fast enough to avoid UFLS operation.

Goal 3.2: with encryption methods

Under this goal, the capability of the proposed demand curtailment approach is evaluated considering the implementation of cyber security technologies. The limitations of encryption methods, e.g., 3DES (Triple Data Encryption Standard), AES (Advanced Encryption Standard), Blowfish, etc. are compared taking into account extra data rates and the processing time. Implementing encryption methods on the proposed demand curtailment allocation are simulated. And then, the limitation of applying different encryption methods to secure the proposed demand curtailment allocation is analyzed.

1.3 Contributions

This dissertation provides the following contributions.

- A novel demand curtailment allocation approach that allows aggregated end-use electrical demand to be responsive, thus mitigating the sudden loss of generation and fluctuation in renewable energy sources.

- Evaluation of the capability of different communication technologies to support the proposed demand curtailment application considering operations of other smart grid applications.

- Analyze limitation of applying different encryption methods to secure the proposed demand curtailment allocation approach.

1.4 Outline

In this dissertation, there are six chapters. Chapter one includes background, objectives & scope of the dissertation and contributions. Literature search is summarized in chapter two. Chapter three proposes an expert-based strategy for electrical demand curtailment allocation.

Evaluation of the capability of communication networks for the proposed demand curtailment allocations strategy is shown in chapter four. Chapter five analyzes the limitation of applying cyber security technologies based on different encryption methods on demand curtailment allocation approach. Conclusion and future work are summarized in chapter six.

2. LITERATURE SEARCH

There are two sections in this chapter. The first section discusses previous work in the areas of basic information about the smart grid, popular smart grid applications, demand response (DR), Analytic Hierarchy Process (AHP), communication network for smart grid, communication technology, cyber security. Knowledge gaps are summarized in the second section of this chapter.

2.1 Smart Grid

As stated by the U.S. Department of Energy (DOE), over last several decades, the traditional power system has transformed into a smart grid with the integration of smart devices and two-way communications. Smart grids are deemed to make the traditional electric power system to be [2]:

1) More reliable – the smart grid needs the ability to provide ample warnings of growing problems and withstands most disturbances without failing.

2) More secure – the smart grid should withstand both physical and cyber-attacks without suffering massive blackouts or exorbitant recovery costs.

3) More economical – an economic grid provides fair prices and adequate supplies.

4) More efficient – an efficient grid has minimal transmission and distribution losses efficient power production, and optimal asset utilization while providing consumers with options for managing their energy usage.

5) More environment friendly – a smart grid should support the integration of a larger percentage of renewable energy.

6) Safer - A safe grid does no harm to the public or to grid workers and is sensitive to users who depend on it for medical necessities

According to "A system view of the modern grid v2.0" [5], the smart grid should have following characteristics:

1) Self-heals - The traditional grid can monitor its own operation, detect and analyze the problem. The smart grid should be able to restore services as well.

2) Motivates and includes consumers - With the two-way communication, consumers can exchange information with an electric utility about the price and usage situation. Based on a prior agreement, consumers can participate in a demand response program.

3) Resists attack - With remote digital controlled devices, the smart grid should be more resilient than the traditional power system.

4) Provides high power quality for the 21st century needs - the revolution in home electronics requires better power quality. In order to meet this requirement, harmonics, distortion, imbalance, sags and spikes are needed to be minimized.

5) Accommodates all generation and storage options - cleaner energy sources, such as solar and wind, help reduce the dependence on fossil fuels. The smart grid can help to accommodate various types of generation and storage.

6) Enables markets - the smart grid should bring in more participants and options to improve the efficiency of the system.

7) Optimizes assets and operates efficiently – the smart grid assets and its maintenance will be managed towards to one goal: delivering the desired functionality at the minimum cost. This can be accomplished by applying optimization algorithms, complicated decision making, etc.

"A system view of the modern Grid v2.0" [5] also summarized smart grid technologies into the following categories:

1) Integrated communications – most smart grid applications depend on high-speed two-way communication technologies. With two-way communications, customers and utility can exchange real-time information, which makes the system more efficiency.

2) Sensing and measurement – as power system measurements are enhanced, end-use customers are provided more choices, such as participating in demand response to help keep the balance between demand and generation.

3) Advanced components – applying these components provide higher power densities, greater reliability and power quality, enhanced electrical efficiency producing major environmental gains and improved real-time diagnostics.

4) Advanced control methods – as new methods are applied to control essential components, rapid diagnosis and timely response can be enabled.

5) Improved interfaces and decision support – the time for operators to make decisions is as short as seconds in some situations. Improved interfaces and decision making tools/methods are applied to support the smart grid operation.

2.2 Popular Applications in a Smart Grid

With integrated communications, many applications are enabled in the smart grid, such as: wide-area control, protection and monitoring, intelligent meter reading, pricing, demand response, utility service switch operation, outage and restoration management, distribution customer storage, electric transportation, customer information and messaging, premises network administration, etc. [10]. The description below provides the overview of six commonly used smart grid applications.

2.2.1 Pricing Applications

Pricing applications involve broadcasting of electricity price information to smart meters and other smart devices. The pricing program can be classified into three types: time-of-use (TOU), real-time pricing (RTP) and critical peak pricing (CPP).

In TOU programs, customers can decrease their electric bills if they shift their electricity usage to off-peak periods. TOU has different electricity price schedules for different time periods. RTP programs offer short-term time-varying electricity price information. RTP's time intervals can be one hour, 15 minutes, or shorter as designed. Based on real-time pricing information, customers can manage their energy consumption accordingly in order to reduce their energy bills. CPP programs specify extremely high electricity prices to encourage load curtailment during grid stress conditions.

2.2.2 Metering Applications

Meter reading allows a utility to collect data from electric/gas/water meters and transfer data to a central database for billing and analysis. Advanced metering infrastructure (AMI) is required to support metering applications in the smart grid environment. AMI refers to a measurement and collection system that makes meter data available to an electric utility. In general, AMI is deployed to enable a utility to collect real-time electricity consumption information, and enable end-use customers to be informed about real-time pricing information. There are three components in an AMI system: smart meters, an MDMS or metering data management system and a communication network.

A smart meter is a digital meter that can be used to record consumption of electric power, water or gas, and transfer consumption information to a utility. It is also used to receive commands or price signals from a utility. MDMS is another critical component in realizing potential functions of AMI. Major functions of MDMS include: automating and streamlining the complex process of collecting meter data from multiple data collection technologies; evaluating the quality of that data and generating estimates where errors and gaps exist; and delivering that data in an appropriate format to utility billing systems. A communication network is another important component of AMI, which provides a channel to exchange information between end-use customers and a utility. With two-way communications, a utility can monitor real-time consumption from end-use customers; and at the same time, end-use customers are able to participate in the system operation actively by receiving price or control signals from a utility.

There are several kinds of meter reading modes: on-demand meter reading, scheduled interval meter reading, bulk transfer of meter reading and also real-time metering. On-demand meter reading provides readings when needed. Scheduled interval meter reading allows a utility to collect information from one customer with a certain frequency. Bulk transfer of meter reading allows a utility to collect information from all meters within the whole service area [41]. Real-time metering is the process of measuring the amount of electricity consumption in real time (the application interval can be one second or even shorter). For example, PG&E provides real-time electricity meters to large non-residential customers throughout California [11]. Residential customers have begun to be considered in real-time programs. Real-time metering draws a lot of utilities' attentions since it can provide better quality of service, lower costs, fast access to data, which allows making better decisions and creating values in response to changing markets, notification of new peak demand being set, etc. [12]

2.2.3 Electric Transportation

Electric transportation applications contain two major components: grid-to-vehicle (G2V) and vehicle-to-grid (V2G). In the V2G mode, an electric vehicle (EV) is considered as a mobile distributed generation source. EV can also be considered as a load to the grid in G2V. The major communication traffic for electric transportation applications is for updating status of EV to a utility and broadcasting electricity price information.

2.2.4 Under Frequency Load Shedding (UFLS)

The predominant system condition addressed by IEEE C37.117 involves the use of protective relays for under frequency shedding of connected load in the event of insufficient generation or transmission capacity within a power system. UFLS is applied to minimize the risk of a further uncontrolled system separation, loss of generation, or system shutdown. The system can be restored if sufficient load is shed to preserve interconnections and keep generators on line. If the system collapses, an outage will happen. Severe frequency decline usually occurs within seconds. As a result, the manual or SCADA (supervisory control and data acquisition system) initiated under frequency load shedding generally cannot be accomplished fast enough to prevent partial or complete system collapse. On the other hand, UFLS is triggered to shed loads when frequency drops to the set point. It functions quickly enough to stop power system frequency decline by decreasing power system load to match available generating capacity. These set points are predetermined based on guidelines created by power pools covering a wide geographic area. [13]

The activation of UFLS is the last automated reliability measure associated with a decline in frequency in order to rebalance the system. UFLS's operation will bring a large scale of load lost in a service area. According to [14], single events had a load shedding range from 24 MW to 17,644 MW.

2.2.5 Demand Response (DR)

DR is one of the most popular applications nowadays. Many kinds of DR programs are introduced and implemented widely around the world. The detailed information of DR is introduced in Section 2.3.

2.3 Demand Response (DR)

In order to keep the balance between generation capacity and electrical demand during peak hours, electric utilities usually turn on expensive peaking generation units, or buy high cost electricity at the power pool level. Among many methods in use today, DR is considered as one of the most effective means to curtail or shift loads to alleviate grid stress conditions.

Federal Energy Regulatory Commission (FERC) defines the Demand Response as: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." [15]

2.3.1 Demand Response Classification

According to a report by Federal Energy Regulatory Commission (FERC) [16], DR programs can be classified into five types.

Dynamic pricing without enabling technology: The electricity price in this kind of programs is time-varying. The utility broadcasts the price information day-ahead or in real-time. Since the price is higher during peak periods, customers may reduce their electricity demands in order to cut bills.

Dynamic pricing with enabling technology: the difference from the previous program is end-use customers equipped with devices which can automatically reduce the electricity consumption during high priced hours.

Direct load control (DLC): the utility can control end-use customers' power consumption during peak hours, either by shutting down the usage or moving the consumption to non-peak hours.

Interruptible tariffs: this kind of program aims at medium and large commercial and industrial customers. Customers keep power consumption under certain limits during system reliability periods; in return, these customers get incentive payments.

Other DR programs: Capacity bidding, demand biding, demand response being bid into capacity markets, etc.

In “National Action Plan on Demand Response” [17] by FERC, DR falls into two basic categories. And in [18], a comprehensive explanation of each type of DR is given.

1) Time-based demand programs:
    1. Direct Load Control (DLC)
    2. Interruptible/curtail able service (I/C)
    3. Emergency Demand Response Program (EDRP)
    4. Capacity Market Program (CMP)
    5. Demand Bidding/Buy Back
    6. Ancillary Service Markets (A/S)

2) Price-based demand response (also called Time-based DR):
    1. Time-of-Use (TOU) program
    2. Real Time Pricing (RTP) program
    3. Critical Peak Pricing (CPP) Program

Direct Load Control (DLC): In a DLC program, a utility or system operator remotely shuts down or cycles a customer’s electrical equipment on a short notice to address system or local reliability contingencies in exchange for an incentive payment or bill credit.

Interruptible/curtailable service (I/C): Customers on interruptible/curtailable service receive a rate discount or bill credit in exchange for agreeing to reduce load during system contingencies. Penalty will be applied if the customers do not curtail the load.

Emergency Demand Response Program (EDRP): EDRP provides an incentive payment to customers for reducing their loads during reliability-triggered events, but curtailment is voluntary. Customers can choose to forgo the payment and not curtail when notified.

Capacity Market Program (CMP): In capacity-market programs, customers commit to providing pre-specified load reductions when system contingencies arise, and are subject to penalties if they do not curtail when directed. Capacity market programs can be viewed as a form of insurance. In exchange for being obligated to curtail load when directed, participants receive guaranteed payments.

Demand Bidding/Buy Back: These programs encourage large customers to offer load reductions at a price at which they are willing to curtail their load, or to identify how much load they would be willing to curtail.

Ancillary Service Markets (A/S): The final type of incentive-based demand response is ancillary-service market programs. Ancillary services programs allow customers to bid load curtailments in Independent System Operator (ISO) markets as operating reserves.

TOU, RTP and CPP have been discussed in Section 2.2.1 and will not be repeated here.

2.3.2 Development of Demand Response

In a traditional power system, to keep the balance between demand and supply an electric utility first forecasts the demand and then determines optimal supply methods. While with the increasing penetration of renewable energy and growing electrical demand, the traditional demand driven planning becomes more and more difficult. Electric utilities started to consider another solution which is by varying demand in order to keep the system balance. This method is referred to Demand Side Management (DSM) when it is first introduced.

With the implementation of DSM, electric utility noticed that large consumers, such as industry and commercial customers, can bring more significant demand reductions. Direct Load Control (DLC), one the most straight-forward DSM methods, is widely used since 1980s. Even though the DLC can fulfill the deduction task, it also brings inconvenience to customers. In order to reduce the inconvenience, many electric utilities introduced various types of improved DR programs which can be classified into two major groups according [17, 19]:

Group 1: Price-based demand response: Real-time pricing (RTP); Critical-peak pricing (CPP); Time-of-use (TOU) tariffs.

Group 2: Incentive-based demand response: Direct Load Control (DLC); Interruptible/curtail able service (I/C); Demand Bidding/Buy Back; Emergency Demand Response Program (EDRP); Capacity Market Program (CAP); Ancillary Service Markets (A/S);

Siemens has introduced its DR approach called Surgical Demand Response (Surgical DR). Different from traditional DR, the Surgical DR is flexible in load aggregation, which can be defined by substation, feeder line, zip code, map interface or several other associations [20]. California Independent System Operator (CAISO) implements Day-Of DR programs which are initiated by DR providers and are triggered based on various conditions such as forecasted temperature, day-ahead forecasted demand and high price forecasts [21]. Economic DR, a price-based DR, is introduced by PJM [22]. Emergency demand response programs (EDRP) are adopted by many utilities and ISOs. For example, the PJM has two kinds of EDRP: Energy-Only and Full Emergency [23]. Both of these programs require 100 KW as the minimum reduction and 2 hours of interruption duration. On the other hand, both types need at least 2 hours for the advance notification. Similarly, NYISO's EDRP also requires 2 hours for advance notification [24].

In addition to the real-world DR implementation, advances in this field can be seen in many publications. In [23, 24], authors introduce DR to alleviate the stress condition of electric power systems brought about by EV charging. In [25], DR is used to manage variability of renewable energy sources. Authors in [26, 27] mention implementation of DR to shave the peak demand to reduce electricity bills. In [28, 29], DR is considered as interruptible loads to improve the security of the grid. DR can also be used as system reserves for ancillary services [30-33]. Authors in [34] examine the automation of residential loads for participation in DR.

2.3.3 Potential of Demand Response

Both the FERC's National Assessment of Demand Response Potential [35] and Electric Power Research Institute's (EPRI) reports [36] gave estimations about the nationwide DR potential in the next ten years.

In the December of 2014, FERC issued a staff report [37]. In the report, annual resource contributions of demand resources from retail demand response programs, as well as Regional Transmission Operator (RTO)'s and Independent System Operator (ISO)'s demand response programs on a national and regional basis in 2011 through 2013 are summarized. According to the data collected by U.S. Energy Information Administration (EIA), the total U.S. potential peak reduction from retail demand response programs increased by 1,907 MW between 2011 and 2012 (7.2 percent). Demand response programs within the Western Electricity Coordinating Council (WECC) accounted for 1,253 MW of potential peak reduction or nearly two-thirds (65.7 percent) of the increase in the U.S. total.

2.4 Mathematical Decision-Making: An Overview of the Analytic Hierarchy Process

An electric power system, especially a smart grid, is a complex system. In order to help utilities make faster and better choices, an efficiency decision-making technology is needed.

Both Analytic Hierarchy Process (AHP) and Principal Components Analysis (PCA) are commonly used multi-criteria decision-making techniques [38]. The primary difference is - PCA reduces the number of principal components by orthogonal transformation [39], while AHP uses orthogonal transformation to judge related weights of principal components.

The AHP is defined as "a basic approach to decision making. It is designed to cope with both the rational and intuitive to select the best from a number of alternatives evaluated with respect to several criteria." [40]. Figure 2-1 shows a typical hierarchy for AHP.

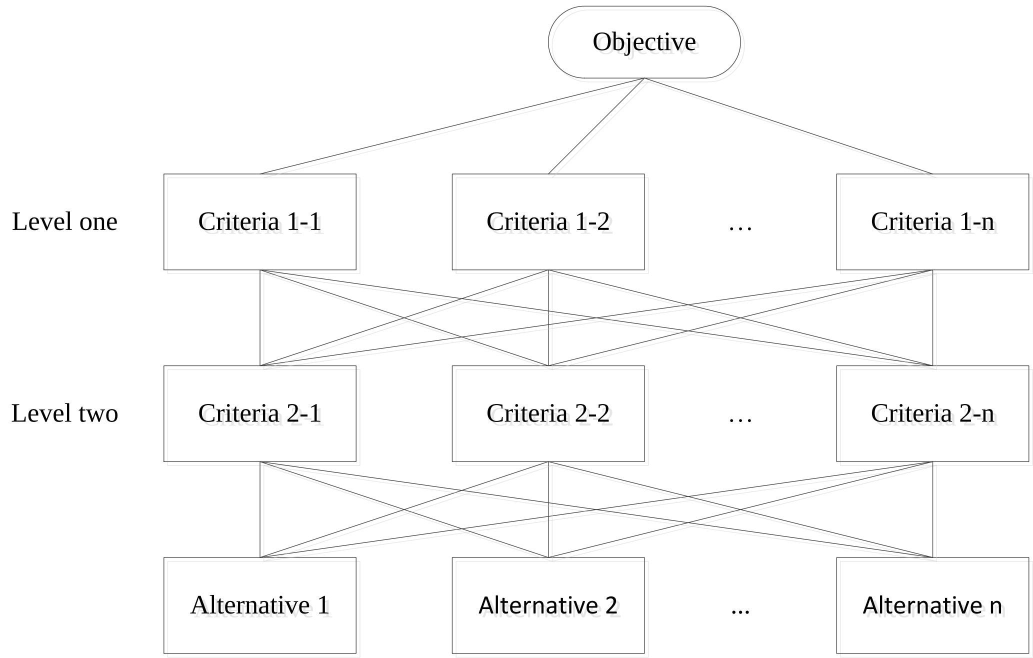


Figure 2-1. Typical AHP structure

Since AHP is an efficient decision-making algorithm, it is being used in many areas for evaluation, resource allocation, forecasting, decision making and so on [41]. Following are some examples of AHP applications.

Authors in [42] present a unified power quality index using AHP, which can provide an overall assessment of distribution system performance. In [43], authors have used AHP to determine values of reactive power in an electric power system based on voltage sensitivity, voltage adequacy and voltage stability. AHP method is also used to evaluate the power system's failure rate and power quality [44, 45]. In [46], AHP is used to help decision-making about remote controllable switch allocation. In [47], AHP is used for assessing equipment health for substation maintenance and upgrade planning. Authors in [48] introduce a new short term load forecasting technique using pairwise comparisons.

2.5 Communication Networks for Smart Grid

In the smart grid, many intelligent features and functions can be achieved by incorporating two-way communications into the power system. The key to realizing smart grid features is to appropriately choose communication technologies and associated communication networks that provide bidirectional end-to-end data communications in the smart grid [3]. In this section, the communication network classification, communication media and technologies, as well as characteristics of communication networks are discussed.

2.5.1 Communication Network Classification

Communication networks in the smart grid - according to their coverage - can be divided into three types: wide area network (WAN), neighborhood area network (NAN) and the premises area network. The WAN is the network architecture at the utility side, while NAN is the bridge between WAN and premises area networks.

The premises area network is at the end-use customer premises. It can be categorized as a home area network (HAN), a building area network (BAN) or an industrial area network (IAN), depending on the environment, i.e., residential, business, or industrial. The premises network is the fundamental element in the smart grid communication network. It enables the automated demand response at customer promises and provides the communication access to appliances such as air conditioners (AC), water heaters and electric vehicles (EV). Home automation and building automation are two major applications. Design and implementation of an HEM system are discussed in [49, 50, 51]. In [52], authors show the hardware demonstration of an equivalent system in a laboratory environment, while authors in [53] present a set of algorithms for an HEM system.

NAN is located within the distribution system of the smart grid. Though the coverage area and data rate requirements for different NAN applications can vary depending on applications [54], the major aim of NAN is to support the information flow between WAN and a premises area network. Through the NAN, end-use customers can communicate with an electric utility company. NAN also enables the utility company to collect and send commands to field devices. Major smart grid applications in NAN are meter reading, pricing, DR and distribution automation.

WAN provides a backbone communication network for a smart grid. It provides an interface between NAN and the control center. Major smart grid applications in WAN include wide-area monitoring, control and protection applications, supervisory control and data acquisition (SCADA) and energy management systems (EMS).

2.5.2 Communication Media and Technologies

There are two types of communication media - wired and wireless. Low-cost infrastructures and ease of connection to unreachable areas are advantages of wireless communication media. On the other hand, wired communication media have mirror interference problems and no-battery issues [55]. Popular wired technologies include Ethernet, Power Line Communication (PLC) and fiber optic. Popular wireless communication technologies include ZigBee, Wi-Fi, cellular (4G, LTE, WiMAX), WLAN and RF mesh (900MHz). In this section, advantages and disadvantages of each communication technology are discussed.

Wired Communication Technology:

Ethernet, one of the most popular wired communication technologies, is commonly used in the short-range network such as local area networks (LANs). Ethernet standard is based on IEEE 802.3. Ethernet implementation requires cables, which can be coaxial, twisted-pair or fiber optic, as well as a hub or a network switch. Ethernet can provide data rates ranging from 10 Mbps to 100 Gbps. Since Ethernet is a wired network, it is noise immune. However, once the network is placed, it is difficult to make changes.

PLC uses exiting power lines to realize data transmission. PLC is promising for smart grid applications due to the availability of existing infrastructure. PLC is a good choice for many control applications including smart metering, home automation and others. It is especially suited for rural areas that have access to power but other communication infrastructures are not available. However, PLC faces several technical challenges, e.g., noisy channel, low-bandwidth and difficulty for signals to pass through power distribution devices. Another drawback of PLC is its security concerns.

With advantages of high data rate and immunity to noise, the fiber optic option has become a popular communication technology to provide backbone communications to support various smart grid applications. Fiber optic is best suited for a long distance network with limited number of access points. However, the high installation cost is its major drawback.

Wireless Communication Technology:

ZigBee is one of the communication protocols for personal area networks. It is based on the IEEE 802.15.4 standards, and used in the network that requires low data rate and long battery life. ZigBee has a defined data rate of 250 kbps which is suitable for periodic or intermittent data transmission. ZigBee is typically used in wireless switches and smart meters in a home area network (HAN), as well as other equipment that requires short-range wireless data transfer at relatively low rates. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other wireless premises area networks, such as Wi-Fi. ZigBee networks are secured by 128-bit symmetric encryption keys. A typical ZigBee transmission range can be up to 100 meters depending on power output and environmental characteristics. This distance can be extended up to 1,600 meters with ZigBee-Pro. The range of ZigBee pro is sufficient for AMI applications. Its data rate varies from 20kbps to 250kbps. Advantages of ZigBee include low power consumption, low implementation cost and provision of sufficient security. However, the low data processing capability, small memory size and easily being interrupted by other devices using same frequency bands are major drawbacks of ZigBee.

Wireless Local Area Network (WLAN), also known as Wi-Fi, is a kind of high-speed wireless network technology. It is based on the IEEE 802.11 series of standards and operates on 2.4GHz, 3.6GHz and 5GHz bands. WLAN can provide reliable secure and high-speed communications. However, its implementation cost and power consumption are relatively higher than other short-range technologies, such as ZigBee. Access points are usually needed for setting up the network. Similar to ZigBee, the mesh topology is commonly used.

900 MHz band is unlicensed ISM (industrial, scientific and medical) Radio Frequency (RF)

bands. It does not need an individual license from telecommunication regulatory authorities. 900 MHz has a longer range (approximately two times) than what is possible at 2.4 GHz. In addition, the mesh protocol is generally implemented for the 900 MHz technology. As a result, it inherits mesh network properties, which are self-healing, high reliability and cost effective with wide coverage range. These properties are suitable for deployment in both urban and suburban areas. The RF (900 MHz) mesh network is a good choice for an AMI mesh network connecting smart meters. On the other hand, similar to all other networks using mesh protocol, 900 MHz has several drawbacks, e.g., high bandwidth consumption, lack of interoperability and privacy protection issues as well as latency.

An existing cellular (4G, LTE and WiMAX) network is a good option for setting up an AMI system, especially to support data communications between concentrators and the control center. If the cellular network infrastructure exists, there is no extra time and cost for a utility to set up the network to support smart grid applications. Furthermore, the security of cellular network is very strong. However, a possible drawback includes sharing cellular networks with other customers, which can result in network congestion in certain emergency situations. Additionally, cellular networks may not provide a guaranteed service during abnormal situations, such as a wind storm. Among all cellular technologies, WiMAX is the most promising 4G wireless technology based on the IEEE 802.16 series of standards. Its data rate is up to 75 Mbps with the coverage distance of up to 50 km. WiMAX also provides low latency communications. These qualities make WiMAX a good candidate for smart grid applications. However, WiMAX requires high power consumption and it is relatively expensive to deploy.

2.5.3 Characteristics of Communication Network

Quality of Service (QoS) is considered to be the major factor in evaluating the performance of a network. It refers to the capability of a network to provide better service to selected network traffic over various technologies. The primary goal of QoS is to provide priority including dedicated bandwidth, controlled jitter and latency, and improved loss characteristics [56]. In this section, only latency and reliability are discussed.

Latency, also known as the end-to-end delay, refers to the time it takes for a message to be transmitted across a network from a source to a destination. Generally, it covers three kinds of delay: transmission delay, propagation delay and processing delay. The transmission delay is the amount of time required to push all packets into the channel. The propagation delay is the amount of time it takes for the signal to travel from a sender to a receiver. The processing delay is the amount of time it takes for a destination to receive all packets and store them in its storage/memory.

$$T_{\text{end-to-end}} = \sum (T_{\text{transmission}} + T_{\text{propagation}} + T_{\text{processing}}) \tag{2.4}$$

Reliability is the characteristic showing how reliable a communication system is when performing a data transfer. Reliability can simply be calculated as a ratio of bits of data received correctly to bits of data sent. The most reliable network is the one with 100% reliability. Radio

Frequency Interference (RFI) – the electronic noise produced by electrical and electronic devices, e.g., motors and personal computers – may affect the reliability of wireless communications. Since frequency ranges of these noises are between 10 kHz and 1 GHz [57], RFI on Wi-Fi and ZigBee operated at 2.4 GHz can thus be ignored.

2.5.4 Related Research and Projects on Communication Network

Many smart grid applications, e.g., home energy management (HEM), metering, demand response, etc., are discussed in [58, 59, 60, 61]. In [62], authors compare different communication technologies (i.e., fiber-optic, digital subscriber line (DSL), coaxial cable, power line carrier (PLC), ZigBee, Wi-Fi, Ethernet, etc.) and assess their suitability for deployment to serve various smart grid applications. In [55], authors provide a contemporary look at the current state of the art in smart grid communications as well as discuss the still-open research issues in this area. In [63], authors provide an overview of issues related to the smart grid architecture from the perspective of potential applications and the communications requirements needed to ensure performance, flexible operation, reliability and economics. In [64], authors present a ZigBee wireless sensor network simulation in OPNET, while, in [65], authors propose an energy efficient cluster tree architecture for home area network using ZigBee.

According to the U.S. Department of Energy's Smart Grid Investment Grant Program (SGIG), majority of the SGIG projects (65 out of 98) are categorized as Advanced Metering Infrastructure (AMI) [66]. These AMI projects aim at installation of smart meters to allow the use of real-time pricing, demand response, load management and more. It appears that out of many smart grid applications, AMI applications draw the most attention. This is due to AMI's promising potential. For example, AMI can be used to achieve the supervisory control and data acquisition (SCADA) based distribution automation [67]. AMI can also be used for demand side management [68], realizing transformer identification and phase identification [69], smart energy management [70] and can help implement distribution state estimation [71].

To fully realize benefits of AMI, it is necessary to appropriately choose communication technologies and associated communication networks that provide two-way communications. There are several previous studies that discuss AMI communication technologies and network structure [72-79]. Authors in [72] provide scalable distributed communication architectures to support AMI. In [73], a bi-directional communication protocol is introduced considering the effect of AMI environment. The discussion of ZigBee and Power Line Communication (PLC) technologies for AMI is presented in [74-76]. Authors in [77] show a heterogeneous WiMAX-WLAN network for AMI communications. A novel path-sharing scheme for AMI network is shown in [78]. Authors in [79] develop a multipath routing method for AMI networks in smart grid.

2.6 Cyber Security for Smart Grid

2.6.1 Definition of Cyber Security

Major concerns in the smart grid environment may include security threats, privacy issues, etc. Vulnerabilities may allow an attacker to penetrate a system, get access to a control center, and modify load conditions to destabilize a smart grid in unpredictable ways leading to serious results, for example, brownouts or catastrophic blackouts [80]. Among all concerns, cyber security is an important issue in the modern smart grid technology [81].

Cyber security is defined as a combination of both hardware and software designed to protect networks, computer programs and data from attack, damage or unauthorized access. In a smart grid system, cyber security must be addressed in terms of both deliberate attacks from dissatisfied employees, industrial spies, and terrorists, and unintended compromises of the cyber infrastructure due to user errors, equipment failure, and natural disasters) [82].

2.6.2 Real Cyber Security Incidents

In January 2003, the Davis-Besse nuclear power plant in Ohio's monitoring system was disabled by the Slammer worm [83]. The nuclear plant's network was infected by a contractor's computer which was connected via a telephone dial-up directly to the plant network. The nuclear plant was shut down and repaired for nearly five hours [84].

In March 2007, the U.S. Department of Energy's Idaho National Laboratory produced a real evidence of targeted cyber-attack within the "Aurora" project [85].

In March 2008, the Hatch nuclear power plant near Baxley, Georgia was forced to shut down for 48 hours after an updated computer which reset the data on the control system [86].

In July 2010, the Siemens SIMATIC WinCC supervisory control and data acquisition (SCADA) system was attacked by the Stuxnet worm. The Iranian government reported that the Bushehr nuclear power plant has been attacked by Stuxnet [87].

2.6.3 Smart Grid Security Objectives and Cyber Attacks Classification

The cyber security working group in the NIST smart grid interoperability panel has released a comprehensive guideline for smart grid cyber security and three high-level smart grid security objectives as summarized below [88].

- Availability: Ensuring timely and reliable access to and use of information is of the most importance in the smart grid.
- Integrity: Guarding against improper information modification or destruction is to ensure information nonrepudiation and authenticity.

- Confidentiality: Preserving authorized restrictions on information access and disclosure is mainly to protect personal privacy and proprietary information.

Sources of security attacks can be classified into two types, which are misbehaving users and malicious users. Selfish misbehaving users are those attempting to obtain more network resources than legitimate users by violating communication protocols [89]. On the other hand, malicious users are those who aim to illegally acquire, modify or disrupt information in the network. According to smart grid's security objectives, cyberattacks in a smart grid are classified into three types [90]: (1) attacks targeting availability, also called denial-of-service (DoS) attacks, is an attempt to delay, block or corrupt the communication in the smart grid; (2) attacks targeting integrity aim at deliberately and illegally modifying or disrupting data exchange in the smart grid; and (3) attacks targeting confidentiality intend to acquire unauthorized information from network resources in the smart grid.

2.6.4 Cyber Security Standards

"Smart Grid Cyber Security" [91] chooses a European electrical grid stability scenarios as reference to define security levels [92]. See Table 2-1.

Table 2-1. Smart Grid Security Level

Security Level	European Grid Stability Scenario Security Level Examples
5 – Highly Critical	Assets whose disruption could lead to a power loss above 10 GW; Pan-European incident
4 – Critical	Assets whose disruption could lead to a power loss from above 1 GW to 10 GW; European/country incident
3 – High	Assets whose disruption could lead to a power loss from above 100 MW to 1 GW; Country/regional incident
2 – Medium	Assets whose disruption could lead to a power loss from 1 MW to 100 MW; Regional/town incident
1 - Low	Assets whose disruption could lead to a power loss under 1 MW; Town/neighborhood incident

2.6.5 Objectives and Requirements of Cyber Security in Smart Grid

Since a smart grid has three high-level cyber security objectives which are availability, integrity and confidentiality, cyber security technologies used in a smart grid should meet the following requirements [90].

Attack detection and resilience operations: the smart grid is a relatively open communication network over large geographical areas. Therefore, the communication network needs to consistently perform profiling, testing and comparison to monitor network traffic status. Moreover, the network must also have the self-healing ability.

Identification, authentication and access control: the smart grid network infrastructure incorporates millions of electronic devices and users. Identification and authentication are key processes of verifying the identity of a device or user as a prerequisite for granting access to resources in the smart grid information system.

Secure and efficient communication protocols: message delivery in a smart grid requires both time-criticality and security in the smart grid. Since these two objectives contradict with each other, it is necessary to develop a method to balance requirements on both secure and efficient.

2.6.6 Popular Encryption Methods

Among many kinds of cyber security methods applied in smart grid applications, the data encryption is the most widely used. Encryption algorithm is a mathematical function used in the encryption and decryption process. A key is needed to encrypt and decrypt data.

In an encryption process, the information is protected with the supplied key. At the receiving end, the encrypted information is decrypted using a supplied key. The aim of an encryption method is to make the encrypted information as complex as possible, making it difficult to decipher. However, the complex encryption method may be time consuming to transmitted and decrypted.

Encryption methods can be classified into three types: hashing, symmetric cryptography and asymmetric cryptography. The hashing encryption creates a unique, fixed-length signature for a data set. Different from the hashing encryption method, both symmetric and asymmetric encryption methods rely on supplied keys. Symmetric cryptography, also called private-key cryptography, is the one of most traditional and secure encryption methods. In the symmetric encryption method, the same key is applied at both encryption and decryption processes. Besides, anyone who has the key can decryption coded messages. More secure than the symmetric encryption method, the asymmetric encryption method uses two different keys. The public key is used to encrypt messages and is available for everyone. At the decryption side, each receiver has a different private key to decrypt the coded messages.

Selected encryption methods are described below.

Digital Encryption Standard (DES): In 1977 the Data Encryption Standard (DES), a symmetric algorithm, was adopted in the United States as a federal standard. DES encrypts and decrypts data in 64-bit blocks, using a 56-bit key. It takes a 64-bit block as an input and the encrypted block is a 64-bit block. 16 rounds are usually used in DES to produce the coded message. And the number of rounds in DES is exponentially proportional to the amount of time required to hack the key to decrypt the coded message [93, 94]. For many years, the DES encryption method is widely applied since its easy application. However, in July 1998 a team of cryptographers cracked a DES-enciphered message in 3 days, and in 1999 a network of 10,000 desktop PCs cracked a DES-enciphered message in less than a day. [95]

Triple DES (3DES): Since DES can be vulnerable in some cases, the Triple DES (3DES) has emerged as a stronger method. Triple DES encrypts data three times and uses a different key for at least one of the three passes. The common key size will be 112-168 bits. As mentioned before, the amount of time to hack the key is exponentially proportional to the number of rounds. The 3DES is much stronger than (single) DES. Nonetheless, the 3DES is rather slow. [96, 97]

Advanced Encryption Standard (AES): AES is a symmetric key encryption technique. It is used to replace DES and 3DES. It was the result of a worldwide call for submissions of encryption algorithms issued by the US Government's National Institute of Standards and Technology (NIST) in 1997 and completed in 2000 [95]. Although the key of 128 bits is efficient, AES also uses keys of 192 and 256 bits for heavy-duty encryption purposes. AES is largely considered impervious to all attacks, with the exception of brute force, which attempts to decipher messages using all possible combinations in the 128, 192, or 256-bit cipher [98, 99, 100].

Blowfish encryption algorithm: Bruce Schneier designed the Blowfish (a symmetric encryption algorithm) in 1993. Blowfish has a 64-bit block size and a variable key length - from 32 bits to 448 bits. It is a 16-round Feistel cipher and uses large key-dependent S-boxes. [95] Blowfish generates large pseudo-random lookup tables by doing several encryptions to schedule choosing keys. It has been proven to be highly resistant against many attacks such as differential and linear cryptanalysis. The disadvantage of blowfish is that large memory space is occupied [101, 102, 103].

Rivest-Shamir-Adleman (RSA): Ron Rivest, Adi Shamir and Leonard Adleman designed RSA in 1978. [104] It is an asymmetric cryptosystem based on number theory, which is a block cipher system. Two prime numbers are used to generate the public and private keys which are used for encryption and decryption purpose. Operation of RSA can be decomposed into three major steps: key generation, encryption and decryption. The complication level of the RSA algorithm can be varied by using different prime numbers to create the public and private keys. [105, 106] The disadvantage of the RSA is this algorithm requiring similar lengths for two prime numbers which is very tough conditions to satisfy. Padding techniques are required in such cases increases the system’s overheads by taking more processing time. [107]

2.7 Conclusions and Knowledge Gaps

This section summarizes the literature search and identifies three major knowledge gaps, as follows:

2.7.1 A Novel Demand Curtailment Allocation Strategy Using AHP Method

To keep the balance between generation capacity and electrical demand, load curtailments through implementation of DR (due to high system peak demand) and load shedding based on UFLS (due to rapid system frequency declines) are applied in the current practice. DR is the first choice to alleviate power system stress conditions if there is enough time for advance notifications. Nonetheless, when the power system faces a sudden loss of large generators, failure of transmission lines or drop in renewable energy output, the grid frequency may decline so rapidly that UFLS is activated.

Much work has been done on designing, improving and implementing DR programs. While, as stated in Section 2.3, most previous work has focused on DR programs that are implemented at the end-use customer level. These kinds of DR programs are incentive-based, which provide utilities with some demand reduction during a grid stress condition. And all DR operations need a notification of at least 2 hours in advance. Besides, most of the DR strategies only focus on larger consumers, such as: commercial and industrial customers. In fact, the electric demand from residential consumers should not be neglected because they share a large percentage of total electricity consumption.

On the other hand, operation of UFLS needs to keep the frequency back to its allowable operating range rapidly. UFLS operation will cause large-scale load loss and this load shedding scheme always ignores customer convenience in order to meet the demand reduction amount rapidly.

There is definitely a need to develop a novel demand curtailment allocation strategy which can curtail end-use loads faster than traditional DR programs and also can prevent operation of UFLS. This novel demand curtailment allocation strategy to help utilities keep the balance between generation and demand relies on two major steps. First, the system level load curtailment amount (MW) needs to be determined in order to keep the balance between generation and customers. Then, this load curtailment amount needs to be allocated among DSs or feeders within the utility service area. The total amount of central demand curtailment (MW) can be estimated from the total available generation and forecasted electricity demand in the service area. However, the distribution of this curtailment among DSs is a complex problem. It needs to involve both expert opinions (i.e., importance of customers in different time periods) and objective parameters of DSs (i.e., loading ratio, capacity, and amount of interruptible, deferrable and critical loads). It is one of the objectives of this dissertation to introduce an expert-based demand curtailment allocation approach using the AHP method. The proposed method can be used to determine appropriate load curtailment amounts (MW) for different DSs. This is based on DSs’ loading condition, load classification, customer type, and their importance.

2.7.2 Evaluate the Capability of Proposed Demand Curtailment Strategy with Integrated Communication Network

The operation of the proposed demand curtailment strategy takes into account the DR potential and the load curtailment priority of each group of end-use customers. These factors are calculated using the information measured from customers. The proposed demand curtailment method needs to operate rapidly to avoid operation of UFLS, and its operation highly relies on the performance of the communication network.

Capability of communication technologies and network are widely evaluated in many papers which are discussed in Section 2.5. Since smart grid networks, especially the WAN and NAN, are typically shared with many kinds of smart grid applications, operations of other smart grid applications may impact the speed at which the proposed demand curtailment strategy can take action. Therefore, it is necessary to evaluate the capability of communication technologies in such situations.

In this dissertation, popular communication technologies for NAN and WAN are evaluated to understand their latency, throughput, reliability, etc. The performance of the proposed demand curtailment strategy is evaluated considering the background traffic generated based on popular smart grid applications that share the same network. These applications include distribution automation, pricing application, metering application and electric vehicles application. Characteristics of each smart grid application, such as data package size, data sampling frequency, latency and reliability requirements is considered when modeling the application.

Popular communication technologies for the premise area network are evaluated to understand their latency, throughput, reliability, etc. The performance of the proposed demand curtailment strategy is within a premise area network by applying energy management system.

2.7.3 Analyze the Limitation of Using Cyber Security Technologies based on Encryption Methods in Deploying the Proposed Demand Curtailment Allocation Approach

Many cyber security technologies have been implemented into smart grid’s communication networks in order to protect customer privacy and to keep smart grid from being attacked. Nonetheless, the additional processing time and encryption bytes added to smart grid data negate operation of smart grid applications, especially, by applying strict cyber security standards. On the other hand, some smart grid applications are strict with operation speed. As a result, it is necessary to analyze the limitation of using encryption methods in deploying the proposed curtailment allocation approach.

In this dissertation, the limitation of using cyber security technologies based on different encryption methods on the proposed curtailment allocation approach is analyzed. The capability of encryption methods, e.g., 3EDS (Triple Data Encryption Standard), AES (Advanced Encryption Standard), Blowfish, etc. is compared taking into account of extra data rates and the processing time. Implementing encryption methods on the proposed demand curtailment allocation approach is simulated. And then, the limitation brought by applying different encryption methods to secure the demand curtailment allocation approach is analyzed.

3. An Expert-based Strategy for Electrical Demand Curtailment Allocation

The aim of this chapter is to discuss the proposed expert-based approach for electrical demand curtailment allocation. This is to address the knowledge gap summarized in Section 2.7.1.

In this chapter, the methodology of an expert-based demand curtailment allocation strategy using AHP method is first introduced. Based on opinions from experts, the proposed approach allows an electric utility to prioritize and allocate their demand curtailment at the distribution substation based on importance of customers and type of loads. To allow the implementation of the proposed approach, an automated load curtailment platform, e.g., home energy management (HEM) or building energy management (BEM) systems can be used to enable automated DR features. With an HEM or a BEM system, loads can be shed/deferred according to their priority based on customer preferences. This chapter assumes ideal transmission and distribution systems by neglecting losses and transmission congestions. It is also assumed that all distribution substations involved in the demand curtailment allocation approach are grouped by geographic locations.

Then, two case studies are presented, following the methodology. The first case study shows the demand curtailment allocation from a transmission substation to distribution substations. And the second case study shows the demand curtailment allocation from a distribution substation to feeders.

3.1 Algorithm for Demand Curtailment Allocation Strategy

3.1.1 Definition of Customer Type and Load Classification

Customer Type:

Different types of customers usually have different load patterns which makes customer type a very important factor. In general, customers are classified into the following major categories based on their load patterns: residential, industrial, offices, education, mercantile (e.g., shopping malls and small retails), food (e.g., restaurants, grocery stores), 24hr operation (e.g., health care centers, police stations and fire departments) and others. This section considers residential and commercial (especially office buildings) customers for demand curtailment allocation because of the following reasons: (1) These customers have higher flexibility to adjust their loads in responding to curtailment requests; and (2) Consumption patterns of these two load types can be easily distinguished from each other. This allows effective analysis of simulation results. If a finer classification of load types is desired, that can easily be done using the same process mentioned here.

Note that each customer may have on-site distributed energy sources, including renewable energy sources and energy storage. Such energy sources could be used to partially or fully meet the curtailment request. The analysis presented in this chapter can also be applied to a stand-alone microgrid which may be stressed due to high load and limited supply.

Load Classification:

This part categorizes residential/commercial loads into deferrable, interruptible and critical loads:

Deferrable loads are those that can be deferred from peak hours and can be deployed any time during off-peak hours.

Interruptible loads are those that can be interrupted momentarily. Load compensation may be necessary as soon as a DR event ends.

Critical loads are those that are non-deferrable and non-interruptible.

For residential customers, power-intensive electrical loads in home are air conditioners (AC), water heaters, clothes dryers and electric vehicles (EV). EV and clothes dryers are considered as deferrable loads; AC and water heaters are classified as interruptible loads; and all others are critical loads. In this chapter, major loads in typical commercial buildings include: cooling, ventilation, lighting and other loads (e.g., computers, printers, etc.). For this customer type, cooling loads are considered interruptible; and all others (ventilation, lighting and others) are considered critical. There is no deferrable load in this case.

3.1.2 **Demand Curtailment Allocation Algorithm**

The flowchart of the proposed algorithm is shown in Figure 3-1.

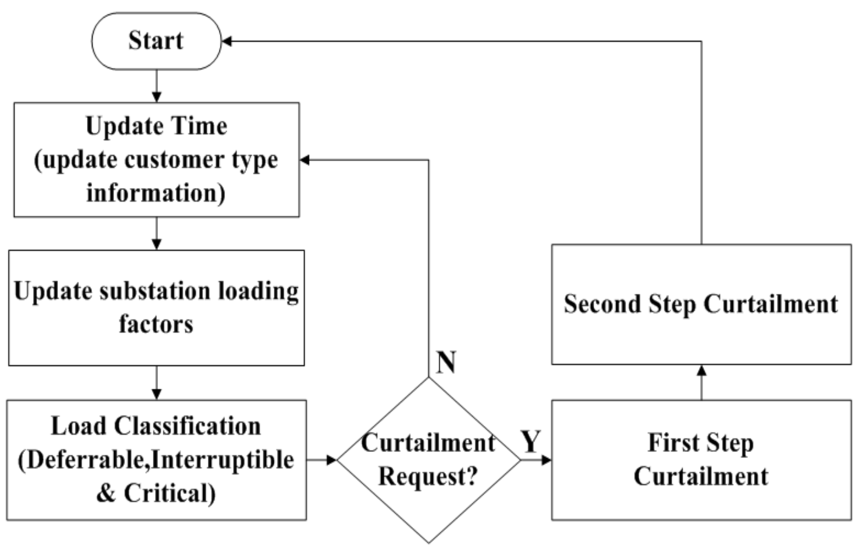
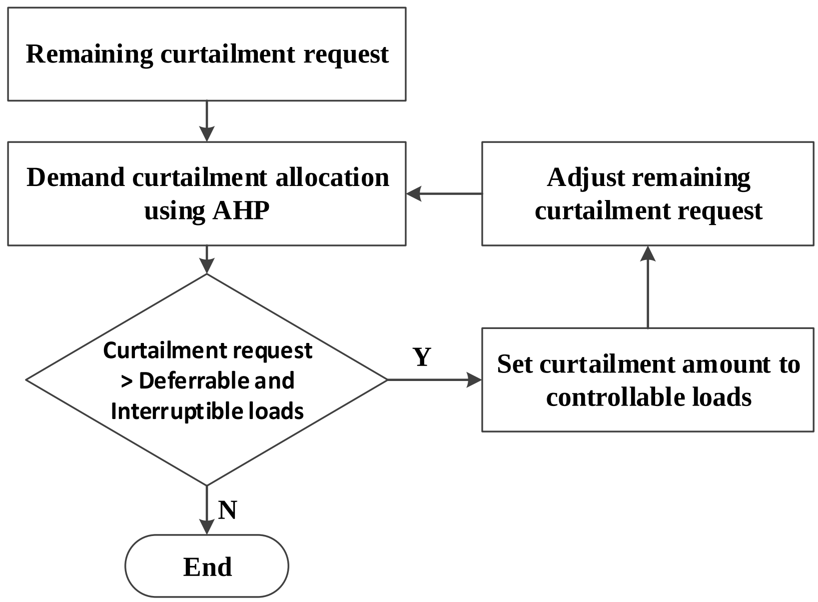


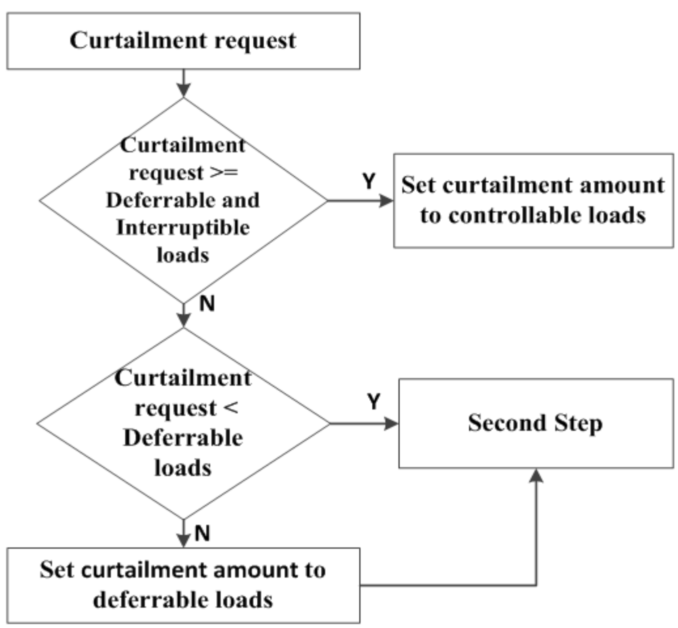
Figure 3-1. Flowchart of the proposed demand curtailment allocation algorithm

The proposed algorithm starts by updating information at each DS every fixed time intervals, e.g., 15 minutes. The information to be updated includes: DS capacity, load (MW) by category (i.e., residential/commercial), load (MW) by classification (i.e., deferrable/interruptible/critical) and forecasted loading level of each DS. It is assumed that a demand curtailment request (MW) is sent from an ISO/RTO and crosschecked. Once a curtailment request is received, the first-step curtailment process as shown in Figure 3-2 (a) is initiated.

The process starts by comparing the requested demand curtailment amount (MW) with the total amount of all deferrable and interruptible loads in the curtailment-requested service area, which can span multiple DSs. If the requested amount is equal or larger than the sum of deferrable and interruptible loads, all deferrable and interruptible loads will be curtailed first, and the balance will come from demand response at the customer level.



(a) First-step curtailment



(b) Second-step curtailment

Figure 3-2. Two Steps of Curtailment

The second-step curtailment process as shown in Figure 3-2 (b) will be initiated: (1) to manage the remaining curtailment requested amount; or (2) to manage the original curtailment requested amount that is less than deferrable loads. This step is to allocate the (remaining) requested demand curtailment amount among different DSs based on their curtailment priority factor, which is determined using 3-level AHP as discussed in the next section. Outcomes of AHP are curtailment allocation to each DS in the same service area. According to Figure 3-2 (b), if the curtailment amount allocated to a particular DS is larger than its sum of deferrable and interruptible loads, the curtailment contribution of that particular DS will be set equal to its sum of deferrable and interruptible loads; and the remaining amount will be reallocated to other DSs.

3.1.3 Determination of Curtailment Priority Factor using AHP

In this chapter, a 3-level AHP method is proposed to determine-the curtailment percentage of each DS. The structure of AHP is shown in Figure 3-3. Decision criteria have three levels as explained below.

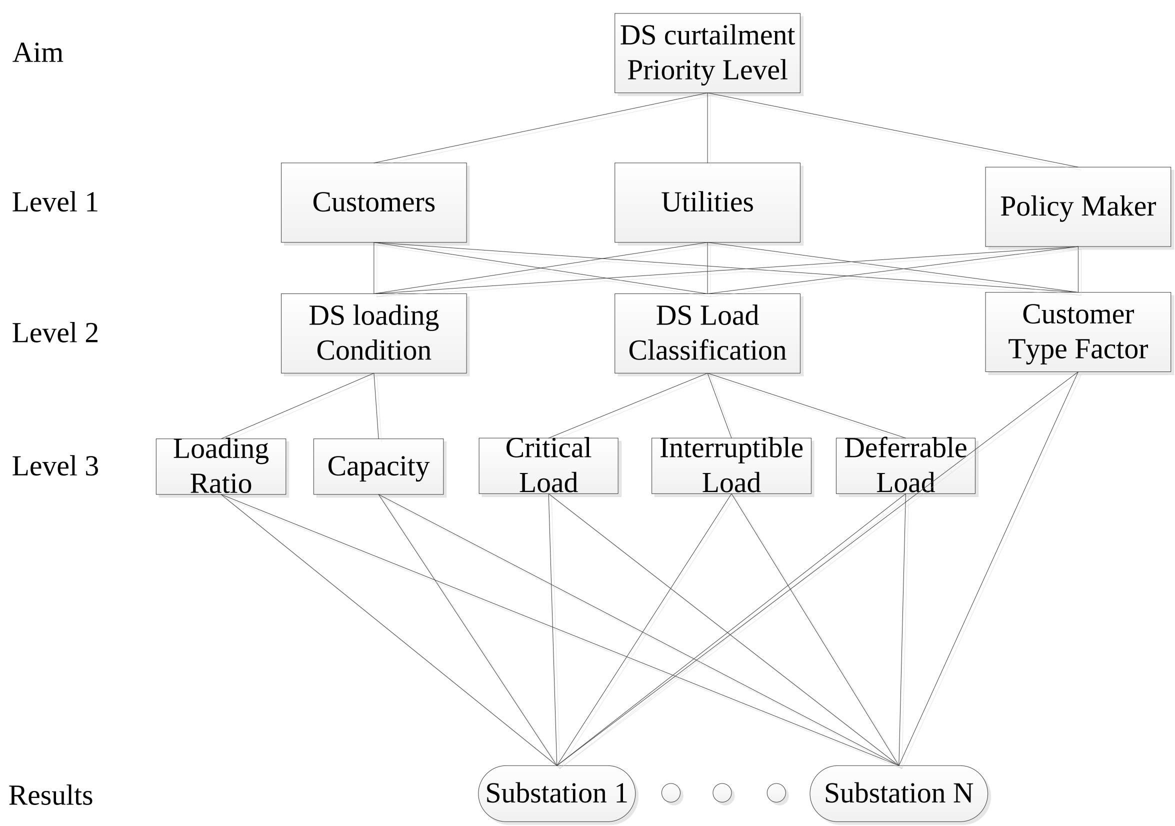


Figure 3-3. Three-level AHP structure

The **1st-level criteria** involve three different groups of experts' judgments, representing weight of their opinions. The experts in this section: customer relation department, system operators/dispatchers, and utility commission staff. Note that in using the AHP method, relative importance – as given by various experts – is used as opposed to their absolute judgments. Thus, the unlikely off-scale remark by one expert will not skew results.

The **2nd-level criteria** are criteria related to each DS, including DS loading condition, load classification and customer type factor.

The **3rd-level** criteria expand the above criteria as follows:

(i) DS loading condition includes DS loading ratio and its capacity. The DS loading ratio is calculated using Eq. (3.1).

$$\text{DS loading ratio} = \frac{\text{DS load (MW)}}{\text{DS capacity (MW)}} \qquad (3.1)$$

(ii) DS load classification is as explained in Section 3.1.1, including deferrable, interruptible and critical loads.

To determine DS load by load classification, Eq. (3.2)-(3.4) show how to calculate the amount of deferrable, interruptible and critical loads in every time step, respectively.

$$\text{Deferrable load} = \sum(\mathrm{L_{it}} * \mathrm{DP_{it}}) \qquad (\mathrm{i} = 1, 2) \qquad (3.2)$$

$$\text{Interruptible load} = \sum(\mathrm{L_{it}} * \mathrm{IP_{it}}) \qquad (\mathrm{i} = 1, 2) \qquad (3.3)$$

$$\text{Critical load} = \sum(\mathrm{L_{it}} * \mathrm{CP_{it}}) \qquad (\mathrm{i} = 1, 2) \qquad (3.4)$$

Where,

L_{it} : Total load (MW) of customer type i, time t;

DP_{it} : Deferrable load percentage;

IP_{it} : Interruptible load percentage;

CP_{it} : Critical load percentage;

i : 1 – residential customers; 2 – commercial customers.

(iii) Customer type factor (CTF) is used to present the importance of DS's customers in different time periods. DS's customer type factor is determined using Eq. (3.5).

$$\text{DS customer type factor} = \sum_{\mathrm{i}=1}^{2}(\mathrm{P_{it}} * \mathrm{I_{it}}) \qquad (3.5)$$

Where,

P_{it} : load percentage of customer i in time interval t;

I_{it} : Important level of customer i in time interval t;

i : 1 – residential customers; 2 – commercial customers.

The important level (I_{it}) is further explained in Section 5.3(c).

1) DS curtailment priority factor

The DS curtailment priority factor is determined using Eq. (3.6). Where, W is DS criteria weight (a 1xn matrix, n is the number of criteria being considered); and F is DS criteria factor (an mxn matrix, m is the number of DS). The method to determine W and F are explained below.

$$\text{DS curtailment priority factor} = [W_{1xn}] * [F_{m*n}]^T \qquad (3.6)$$

2) DS criteria weights (W)

DS criteria weights (W) are used to show the importance levels of criteria. In this case, W is a matrix of size 1x6, representing six criteria namely (i.e., loading ratio, DS capacity, critical load, deferrable load, interruptible load and customer type factor). This can be obtained by calculating weights of each level of criteria in AHP (Figure 3-3) according to the following steps [64]: Firstly, a pairwise comparison matrix is generated for each criterion based on Saaty's levels [104]. For example, 1 as equal importance; 3 as moderate importance of one over another; 5 as essential or strong importance; 7 as demonstrated importance; and 9 as extreme importance; and 2,4,6,8 are intermediate values between the two adjacent judgments. Secondly, a pair-wise comparison table is created and a judgment matrix J is derived for each criterion. Thirdly, the Eigenvector corresponding to the maximum Eigenvalue of J is calculated. This Eigenvector reflects priority levels of elements in matrix J [104]. Finally, Eigenvectors are normalized by making the sum of all normalized Eigenvectors equal to 1.

The normalized Eigenvector for the 1st-level criteria directly serves as the weight for each criterion i in level one ($W_{1i} = [W_{11}, W_{12}, W_{13}]$). Then, weight for each criterion j in level two ($W_{2j} = [W_{21}, W_{22}, W_{23}]$) can be obtained by multiplying the level-1 weight (W_{1i}) with the normalized Eigenvector associated with each criterion j in level two with respect to criterion i in level one (A_{ij}). See Eq. (3.7).

$$W_{2j} = \text{normalized}\left(W_{1i} * A_{ij}\right) \qquad (3.7)$$

By repeating above steps for each level, the overall weight matrix can be obtained. This is the DS criteria weight (W).

3) DS criteria factors (F)

To calculate F, a table with actual data of all six criteria of each DS (i.e., loading ratio, DS capacity, critical load, deferrable load, interruptible load and customer type factor) must be obtained. For each criterion, a pair-wise comparison matrix is created. The Eigenvectors are calculated; and the resulting normalized Eigenvectors associated with the maximum Eigenvalue are taken as DS criteria factors for that particular criterion. Repeat the above steps to obtain DS criteria factors (F) for the rest of the criteria in order. By combining all DS criteria factors for all six criteria, the resulting matrix F of size 5x6 can be obtained.

3.2 Case Study (From a Transmission Substation to Distribution Substations)

In this section, a case study is presented to show how the proposed demand curtailment allocation strategy operates. Simulation results verify that the proposed demand curtailment allocation strategy can handle different amounts of load curtailment requests from a transmission substation to distribution substations, while satisfying both objective and subjective requirements using the AHP technique.

3.2.1 Description of Distribution Substations

In this study, it is assumed that a utility has its total loads in the area served by five DSs. The capacity and number of residential and commercial customers served by each DS is summarized in Table 3-1.

Table 3-1. Distribution Substation data

DS	Capacity (MW)	No. of Residential Customers	No. of Commercial Customers
1	252	18,698	1,206
2	262	20,132	1,294
3	271	21,499	1,377
4	280	22,873	1,461
5	290	24,336	1,550

Table 3-2. DS load by Customer Type at 15:00

DS	Total Load at 15:00	Residential load (MW)	Residential load (%)	Commercial load (MW)	Commercial load (%)
1	197.50	34.44	17.44	163.06	82.56
2	175.91	37.09	21.08	138.83	78.92
3	153.24	39.60	25.84	113.64	74.16
4	130.30	42.13	32.33	88.17	67.67
5	107.47	44.83	41.71	62.65	58.29

The data used in this case study are derived from distribution feeders in a service area of an electric utility in Virginia. The data are available every 15-minute intervals, and the day selected for the case study is a hot summer day in August. Table 3-2 shows an example of DSs' load (MW) by customer type at 15:00.

3.2.2 **Calculation of DS Criteria Weight (W)**

In order to calculate DS criteria weight, the following pairwise comparison matrices are constructed based on a survey. The whole AHP structure is shown in Section 3.1.

L_{11} represents pairwise comparison matrix of level-1 criteria, i.e., the level of relative importance of customer's, utility's and policy maker's opinions. In this case study, L_{11} implies that the customer's opinion is considered as the most important (marked as 5). This is followed by the policy maker's opinion (marked as 3) and the utility's opinion (marked as 1). The Eigenvector corresponding to the maximum Eigenvalue of L_{11} are [0.92; 0.15; 0.37].

$$L_{11} = \begin{bmatrix} 1 & 5 & 3 \\ \frac{1}{5} & 1 & \frac{1}{3} \\ \frac{1}{3} & 3 & 1 \end{bmatrix} \tag{3.8}$$

L_{21}, L_{22} and L_{23} are pairwise comparison matrices of level-2 criteria, which show customer's, utility's and policy maker's opinions respectively about the importance of DS loading condition, as compared to DS load classification and customer type factor. The Eigenvectors corresponding to the maximum Eigenvalues are [0.1; 0.39; 0.91], [0.92; 0.14; 0.36], [0.15; 0.37; 0.92].

$$L_{21} = \begin{bmatrix} 1 & \frac{1}{5} & \frac{1}{7} \\ 5 & 1 & \frac{1}{3} \\ 7 & 3 & 1 \end{bmatrix} L_{22} = \begin{bmatrix} 1 & 5 & 3 \\ \frac{1}{5} & 1 & \frac{1}{4} \\ \frac{1}{7} & 4 & 1 \end{bmatrix} L_{23} = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{5} \\ 3 & 1 & \frac{1}{3} \\ 5 & 3 & 1 \end{bmatrix} \tag{3.9}$$

L_{31} and L_{32} show the importance of DS loading ratio, as compared to DS capacity; and that of deferrable load, as compared to interruptible and critical loads, respectively. The Eigenvectors corresponding to the maximum Eigenvalues are [0.89; 0.45], [0.94; 0.31; 0.16].

$$L_{31} = \begin{bmatrix} 1 & 2 \\ \frac{1}{2} & 1 \end{bmatrix} L_{32} = \begin{bmatrix} 1 & 3 & 6 \\ \frac{1}{3} & 1 & 2 \\ \frac{1}{6} & \frac{1}{2} & 1 \end{bmatrix} \tag{3.10}$$

Based on the steps described in 3.1.2 C, and Eq. 3.7, the weights of each level can be calculated. The overall DS criteria weights are shown in Table 3-3.

Table 3-3. DS Criteria weight (W)

	Loading Ratio	Capacity	Deferrable	Interru-ptible	Critical	CTF
Weight	0.1822	0.0911	0.1270	0.0635	0.0212	0.5150

3.2.3 Calculation of DS Criteria Factor (F)

To calculate DS criteria factor (F), DS loading ratio, capacity, 3-level loads and customer type factor are needed.

1) Determination of Loading Ratio

An example of DS loading ratio at 15:00 as shown in Table 3-4 is calculated based on information from Table 3-1 and Table 3-2 using Eq. (3.1).

2) Determination of Load Classification

Load classification at 15:00 (also shown in Table 3-4) is calculated based on Eq. (3.2)-(3.4).

Table 3-4. DS loading Condition and Load Classification at 15:00

DS	Load (MW)	Capacity (MW)	Loading ratio	Deferrable (MW)	Interruptible (MW)	Critical (MW)
1	197.50	252	0.7837	1.95	58.70	136.85
2	175.91	262	0.6714	2.10	52.02	121.79
3	153.24	271	0.5655	2.24	45.01	105.99
4	130.30	280	0.4654	2.39	37.93	89.99
5	107.47	290	0.3706	2.54	30.87	74.06

Load percentage by classification (D_{Pit}, I_{Pit}, C_{Pit}) for residential and commercial customers by can be calculated from Figure 3-4 and Figure 3-5, respectively.

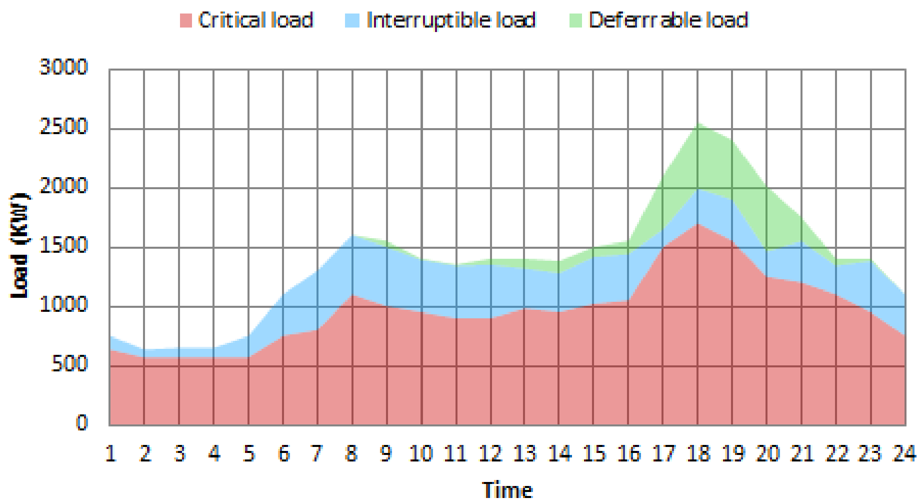


Figure 3-4. Load classification for 1000 residential houses in a 24-hour period

Figure 3-4 shows load classification (deferrable/interruptible/critical) for 1000 residential houses with 20% electric vehicle penetration on a summer day, generated based on the Monte Carlo simulation method presented in [106]. Simulated data are used in this case study mainly because data of household load profiles by load type is not easily obtainable in the literature; and the model in [106] has been validated with real-world data from an electric utility. For example, at 15:00, the three types of loads are 85.5 kW, 394.5 kW and 1020 kW; the percentages of all three types of loads are 5.7%, 26.3% and 68.0%.

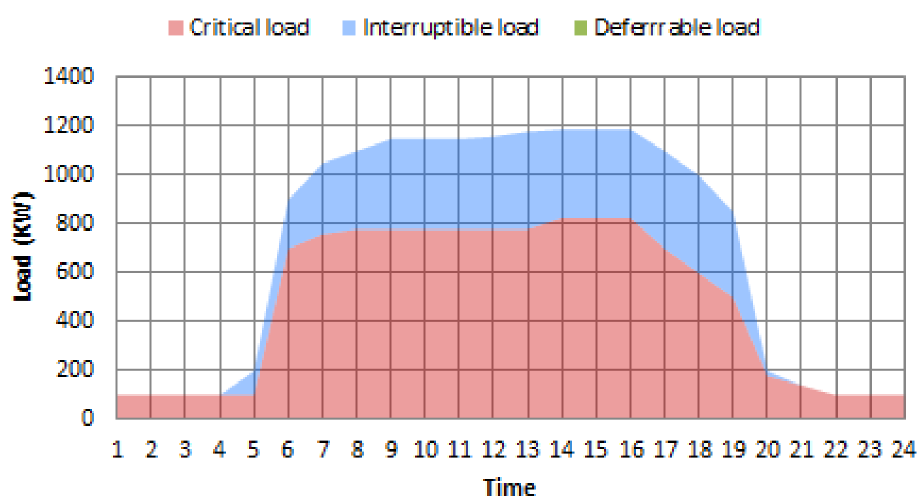


Figure 3-5. Load classification for a typical office building in a 24-hour period

Figure 3-5 shows load classification in a typical office building on a summer day. For example, at 15:00, the three types of loads are 0 kW, 362 kW and 828 kW the percentages of all three types of loads are 0%, 30.4% and 69.6%.

3) Determination of Customer Type Factor (CTF)

This factor presents DS importance level. A larger this factor implies a more important DS is, and its load curtailment is deferred till the end. CTF is calculated using Eq. (3.5). The load percentage of customer i ($P_{i,t}$) is shown in Table 3-2. Important level of customer i ($I_{i,t}$) is calculated using:

Step 1: In this study, a day is divided into six periods (0:00-6:00, 6:00-9:00, 9:00-11:00, 11:00-13:00, 13:00-17:00 and 17:00-24:00) to represent different activities of different types of customers (e.g., office, residential, and food (sales and services)).

Step 2: Create the pair-wise comparison matrix to compare importance of different customer types. Customer type has been discussed in Section 5.1 (A) (1). Table 3-5 shows an example of a pair-wise comparison matrix for the 13:00-17:00 period. As shown, during business hours, residential is less important than 24-hr operation, mercantile, industry, office and education. 24-hr operation (healthcare/safety department) is always the most important customer type.

Step 3: Calculate Eigenvalues of the pair-wise comparison matrix of interest; select the maximum Eigenvalue; calculate a group of Eigenvectors corresponding to the maximum Eigenvalue; and normalize the Eigenvectors. For the pair-wise comparison matrix as shown in Table 3-5, the maximum Eigenvalue is 7.1143; the corresponding normalized Eigenvectors are shown in the fifth column in Table 3-6. For each period, Steps 2 and 3 are repeated; and the overall customer type importance factors are shown in Table 3-6.

Since commercial (mainly office buildings) and residential customers are the only two customer types in the service area of interest, importance level of customer i from Table 3-6 is adjusted by scaling up the rate between commercial and residential customers and the sum of their importance levels factors should equal to one. Repeating the adjustment for each time period, the adjusted results are shown in Table 3-7. The result is reasonable since office building loads are more important than residential loads during business hours (09:00-17:00); and vice versa.

Table 3-5. Pair-wise comparisons matrix for 13:00-17:00 period

13:00-17:00	24-hr operat-ion	Food	Resid-ential	Merc-antile	Indust-ry	Office	Educa-tion
24-hr operation*	1	5	5	5	3	3	3
Food	1/5	1	1	1	1/3	1/3	1/3
Residential	1/5	1	1	1/2	1/3	1/3	1/3
Mercantile	1/5	1	2	1	1/3	1/3	1/3
Industry	1/3	3	3	3	1	1	1
Office	1/3	3	3	3	1	1	1
Education	1/3	3	3	3	1	1	1

* Healthcare/safety department

Table 3-6. Important level of customer i ($I_{i,t}$)

Customer i	Time Period					
	0-6	6-9	9-11	11-13	13-17	17-24
24hr operation	0.3557	0.3491	0.3437	0.3360	0.3666	0.3440
Food	0.1131	0.1636	0.0465	0.1388	0.0560	0.1540
Residential	0.2072	0.1636	0.0526	0.0544	0.0515	0.1540
Mercantile	0.0243	0.1636	0.0916	0.0544	0.0632	0.1540
Industry	0.1560	0.0773	0.1555	0.1388	0.1542	0.0902
Office	0.0718	0.0495	0.1555	0.1388	0.1542	0.0519
Education	0.0718	0.0332	0.1555	0.1388	0.1542	0.0519

Table 3-7. Adjusted Important level of customer i ($I_{i,t}$)

Customer i	Time Period					
	0-6	6-9	9-11	11-13	13-17	17-24
Residential	0.7427	0.7676	0.2526	0.2818	0.2504	0.7478
Office	0.2573	0.2324	0.7474	0.7182	0.7496	0.2522

Using Eq. (3.5) and the data in Table 3-6 and Table 3-7, the DS customer type factor is shown in Table 3-8.

Table 3-8. DS Customer Type Factor (CTF) at 15:00

	DS1	DS2	DS3	DS4	DS5
CTF	0.6625	0.6444	0.6206	0.5882	0.5414

DS criteria data are summarized in Table 3-9, based on information in Table 3-4 and Table 3-8.

Table 3-9. DS criteria data at 15:00

DS	Loading Ratio	Capacity (MW)	Deferrable load (MW)	Interruptible load (MW)	Critical load (MW)	CTF
1	0.7837	252	1.95	58.70	136.85	0.6625
2	0.6714	262	2.10	52.02	121.79	0.6444
3	0.5654	271	2.24	45.01	105.99	0.6206
4	0.4654	280	2.39	37.93	89.99	0.5882
5	0.3706	290	2.54	30.87	74.06	0.5414

The steps described in Section 3.1.2 (C) are followed to determine DS criteria factor (F), the result of which is shown in Table 3-10.

Table 3-10. DS criteria factors (F) at 15:00

DS	Loading Ratio	Capacity	Deferrable load	Interruptible load	Critical load	CTF
1	0.4185	0.0618	0.0618	0.5128	0.0333	0.0403
2	0.2625	0.0973	0.0973	0.2615	0.0634	0.0593
3	0.1599	0.1599	0.1599	0.1290	0.1290	0.1264
4	0.0973	0.2625	0.2625	0.0634	0.2615	0.2602
5	0.0618	0.4185	0.4185	0.0333	0.5128	0.5138

4) Determination of DS Curtailment Priority Factor

DS curtailment priority factor presents the ranking of DS when facing load curtailment requests. All deferrable and interruptible loads of DSs with higher curtailment priority factor will be curtailed prior to those of DSs with lower curtailment priority factor.

DS criteria weight (W) and DS criteria factor (F) are calculated as explained in Section 3.1.3 (B) and Section 3.1.3 (C). Using data from Table 3-3 and Table 3-10, and Eq. (3.6), DS curtailment priority factor is shown in Table 3-11.

Table 3-11. DS curtailment priority factor at 15:00

DS	Curtailment priority factor	Rank
1	0.1438	3
2	0.1175	5
3	0.1400	4
4	0.2186	2
5	0.3801	1

From Table 3-11, it is easy to tell, DS 5 makes the largest contribution when a demand curtailment request is received. This result is reasonable since DS 5 has the most residential customers which are less important than commercial customers during business hours. Though DS 1 has the least number of residential customers, its highest loading ratio increases its priority factor.

3.2.4 Results and Discussion

This section presents cases when a curtailment is requested in a single time slot, i.e., at 15:00; and when curtailment request is imposed for an extended period of time, i.e., from 14:00 to 19:00. Note that this section assumes that each customer unit is equipped with an HEM or a BEM system that enables automated demand curtailment functions. This makes the response time almost immediate.

1) Curtailment Request at 15:00

Assuming that the curtailment request is required to be initiated in a service area which contains five DSs at 15:00; and the curtailment amount is assumed to vary from 5% to 25% of the total load of all DSs. Figure 3-6 shows that with different amounts of load curtailment request, five DSs made different percentages of contribution.

Figure 3-7 shows the curtailment amount (MW) at 15:00 from each DS. Note that the AHP-based demand curtailment allocation approach presented in this section curtails only deferrable or interruptible loads. Critical loads are not curtailed. In cases with 5% and 10% curtailment requests, no curtailment request is larger than the sum of deferrable and interruptible loads of any DSs. As a result, DS 5, which contains the most residential loads (See Table 3-2), which are less important than commercial loads at 15:00 (See Table 3-7), makes the highest load curtailment contribution. The results are deemed correct.

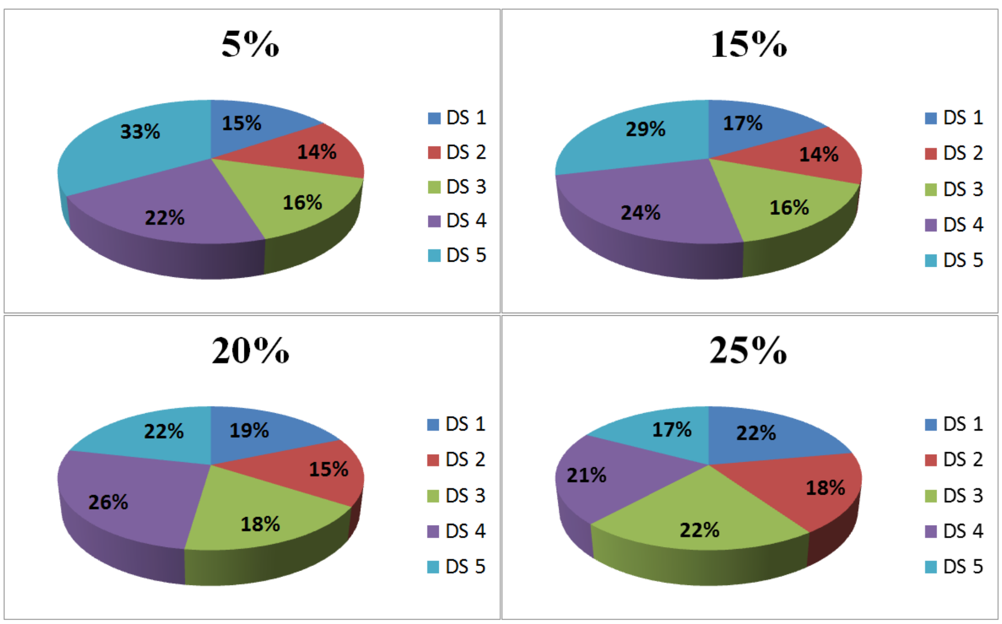


Figure 3-6. Percentage of contribution to selected curtailment requests (5%, 15%, 20% and 25% of the total load) by different DSs

When a curtailment request is higher than the total amount of deferrable and interruptible load of a DS, only this amount of loads will be curtailed. This is considered as the curtailment limit of a DS. Then, the remaining request will be re-allocated to other DSs. In this case, as DS 5 reaches its curtailment limit at 15% curtailment request, its curtailment contribution remains the same in all higher curtailment requests (e.g., 20% and 25%). The remaining amount is then re-allocated to other four DSs. Since DS 4 holds the second rank in the DS curtailment priority factor Table 3-11., it makes the highest load curtailment contribution of the remaining request. At the 20% curtailment request, DS 4 also reaches its curtailment limit and all deferrable and interruptible loads are curtailed. In this case, the other DSs assume the remaining curtailment.

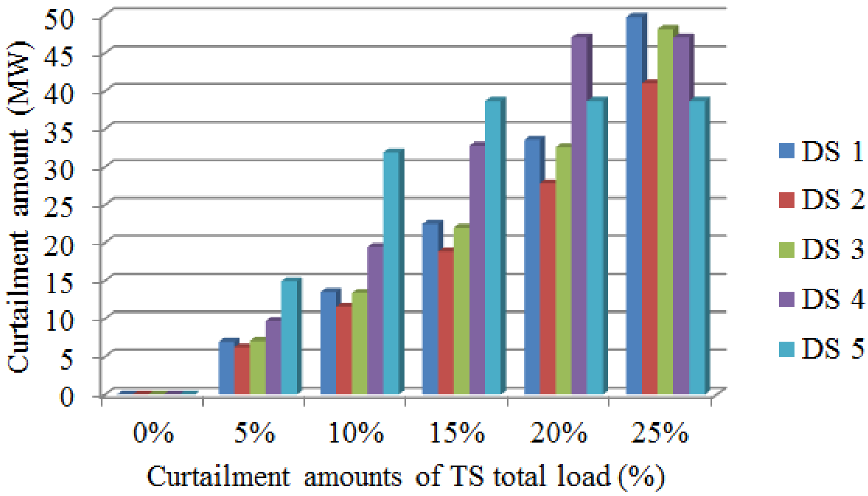


Figure 3-7. DS curtailment amount (MW) at 15:00

2) Curtailment Request from 14:00 to 19:00

In the previous case, the proposed DR allocation algorithm is evaluated in a single time slot. In this case, the curtailment request lasts from 14:00 to 19:00. The curtailment request is assumed to be varied from 5% to 25% of the total load of all DSs (step size is 5%). The demand curtailment allocation is performed in 15-minute intervals based on current load monitoring frequency in many US electric utilities for the purpose of determining demand charge. This duration can be adjusted based on real-world DR implementation if necessary.

A) Comparison of demand curtailment allocation during business and non-business hours

Simulation results at 14:15 and 17:15 are shown in Figure 3-8 and Figure 3-9, respectively. In each figure, X-axis shows different percentage of curtailment requests. Y-axis shows the curtailment amount (MW) from each DS.

When curtailment request is less than or equal to DSs' curtailment limits, DS 5 makes the highest contribution to the curtailment request among all DSs (e.g., 5% and 10% curtailment requests at 14:15 as shown in Figure 3-8). This is because DS 5 has the highest residential loads (See Table 3-2), and residential loads are less important than commercial loads during business hours (See Table 3-7). During non-business hours, i.e., at 17:15, the contribution from DS 1 is the highest. The result is reasonable since it has the highest commercial load and loading ratio. Once a curtailment request is larger than the curtailment limit of a particular DS, i.e., 15%-25%, the curtailment contribution from that DS is set equal to its curtailment limit. And, the remaining curtailment request is re-allocated among other DSs.

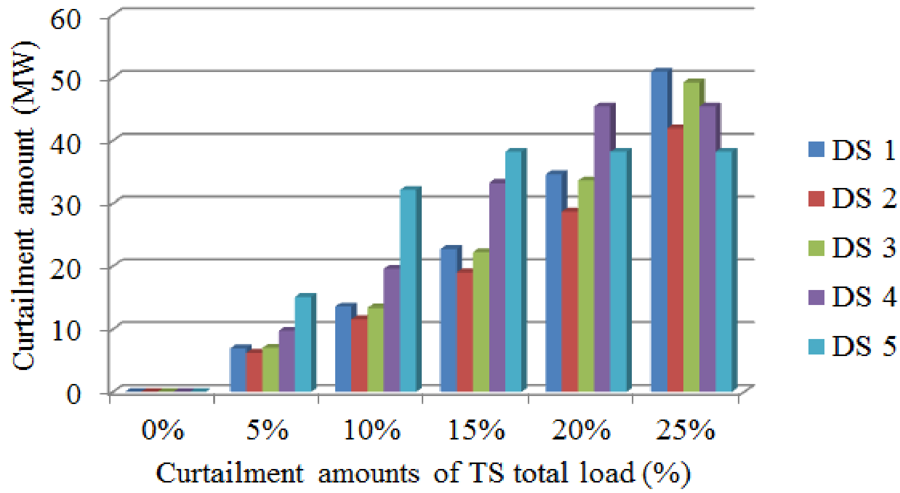


Figure 3-8. DS curtailment amount (MW) at 14:15

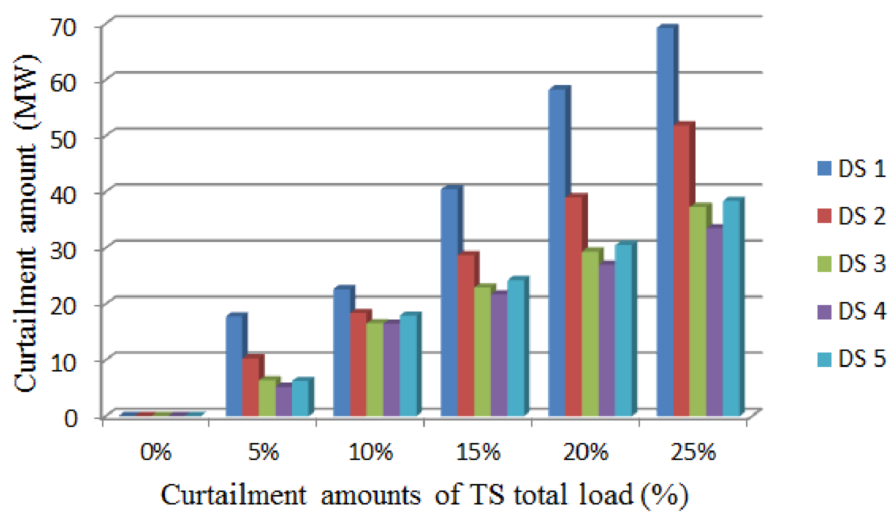


Figure 3-9. DS curtailment amount (MW) at 17:15

B) Demand curtailment allocation with different curtailment request amounts from 14:00 to 19:00

Simulation results at 5% and 25% curtailment requests are representative and shown in Figure 3-10 and Figure 3-11, respectively.

At low curtailment requests (e.g., 5% as shown in Figure 3-10), results indicate that the curtailment amount of DS 5 reduces during non-business hours as compared to that during business hours; while the curtailment amount of DS 1 increases. This is mainly because of the customer type served by DSs (See Table 3-2). The breakpoint is at 17:00 when changing from business hours to non-business hours.

When curtailment requests reach curtailment limits of any DSs: For example, at the 25% curtailment request, DS 5 reaches it curtailment limit from 14:00 to 19:00 which is shown in **Figure 3-11**, thus its curtailment contribution remains comparable from 14:00 to 19:00.

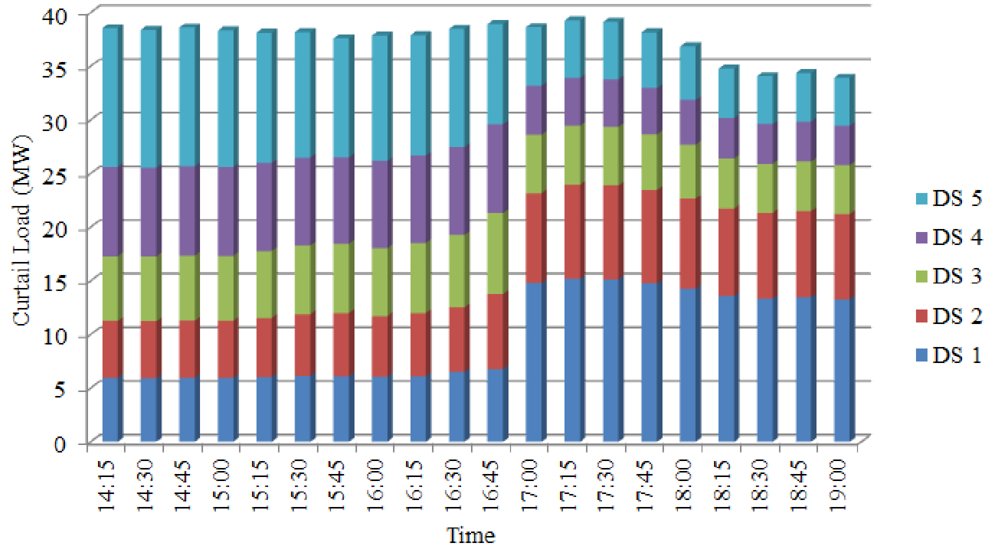


Figure 3-10. DS curtailment amount (MW) at 5% curtailment request

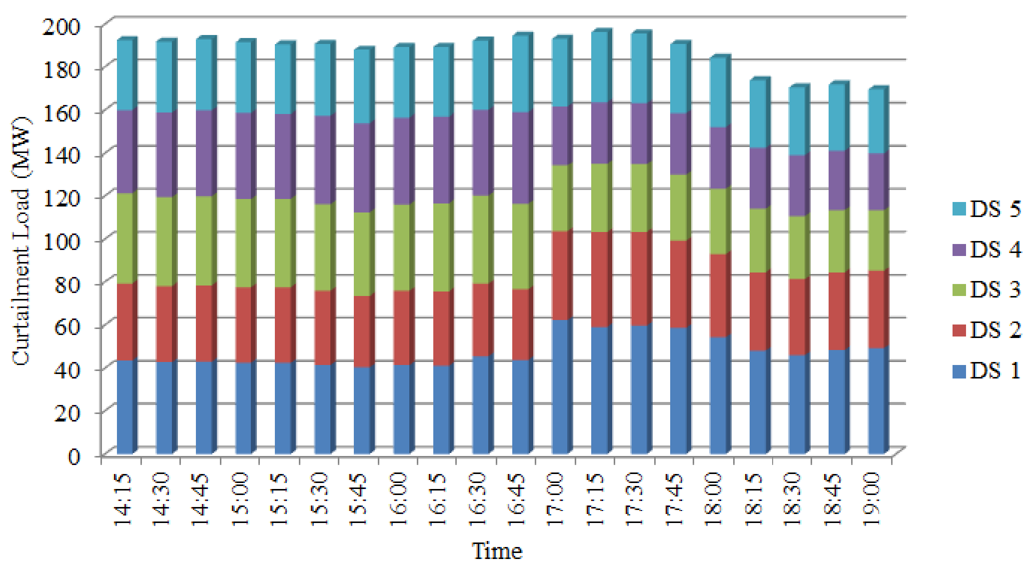


Figure 3-11. DS curtailment amount (MW) at 25% curtailment request

3.3 Case Study (From a Distribution Substation to Feeders)

In this section, a case study will be added to show how the proposed demand curtailment allocation strategy allocates the demand curtailment from a distribution substation to feeders.

This detailed work will be added in the final dissertation document.

3.4 Summary

This chapter introduces a novel expert-based strategy using the AHP method to keep the balance between supply and demand in case of temporary supply shortage. The proposed strategy aims to function rapidly enough to avoid the operation of ULFS. This strategy can keep the system frequency within its allowable operating range, which can be beneficial for a utility to prioritize their demand curtailment allocations in its service area. The proposed approach takes into account the DR potential (according to different load classifications) and load curtailment priority (using an AHP method) of each distribution substation (DS). AHP criteria contains DS loading ratio, DS capacity, load type (deferrable, interruptible and critical), and customer type (residential and commercial). Results of case studies verify that the proposed demand curtailment allocation approach can handle different amounts of load curtailment requests, while satisfying both objective and subjective requirements using the AHP technique.

4. EVALUATE THE CAPABILITY OF COMMUNICATION NETWORKS FOR THE PROPOSED DEMAND CURTAILMENT ALLOCATION STRATEGY

The aim of this chapter is to address the knowledge gap discussed in Section 2.7.2. In Chapter 3, the methodology for the proposed demand curtailment allocation strategy is presented. Results of case studies proof the proposed strategy can realize the demand curtailment allocation which is necessary to keep the balance between supply and demand as expected.

Nevertheless, the proposed strategy requires two-way communications between the control center and end-use customers, that is, it needs data from end-use customers to make a decision; and once the decision is made, the decision needs to be communicated to end-use customers. Three major steps are necessary to achieve this two-way communications. First of all, the information from end-use customers collected by smart meters is sent to local data concentrators. Then, local data concentrators forward the information to base stations. Lastly, base stations package the information and send to the control center. The decision from the control center is sent to end-use customers in a reverse direction. To realize this two-way communications, three layers of smart grid communication networks (WAN-wide area network, NAN-neighborhood area network and premise area network) are necessary. While WAN facilitates information exchange between the control center and base stations, NAN allows information exchange between base stations and end-use customers through local data concentrators and the premise area network helps to control smart appliances within the smart home/buildings.

Among different smart grid infrastructures, the advanced metering infrastructure (AMI) enables the operation of the proposed demand curtailment allocation strategy, as it covers both WAN and NAN and includes necessary building blocks, such as base stations, local data concentrators, etc. Therefore, the communication network supporting AMI applications is used as a basis to simulate the implementation of the proposed approach.

Within a smart home/building, HEM (home energy management) system is widely used to enable automated demand response applications at the customer premise. An HEM can provide the homeowner/building operator the ability to automatically perform smart load controls based on utility signals, as well as customer's preference and load priority. In this chapter, the HEM is generally introduced and simulated to evaluate the performance of the communication technologies and networks for the proposed approach.

In this chapter, the implementation of the proposed demand curtailment strategy is simulated in OPNET to proof that the proposed strategy can be realized in the case of a temporary supply shortage, such as a sudden loss of large renewable energy sources. This is accomplished by:

(1) Within WAN and NAN:

a) Discussing possible options for communication network structures and communication technologies that can support the operation of the proposed demand curtailment allocation strategy within WAN and NAN;

b) Summarizing characteristics of smart grid applications which share the same communication network with the proposed demand curtailment allocation strategy;

c) Presenting case studies to evaluate the performance of the proposed strategy when characteristics of communication network with background traffic from other smart grid applications are taken into account.

(2) Within premise area network: presenting case studies to evaluate the performance of the network for the proposed strategy within premise area network.

4.1 Communication Networks for the Proposed Demand Curtailment Allocation Strategy within WAN and NAN

The smart grid operation is highly dependent on its underlining two-way communication networks. In this section, two communication network structures for implementing smart grid applications are compared. And then, potential communication technologies to support the proposed demand curtailment allocation strategy are discussed.

4.1.1 Network Components and Structures

Since the proposed demand curtailment allocation strategy is mainly implemented in NAN and WAN, this section discusses network components and structures that support its implementation.

Network Components:

Network components that support smart grid applications, such as metering, pricing, demand response, the proposed demand curtailment strategy, are:

A **smart meter** is a digital meter that can be used to record consumption of electric power and transfer consumption information to a utility. It is also used to receive commands or price signals from a utility.

Field devices are devices that allow remote control from a central location to accomplish selected smart grid applications, such as distribution automation. Common field devices include remote controllable voltage regulator, remote controllable capacitor bank, switch, etc.

Data Concentrator is a combination of software and hardware unit that collects information from smart meters, and forwards the information to the utility. Data concentrators are popularly used in densely-populated areas.

Control center is responsible for supervising power system operation. For example, it automates data collection process from smart meters; evaluates the quality of the data; generates estimates where errors and gaps exist; and broadcasts the price information or DR and DA event commands.

Base Station communicates wirelessly with smart meters and field devices – using fiber optic, and connects directly with the control center.

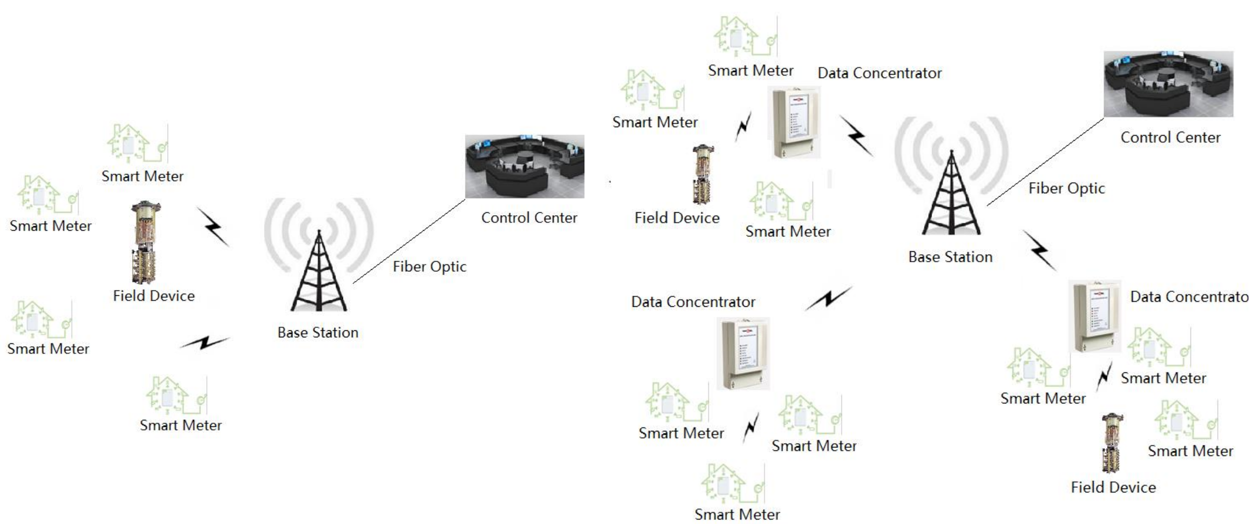
Network Structures:

A communication network provides channels to exchange information between end-use customers and a utility. As discussed earlier that the proposed approach will rely on the existing communication network supporting the AMI application, therefore the AMI network structure is discussed in details in this section.

The network as shown in Figure 4-1 illustrates two possible communication network structures that support the AMI application: without data concentrators and with data concentrators. In the first scenario (Figure 4-1(a)), smart meters and field devices are connected to the control center through the base station directly. The base station forwards all data and information between the control center and smart meters/field devices. The advantage of this kind of network is its simplicity to set up. However, numbers of smart meters and field devices are limited by the ability to access the base station.

In the second scenario (Figure 4-1(b)), a group of smart meters and field devices are connected to one data concentrator, and then all data concentrators are connected to the control center through the base station. This scenario increases numbers of smart meters and field devices which can be connected to one base station. However, the system is more complex and the operation latency is longer.

Considering that the demand curtailment allocation strategy will be implemented with a large number of end-use customers, the second communication network structure is suggested to support this application.



a. Communication network structure without data concentrator

b. Communication network structure with data concentrators

Figure 4-1. Communication networks supporting smart grid applications

4.1.2 Communication Technologies

This section presents potential communication technologies that can be deployed to support the proposed demand curtailment allocation strategy within WAN and NAN. A survey of communication schemes deployed in real-world AMI projects is presented. Then potential communication technologies are suggested. Firstly, potential technologies supporting the communication between data concentrators and the control center are discussed: hybrid fiber optic-WiMAX or hybrid fiber optic-LTE. Then, a commonly used technology that supports the communication between smart meters and data concentrators is discussed based on the radio frequency (RF) mesh network.

Survey of Communication Schemes Deployed in Real-World AMI Projects:

Advanced metering infrastructure (AMI) refers to a measurement and collection system that includes smart meters, communication networks, and data management systems that make the information available to the service provider. In general, AMI is deployed to enable a utility to collect real-time consumption information, and enable end-use customers to be informed about real-time pricing information. The AMI communication network is generally classified into two layers: the smart meter network connecting smart meters, data concentrators and base station; and the backhaul network connecting base stations and a control center.

The smart meter network is a lower-layer network in an AMI communication infrastructure and it has two sub-layers: from smart meters to data concentrators and from data concentrators to base stations. A mesh network is typically used to collect consumption information from end-use customers to data concentrators. A star protocol network is used to connect data concentrators and base stations. The smart meter network also helps to distribute commands/price signals among smart meters. Main network requirements are its cost effectiveness and reliability. The backhaul network consists of base stations and a control center. The control center is the node which manages the whole AMI system. The base station is used to collect consumption data from data concentrators. It is also used to transmit information and receive commands from the control center. Main requirements of the backhaul network are high reliability and low latency.

With the deployment of smart grids, there are more than 100 AMI projects around the world. Table 4-1 summarizes information of selected AMI projects including the number of smart meters and communication technologies deployed to support AMI applications. In this dissertation, these AMI projects are classified into three groups based on the number of smart meters: small-scale (<10K meters); medium-scale (10K-1M meters); and large-scale (>1M meters) projects.

From Table 4-11 it can be seen that fiber optic and WiMAX/LTE are the most popular communication technologies for the AMI backbone network. Between the two choices, the fiber optic option has an advantage over the WiMAX/LTE option in that it can provide higher bandwidth. This is because the bandwidth needs to be shared with other customers in the same cellular network. Furthermore, the fiber optic technology can provide higher reliability level than 4G/LTE during inclement weather conditions.

To support communications for smart meter networks, the 900 MHz mesh network appears to be the most popular technology choice. This is because it has good reliability and flexibility performance. In addition, the implementation cost of 900 MHz mesh network is relatively inexpensive as it can rely on an existing infrastructure. However, 900 MHz mesh has several drawbacks for AMI implementation. The major one is that the RF mesh network consumes high network bandwidth. This makes the RF mesh network facing a hard time to deal with fast increasing number of end-use customers. On the other hand, WiMAX and LTE, with its high reliability, fast data rate and relative large coverage, have emerged as another promising solution for the smart metering network. WiMAX and LTE can serve a large number of customers when WiMAX/LTE base stations and data concentrators are deployed.

Table 4-1. Selected Real-world AMI Deployments

Size	**Utility and State**	**Number of meters**	**Backhaul network**				**Smart meter network**			
			Fiber	**WiMAX, LTE**	**PLC**	**RF 900 MHz**	**ZigBee**	**900 RF**	**PLC**	**WiMAX, LTE**
Small scale	Madison Gas and Electric Company, WI	4,355		X						X
	EUGENE WATER & ELECTRIC BOARD, IL	4,855	X					X		
	Knoxville Utilities Board, TN	3,393		X				X		
	City of Anaheim, CA	7,765	X	X		X			X	
	FirstEnergy, OH	5,033		X				X		
Medium scale	Black Hills Power, SD	68,980		X				X		
	Burbank Water and Power, CA	52,257	X							
	City of Leesburg, FL	16,683	X							X
	Woodruff Electric Cooperative, AR	14,450							X	
	IBM, WA	30,722	X		X			X		
	Black Hills Corporation/Colorado Electric, CO	44,920		X				X		
	Central Lincoln People's Utility District, OR	38,551	X					X		
	Cheyenne Light, Fuel and Power Company, WY	39,102		X				X		
	City of Glendale, CA	85,582	X			X		X		
	City of Ruston, LA	10,596	X					X		
	City of Wadsworth, OH	12,575	X					X		
	Connecticut Municipal Electric Energy, CT	23,449	X					X		
	Detroit Edison Company, MA	688,717		X				X		
	Electric Power Board of Chattanooga, TN and GA	170,000	X				X	X	X	X
	Idaho Power Company, ID	380,928		X					X	
	Indianapolis Power & Light Company, IN	10,275				X		X		
	Lafayette Consolidated Government, LA	63,967	X				X	X		
	Lakeland Electric, FL	124,000				X		X		
Large scale	Florida Power & Light Company, FL	3 million	X	X	X			X		
	Baltimore Gas and Electric Company, MD	1,272,911		X				X	X	
	CenterPoint Energy Houston Electric, TX	2,130,737	X					X		X
	Duke Energy Business Services, NC	1.2 million	X	X	X		X	X	X	X

Potential Communication Technologies for Implementation of Smart Grid Applications

As a typical AMI network structure comprise two layers: a backbone network (in WAN) and a smart meter network (in NAN), based on the findings above: fiber optic is found to be commonly used to support a backbone network; either WiMAX or LTE are potentially used to support the connection between data concentrators and the control center; RF is used to set up the network for smart meters and data concentrators.

Communication Technologies for Backbone Network Simulation in OPNET

For the backbone network that provides communications between data concentrators and the control center, two communication technology schemes are simulated in OPNET.

a) Hybrid Fiber Optic-WiMAX Communication Scheme

The first scheme is the hybrid fiber optic-WiMAX communication scheme. As indicated in the survey, most of the real-world AMI projects deploy the fiber optic technology to serve as the backbone network connecting base stations and the control center; and WiMAX is deployed to support the connection between data concentrators and base stations. To simulate the network in OPNET, data concentrators are simulated by using subscriber stations (SSs); the BS block is used to simulate the base station; the control center is simulated by using a server station. A detailed case study simulated in the OPNET is discussed in Section 4.3.

b) Hybrid Fiber Optic-LTE Communication Scheme

The second scheme is the hybrid fiber optic-LTE communication scheme. Similar to the above case, the fiber optic is selected to serve as the backbone network connecting base stations and the control center. Instead of WiMAX, LTE is used to support the connection between data concentrators and base stations. To set up the simulation, data concentrators are simulated using LTE_work_stations; the base station are simulated using an LTE_enode and the control center is simulated using a server station. A detailed case study to be simulated in the OPNET is discussed in Section 4.3.

Communication Technologies for Smart Meter Network Simulation

For the smart network connecting smart meters and data concentrators, radio frequency (RF) technology is widely used in real world AMI projects. Therefore, the RF mesh network are used for setting up the smart meter network in this dissertation. The major consideration of the RF mesh network is its latency.

According to [116], the total delay of an n-hop routed path for one packet sent from one smart meter to the data concentrator can be calculated using Eq. (4.1).

$$\text{Delay} = \left[n * \left(p + \left(\frac{L}{\text{DataRate}}\right)\right)\right] + [(n-1) * \text{ProcDelay})] \quad (4.1)$$

Where,
n – the number of hops for one packet;
p – propagation delay;
L – is the length of the packet;
ProcDelay – is the time spent processing the packet before forwarding it.

According to [118], the 900 MHz RF network's data rate up to 13.5 Mbps. Besides, its coverage is around 25 miles. For each base station, it allows 300-1000 customers to access. As a result, the 900 MHz RF technology is used in this chapter.

$$T_{\text{latency}} = \sum (T_{\text{transmission}} + T_{\text{propagation}} + T_{\text{processing}})$$

To calculate the latency, it is assumed that the smart meter and data concentrator have the same access speed.

$$T_{\text{transmission}} = T_{\text{processing}}$$

$$= {\text{Package size} * \text{Number of Customers}}/{\text{Data Rate}}$$

To calculate the propagation delay, the distance between each access points and the base station is assumed to be Gaussian distribution. And the propagation speed of signal in free space is as same as the light which is 3*10^8 m/s.

$$T_{\text{propagation}} = \frac{\text{Distance}}{\text{Propagation Speed}} = \frac{D}{S}$$

4.2 Characteristics of Smart Grid Applications and the Smart Grid's Operation Statues

In Section 4.1, communication structures and technologies to realize the proposed demand curtailment allocation strategy are discussed. Nonetheless, the smart grid network, especially, the NAN and WAN are shared by many other smart grid applications. Furthermore, with the rapid development of smart grid, more and more novel smart grid applications are implemented using the same communication network.

Since many smart grid applications share the same communication network, and different smart grid applications have different characteristics, e.g., data size, data sampling frequency, latency and reliability requirements, it is necessary to ensure proper operation of all smart grid applications especially those sharing the same network.

In this section, characteristics of different smart grid applications are summarized, including those of metering, pricing, demand response and electric vehicle applications. Then, the smart grid's operation status is discussed.

4.2.1 Characteristics of Smart Grid Applications

1) Total Data Size and Data Sampling Frequency

Since different contents are exchanged for different smart grid applications, typical package sizes for different applications vary. Additionally, since applications operate in several frequencies, data sampling rates are different. The total data size for each application can be determined by multiplying the package size by its data sampling frequency.

2) Reliability Requirement

Due to characteristics of communication networks, e.g., the noise of communication channel, the communication traffic congestion, the package exchange has certain rates of data dropping. In order to operate smart grid applications properly, reliability requirement for each smart grid application is specified.

3) Latency Requirement

Similar to the reliability requirement, the operation of smart grid applications also requires the delay of information exchanging below a certain range. Too much time delay for the package exchange can cause the failure of an application.

4) Requirements of Smart Grid Applications

Characteristics of four smart grid applications being considered are summarized in Table 4-2. Two kinds of metering applications are considered: (1) on-demand meter reading and (2) meter reading with scheduled time intervals (15-minute or hours).

Table 4-2. Characteristics of selected smart grid application

	Package Size (bytes)	Data Sampling Frequency (time per day)	Latency (second)	Reliability (%)
DR	100	1 per event	< 60	>99.5
Pricing	100	2-6	< 60	>98
Metering (1)	100	As needed	< 15	>98
Metering (2)	1600 - 2400	4-6 per residential; 12-24 commercial	< 4 hours	>98
Electric Vehicle	100	2-4	< 15	>98

It is assumed that all applications in Table 4-2 are implemented on the AMI network. That is, demand response, pricing and EV control signals are assumed to be sent to end-use customers through smart meters.

4.2.2 Status of Smart Grid Operation

The smart grid involves many different applications, which may affect the status of power system operation. Typically, smart grid status can be classified into: Normal (N), Demand Response (DR), and Emergency (E).

The transition among these statuses is shown in Figure 4-2. When the grid is under stress conditions, DR is first implemented to alleviate such stress conditions given that time is sufficient for the advance notification and implementation of DR. This is called a DR event. After a DR event, the smart grid can recover to its normal status. Nonetheless, if DR programs cannot provide sufficient demand curtailment as requested, the system can be in an emergency situation where the under frequency load shedding (UFLS) is activate to keep the balance between electrical supply and demand. In another case, when facing the sudden loss of generation which may be caused by fluctuation in renewable energy output, the smart grid will need the operation of UFLS immediately in order to maintain the system frequency. In this case, the smart grid can turn into an emergency status from its normal status directly. After a UFLS event, the smart grid status can be changed back to either a DR event status or a normal status.

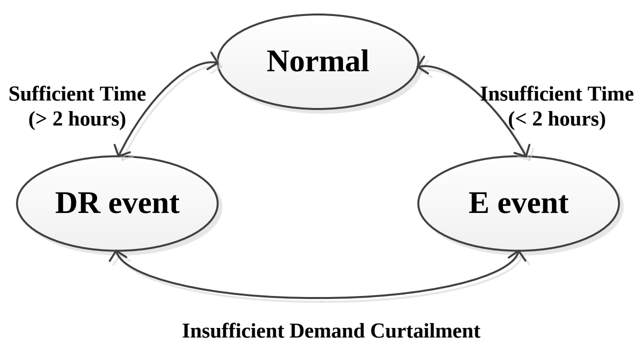


Figure 4-2. Status of Smart Grid Operation

Since a DR program requires at least two hours of advance notifications for end-use customers, the DR implementation is not a suitable means to mitigate sudden fluctuation in renewable energy sources. Neither should UFLS be used since applying UFLS will result in large-scale load loss. In this case, the proposed demand curtailment allocation strategy is involved to keep the balance between supply and demand.

In the proposed framework, the smart grid operation status is classified into: Normal (N), Demand Response (DR) event, Demand Curtailment Allocation Strategy (DC) event and Emergency (E) event. The transition among these statues is shown in Figure 4-3, where the DC event is inserted between the DR event and the emergency event. The demand curtailment allocation strategy will be activated when a DR program cannot fulfill the demand curtailment request. This can help avoid UFLS operation.

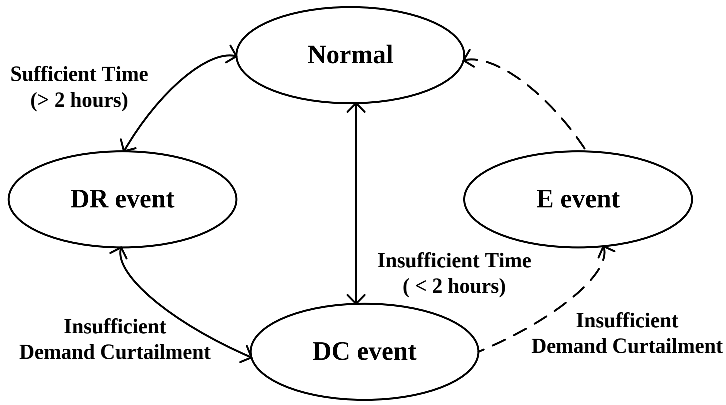


Figure 4-3. New Statuses of Smart Grid Operation

4.3 Case Studies for the Proposed Demand Curtailment Allocation Strategy within WAN and NAN

In Section 4.1, the communication network structure for the proposed demand curtailment allocation strategy within WAN and NAN is presented. And potential communication technologies for the network are suggested. Section 4.2 summarizes characteristics of different smart grid applications that share the same communication network. Smart grid operation status is also explained in Section 4.2. In this section, case studies are set up to simulate the operation of the proposed demand curtailment allocation strategy considering the impact of background traffic from other smart grid applications. Case studies are simulated in OPNET to analyze the operation of the proposed demand curtailment allocation strategy with operation of other smart grid applications.

4.3.1 A Reference Smart Grid Project

In this section, a reference project is introduced. Its information is used as a basis to determine the number of customers, smart meters, data concentrators and base stations required for case studies. For smart applications presented here, major components include smart meters, data concentrators, base stations and a control center. In order to realistically establish a case study, the density of smart meters in servicing area, as well as the ratio between data concentrators and base stations need to be designed based on a real-world smart grid project.

The CenterPoint Energy Houston Electric's Smart Grid Project [117, 118] was launched in Dec. 2011. WiMAX technology is one of the communication technologies used to support its smart meter network. The service area and number of devices are listed in **Table 4-3.** . The density of smart meter in servicing area is 440 meters per sq. mile. And, the ratio between the WiMAX tower and meter data collectors is 1:46. The ratio between the data collector and smart meters is 1:423.

Table 4-3. Detailed Information of the Smart Grid Project

	Reference Case
Servicing Area (sq. mile)	5,000
WiMAX Tower	112
Data Collector	5,200
Smart Meter	2.2 million

4.3.2 Case Study 1: Performance Analysis for the Proposed Demand Curtailment Approach in Communication Network (Hybrid fiber optic-WiMAX)

The hybrid version of fiber optic and WiMAX technologies is used as basis to simulate the communication traffic between data concentrators and the control center. Fiber optic is selected to serve as the backbone network. WiMAX is selected to support the part of the smart meter network which covers from data concentrators to base stations. The simulation is conducted in OPNET to evaluate the performance of the proposed demand curtailment approach in this communication network in terms of its latency and reliability.

Case Study 1 Description:

The service area of interest covers around 600 sq. miles of northern Virginia area which is shown in Figure 4-4. Based on the information from the real-world project discussed above, the number of smart meters in this serving area is assumed to be 264,000 meters.

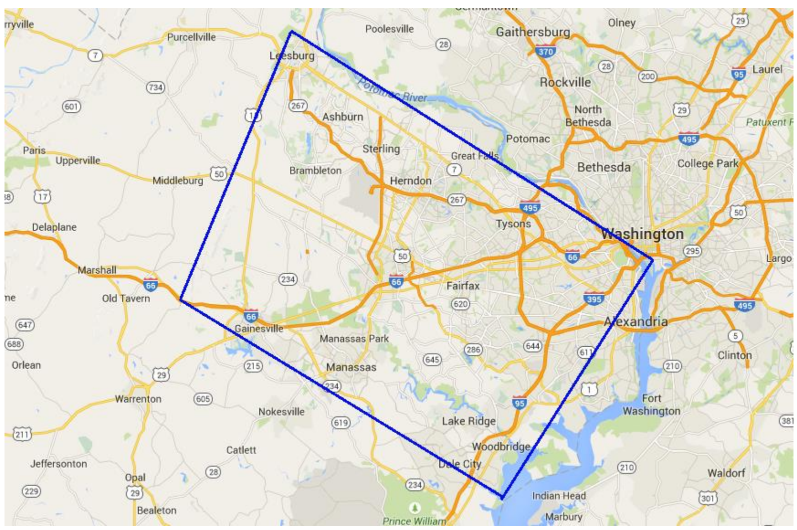


Figure 4-4. Northern Virginia Service Area

The WiMAX technology used in case study one is Wireless OFDMA (orthogonal frequency division multiplexing access) 20MHz. For this type of WiMAX, the base frequency is 5GHz and the bandwidth is 20MHz. The WiMAX technology provides two-way communications which are Uplink (UL) and Downlink (DL). In the case study, the UL transfers the information from smart meters to base stations; the DL transfers the information from base stations to smart meters.

In WiMAX technology, both UL and DL are split into multiple subcarriers with narrow bandwidth. There are four kinds of subcarriers assigned with different functions.

- Guard subcarrier provides "guard interval" which helps minimize the channel interference.
- Data subcarriers are used to transfer data.
- Pilot subcarriers are used for the synchronization.

- DC (direct current) subcarrier marks the center point of the channel.

The 20MHZ OFDMA WiMAX has 2,048 points of FFT (Fast Fourier Transform) which means it has 2,048 subcarriers in both UL and DL. The detailed classification of subcarriers is summarized in **Table 4-4.** .

Table 4-4. Classification of Subcarriers

	UL	DL
guard subcarrier from left	184	184
guard subcarrier from right	183	183
data subcarrier	1,120	1,440
pilot subcarrier	560	240
DC subcarrier	1	1
Total	2,048	2,048

The maximum transmission data rate R that can be achieved in WiMAX physical layer is defined in the IEEE 802.16 standard as Eq. 4.11.

$$R = \frac{N_{data} * b_m * c_r}{T_s} \qquad (4.\ 11)$$

N_{data} – Number of data subcarriers;
b_m – the number of bits per modulation symbol;
c_r – Is the coding rate of the modulation;
T_s – CP-OFDM symbol time;

In OPNET, the Ts is 100.8 microseconds; N_{data} is 1,120 for UL and 1,440 for DL for the 20 MHz OFDMA. The parameters b_m for QPSK, 16QAM and 64QAM are 2, 4 and 6. In this case, the 64QAM3/4 modulation method is used.

Simulation Results for Case Study 1:

To analyze the operation of the proposed demand curtailment allocation approach, the case study is set up in OPNET. Simulation results are presented and discussed below.

In the Northern Virginia service area, the size of the service area is 600 sq. miles and the number of smart meters is 264k. As stated above, the ratio between WiMAX tower and smart meters in the reference case is 112: 2.2 million. In case study one, 15 WiMAX towers are applied which can service up to 300k smart meters. Using Eq. 4.11, the radius of hexagonal area is calculated as 4 miles. In each WiMAX cell, there are 46 data concentrators and each data concentrator is connected with 423 smart meters. The scenario is shown as Figure 4-5.

$$\text{Area} = \frac{3}{2} * \sqrt{3} * r^2 \qquad (4.12)$$

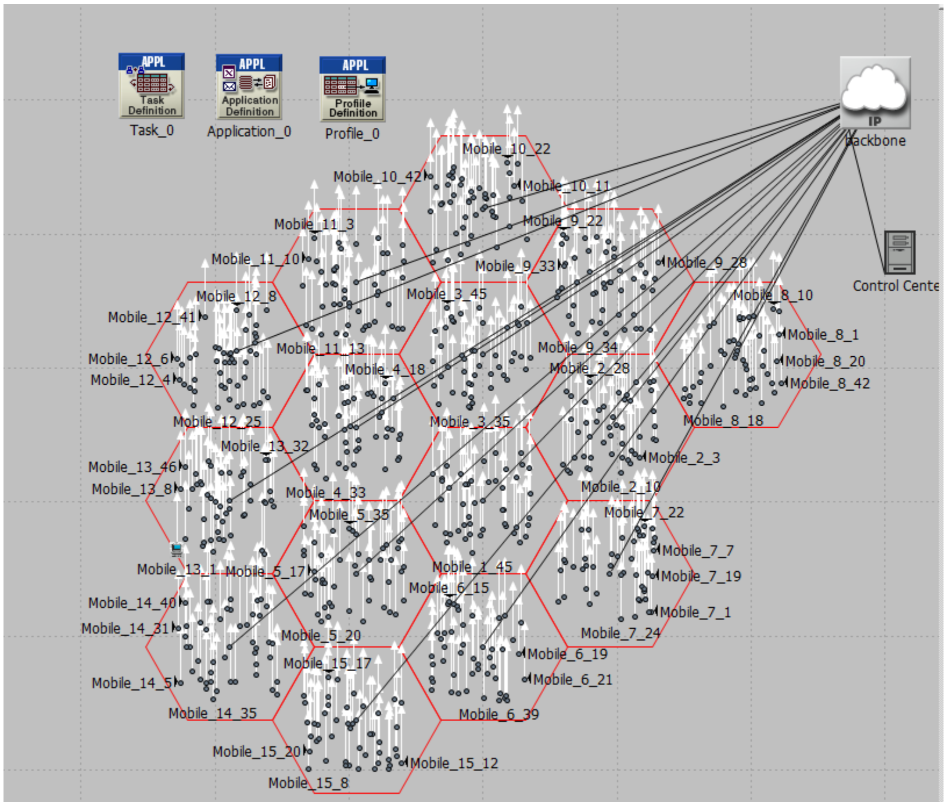


Figure 4-5. . The setting up of case study one

The operation of the proposed demand curtailment allocation approach can keep the frequency of the system within its allowable operating range and avoid the operation of UFLS. The successful operation of the proposed demand curtailment allocation approach highly relies on the real-time two-way communication between end-use customers and the control center. The real-time two-way communication helps to monitor the electricity usage of end-use customers, to send load curtailment allocation requests and to collect the response from end-use customers.

The package size for three kinds of data (information of electricity usage, commands of load curtailment allocation requests and end-use customer’s response) in this case study is assumed to be 100 bytes. At the 55th minute of the simulation, the system frequency begins to drop and approaches the boundary of its allowable operating frequency. The proposed demand curtailment allocation strategy is triggered and its operation will last 3 minutes to realize the demand curtailment allocation and keep the system frequency within its allowable operating range.

The simulation results are shown in Figure 4-6. From Figure 4-6, the peak total data transmission is around 50 Mbps which is near the maximum data rate of the WiMAX with chosen parameters. The latency of the all over network is under one second. As shown, it can be concluded that communication traffic of the fiber optic-WiMAX system provides very good performance in terms of latency. And the zero data dropping means the fiber optic-WiMAX system provides high performance in terms of reliability.

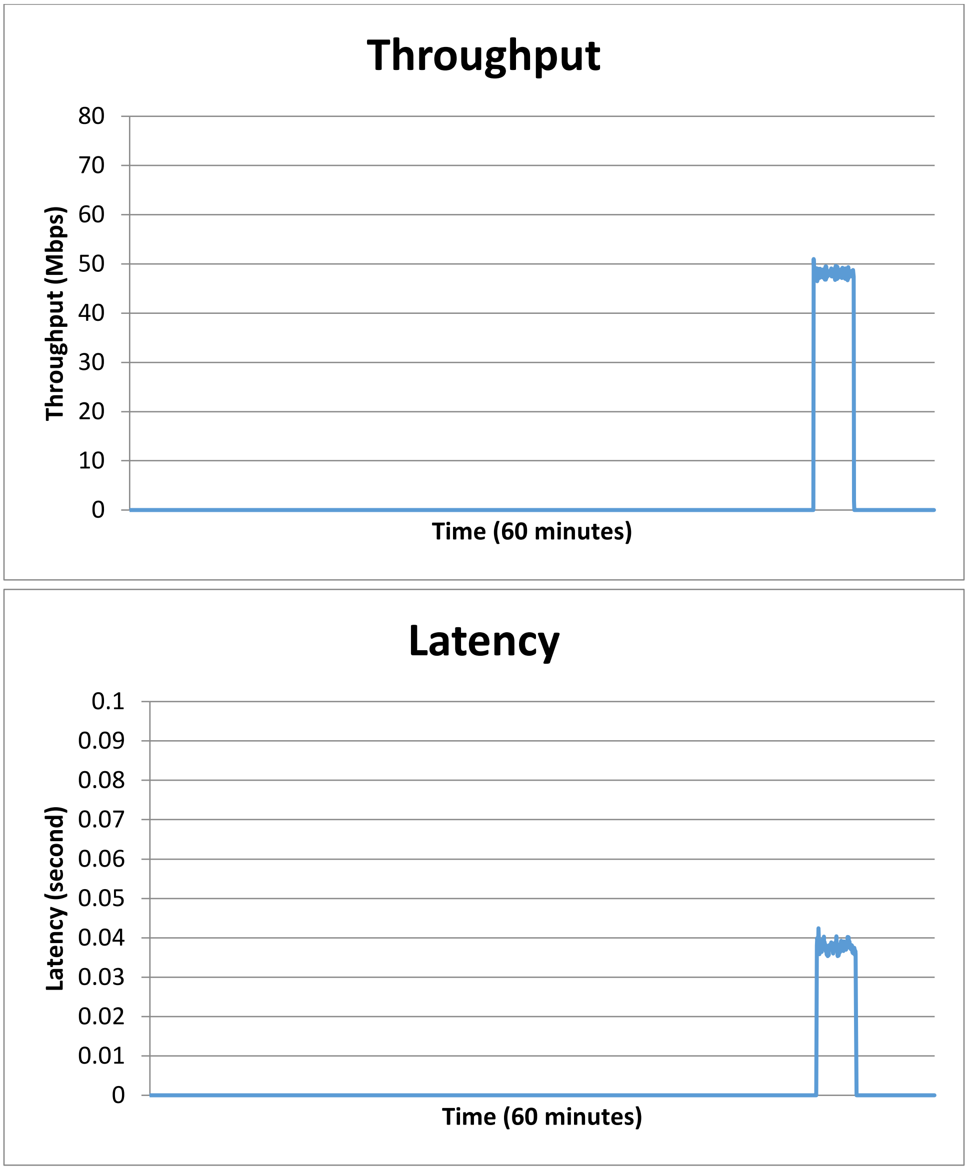


Figure 4-6. The simulation results for the case study one

4.3.3 Case Study 2: Performance Analysis for the Proposed Demand Curtailment Approach in Communication Network (Hybrid fiber optic-LTE)

The hybrid version of fiber optic and LTE technologies is used as basis to simulate the communication traffic between data concentrators and the control center. Fiber optic is selected to serve as the backbone network. LTE is selected to support the smart meter network which covers from data concentrators to base stations. The simulation is conducted in OPNET to evaluate the performance of the proposed demand curtailment approach in this communication network in terms of its latency and reliability.

Case Study 2 Description:

In case study two, the same service area in northern Virginia is simulated. Within the service area, 264,000 smart meters are distributed in 600 sq. miles.

The LTE 20 MHz FDD communication technology is applied in case study two. For this LTE technology, the frequency division duplexing (FDD) is used as the duplexing scheme. The LTE technology also provides two-way communications which are Uplink (UL) and Downlink (DL). In this case study, the UL transfers the information from smart meters to base stations; the DL transfers the information from base stations to smart meters. The multipath channel model for LTE's UL is SCFDMA (Single Frequency Division Multiple Access). The base frequency of UL is at 1,920 MHz and the bandwidth of UL is 20 MHz. The multipath channel model for LTE's DL is OFDMA (Orthogonal Frequency-Division Multiple Access). The base frequency of DL is at 2,110 MHz and the bandwidth of DL is also 20 MHz.

The modulation type and coding scheme (MCS) index for the LTE applied in this case study is 12 which means the 16-QAM modulation method with ¾ coding rate. The 2*2 MIMO (multipole-input and multiple-output) is applied as the MIMO configuration method for the LTE technology used in this case study.

Throughputs of DL and UL can be calculated using Eq. 4.12.

$$\text{Peak Data Rate} = N_{\text{stream}} * \frac{N_{\text{mod sym}} * N_{\text{bit}}}{T_{\text{subframe}}} \quad (4.12)$$

N_{stream} = No. of data stream;
$N_{mod\ sym}$ = No. of modulation symbols per subframe;
N_{bit} = No. of bits per modulations symbol;
$T_{subframe}$ = Time during of a subframe.

Simulation Results for Case Study 2:

To analyze the operation of the proposed demand curtailment allocation approach, the case study is set up in OPNET. Simulation results are presented and discussed below.

Same as the case study one, the size of the service area in northern Virginia is 600 sq. miles and the number of smart meters is 264k. As stated above, the ratio between LTE tower and smart meters in the reference case is 112: 2.2 million. In this case study, 15 LTE towers are applied which can service up to 300k smart meters. Using Eq. 4.12, the radius of hexagonal area is calculated as 4 miles. In each LTE cell, there are 46 data concentrators and each data concentrator is connected with 423 smart meters. The scenario is shown as Figure 4-7..

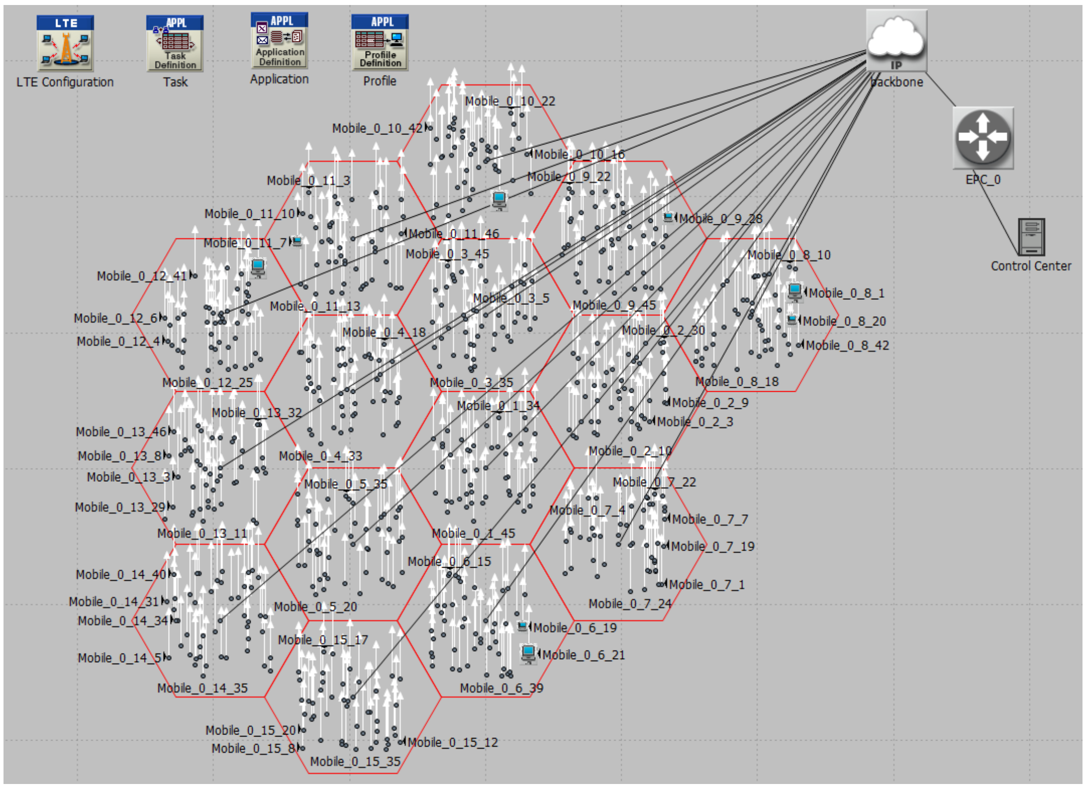


Figure 4-7. The setting up of the case study two

The package size in this case study is assumed to be 100 bytes. At the 55th minute of the simulation, the system frequency drops and approaches the boundary of its allowable operation frequency. The proposed demand curtailment allocation strategy is triggered and its operation will last 3 minutes to realize the demand curtailment and keep the system frequency within its allowable operating range.

The simulation results are shown in Figure 4-8. From Figure 4-8, the peak total data transmission is around 50 Mbps. The latency of the all over network is under one second. As shown, it can be concluded that communication traffic of the fiber optic-LTE system provides very good performance in terms of latency. And the zero data dropping means the fiber optic-LTE system provides high performance in terms of reliability.

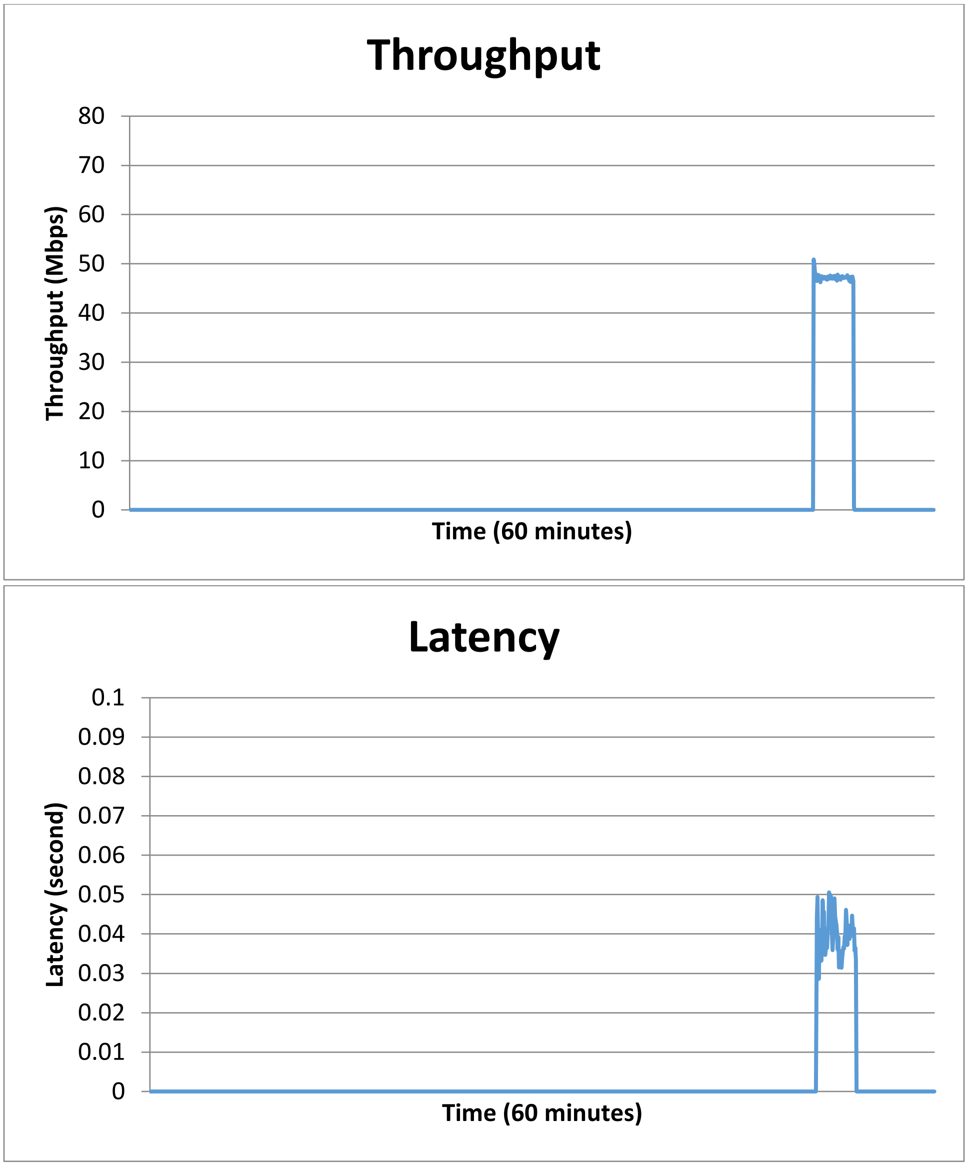


Figure 4-8. The simulation results for case study two

4.3.4 Case Study 3: Performance Analysis for the Proposed Demand Curtailment Approach in Communication Network (Hybrid fiber optic-WiMAX) with Background Traffic from other Smart Grid Applications

In the real world, proper operation of smart grid requires many different smart grid applications function in organize. To realistic the simulation, four other smart grid applications are considered as the background communication traffic in the same network with the proposed demand curtailment approach. Characteristics of these four smart grid applications are listed in Table 4-2 in section 4.2.

For the pricing application, metering applications and the proposed demand curtailment allocation approach, the participation ratio of the end-use customer is assumed as 100%. It means that all end-use customers are involved during the operation of these four smart grid applications. For the EV application, it is assumed that one-half of the end-use customers have electric vehicles and the participation ratio of EV application is 50%. For the distribution automation application, only field devices participate. It is assumed that only five field devices locate in each cell.

In this case study, the simulation lasts 60 minutes. The metering application's operation frequency is 15-minute and it will function four times during the whole simulation. For all other smart meter applications, it is assumed they function only one time during the 60-minute simulation.

For the proposed demand curtailment allocation approach, its operation duration is assumed as 3 minutes. For all other smart grid applications, the operation duration is less than 5 seconds.

Two scenarios are studied in this section. In the first scenario, four smart grid applications (DA application, pricing, metering and EV application) function in a queue. It is assumed that the proposed demand curtailment approach functions during the time gap between other smart grid applications' operation. There is no overlap for any two smart grid applications. Different from the first scenario, the proposed demand curtailment allocation approach functions during the operation of other smart grid application in the second scenario.

The starting points of smart grid applications in two scenarios are listed in Table 4-5.

Table 4-5. Starting Points of Smart Grid Applications

	Scenario One (Second)	Scenario Two (Second)
Metering Application	60, 960, 1860, 2760	60, 960, 1860, 2760
Pricing Application	1300	1300
Distribution Automation	2700	2700
Proposed Demand Curtailment Approach	3000	1250
EV application	3300	3300

The simulation results of the first scenario are shown in Figure 4-9. Since the operation of the proposed demand curtailment allocation approach requests real-time communication, the volume of data exchanging is large. As a result, the latency of this application is a little longer than other smart grid applications. However, the longest latency is under 50 ms which is acceptable. It can be concluded that all smart grid applications function properly.

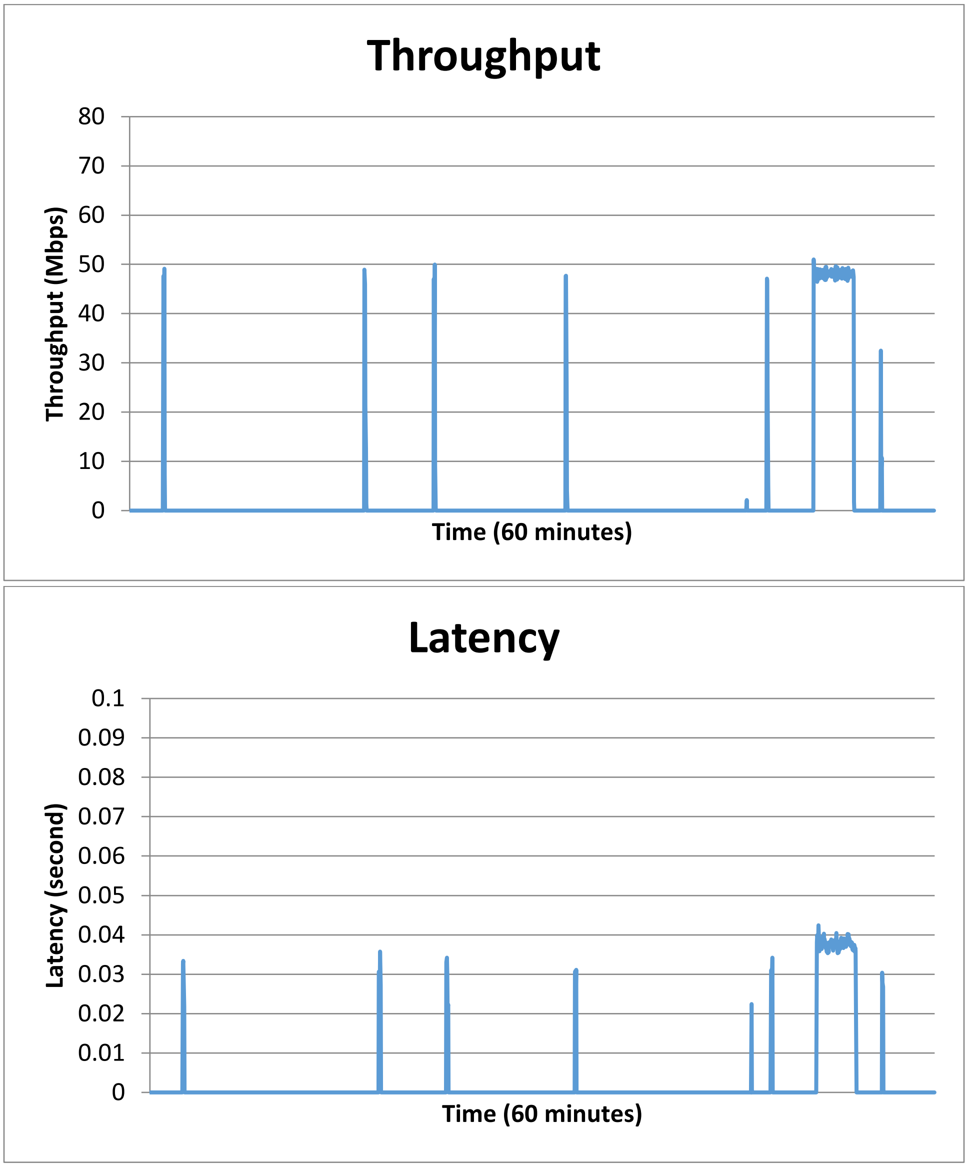


Figure 4-9. Simulation results of scenario 1

The simulation results of the second scenario are shown in Figure 4-10. In this scenario, the operation time of the proposed demand curtailment allocation approach overlaps with the operation of the pricing application. As a result, the latency for pricing application increases but is a little longer than 50 ms which is still acceptable. It also can be concluded that all smart grid applications function properly.

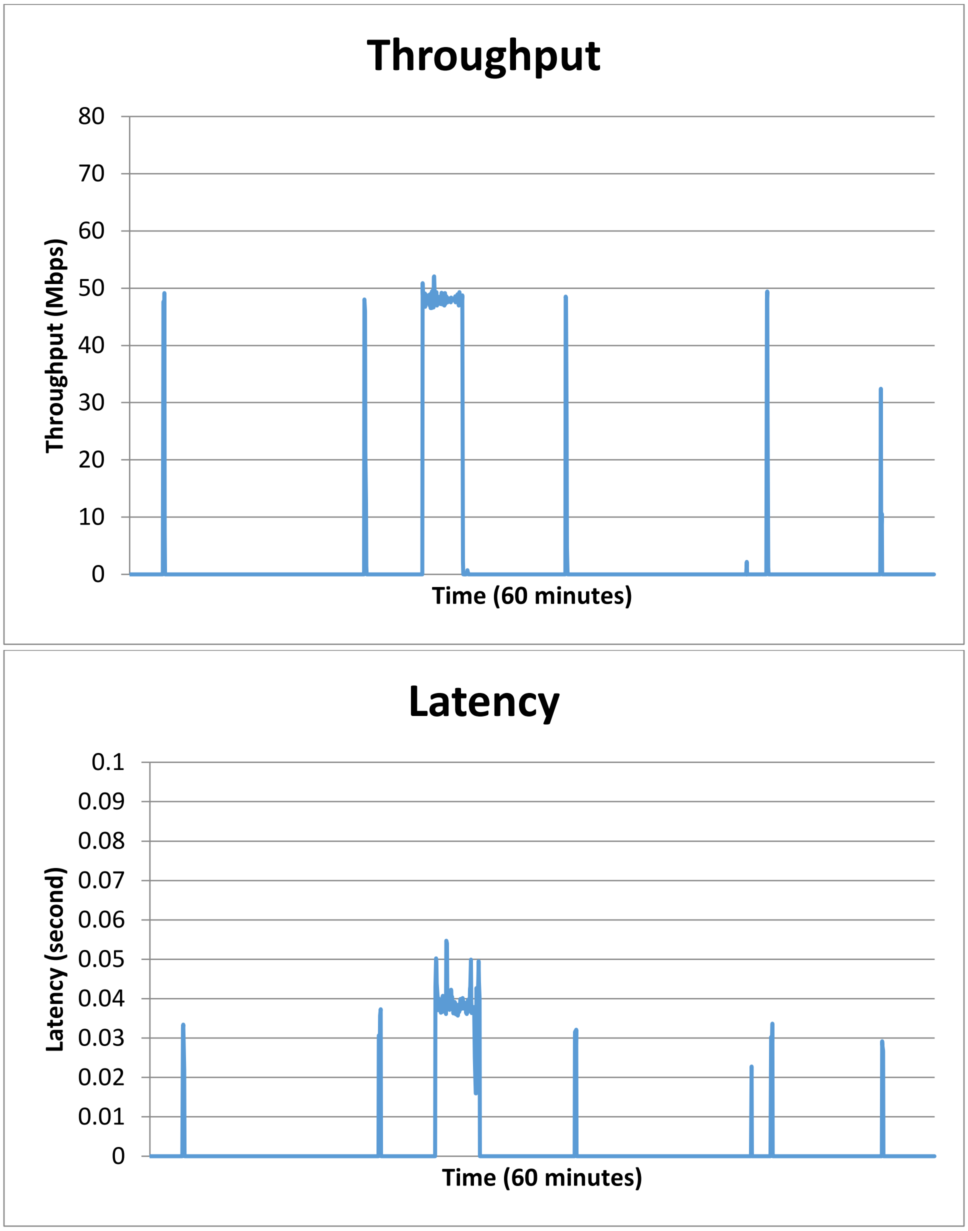


Figure 4-10. Simulation results of scenario 2

4.3.5 Case Study 4: Performance Analysis of the Hybrid Fiber Optic-LTE Network with Background Traffic from other Smart Grid Applications

Similar as the case study three, two scenarios are simulated using the fiber optic-LTE network. The simulation results are shown in Figure 4-11 and 4-12. It can be concluded that all smart grid applications function properly in both two scenarios.

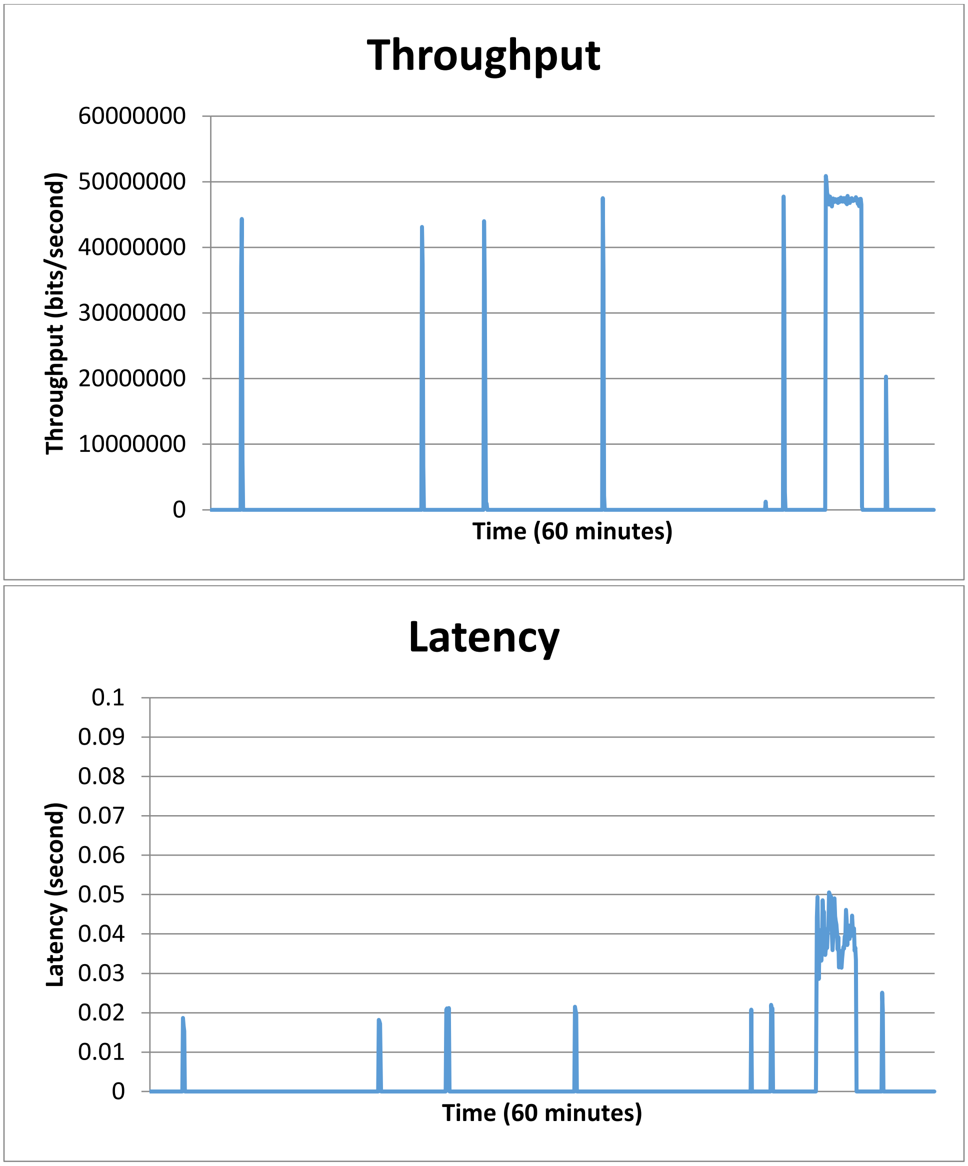
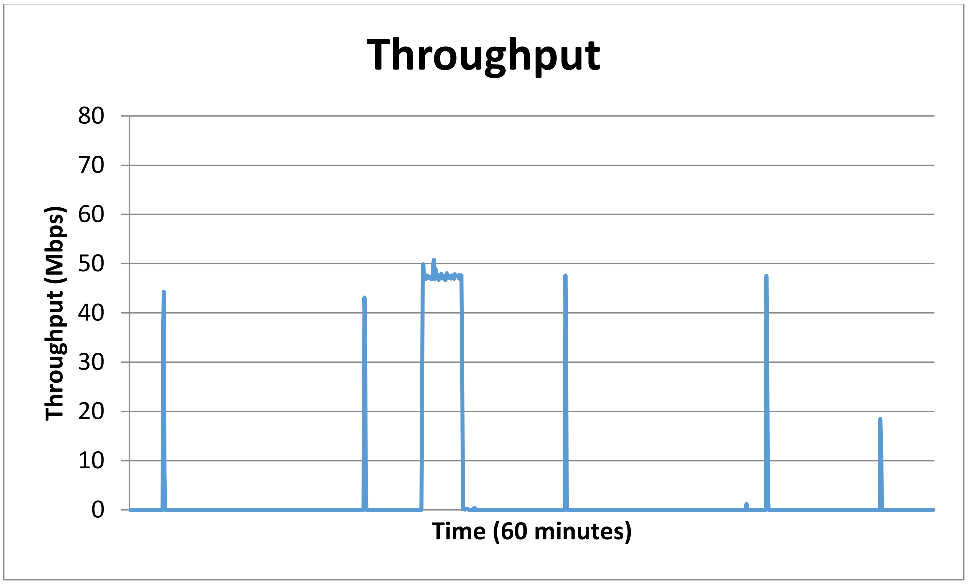


Figure 4-11. Simulation results of scenario 1



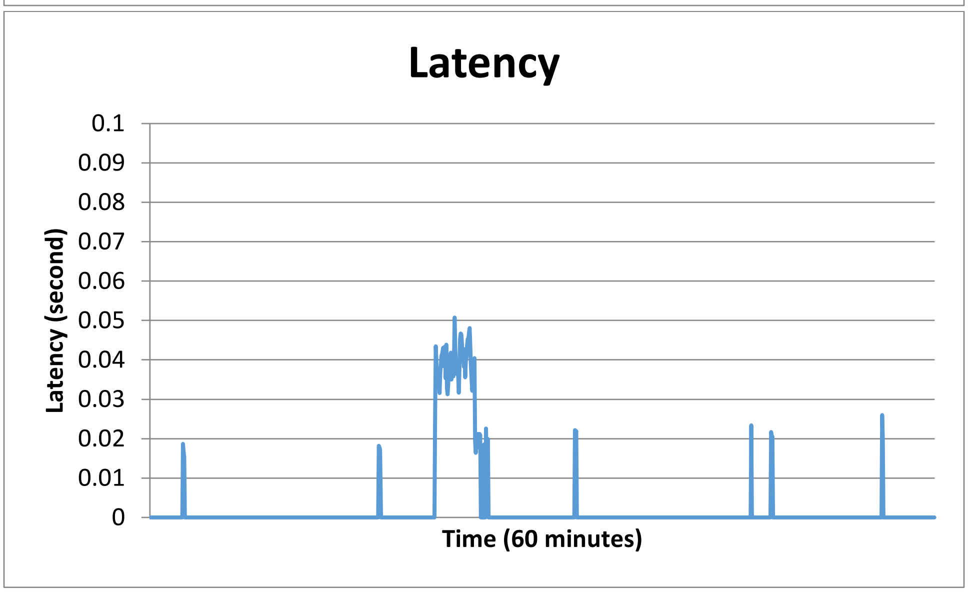


Figure 4-12. Simulation results of scenario 2

4.3.6 Summary

Four case studies are simulated in OPNET. From simulation results, it can conclude that the operation of the proposed demand curtailment approach can function normally using two kinds of hybrid version communication technologies with/without other smart grid applications.

4.4 Communication Networks for the Proposed Demand Curtailment Allocation Strategy within HAN

In this section, the performance of the communication network within premise area network for the proposed demand curtailment allocation strategy is simulated in OPNET. The operation of the proposed strategy within a smart home relies on the HEM (home energy management) system. Design of an effective HEM system requires selection of an appropriate communication technology.

The objective of this section is to compare commonly used communication technologies for HEM implementation in a premises area network, in terms of their latency, throughput, reliability, power consumption and implementation costs. Communication technologies of interest include ZigBee, Wi-Fi and Ethernet. These technologies are simulated in OPNET. This section compares the performance of selected communication technologies using two communication schemes, i.e., Always-on and Turn-on-in-loop. It also analyzes the impact of the number of devices being controlled by the HEM on the technology performance.

In general, the overall HEM system comprises: (i) an HEM unit, which provides monitoring and control functionalities for a homeowner; (ii) load controllers that gather electrical consumption of each appliance, such as AC, water heaters, EV, etc.; and (iii) a home gateway, i.e., a smart meter, which receives a command signal from a utility used as an input for the HEM system. An HEM unit can send an ON/OFF command to load controllers to change appliance status. To enable an HEM implementation, communications among three elements of the HEM system must be enabled. Communication technologies that are typically used to support HEM operation include both wired, e.g., Ethernet and PLC, and wireless, e.g., ZigBee, Wi-Fi, Bluetooth and Z-Wave, communication technologies. In this paper, performance of most commonly used wireless (ZigBee and Wi-Fi) and wired technologies (Ethernet) are discussed and compared.

4.4.1 Various Communication Technologies and Schemes for an HEM System

In this section, ZigBee, Wi-Fi, and Ethernet are discussed, as well as two possible communication schemes.

ZigBee is one of the communication protocols, which is used to create personal area networks built from small, low-power digital radios. It is based on an IEEE 802.15.4 standard, and used in the network that requires low data rate and long battery life. ZigBee has a defined data rate of 250 kbps which is suitable for periodic or intermittent data transmission. Applications of ZigBee include wireless switches, meters for a HAN and other equipment which requires short-range wireless data transfer at relatively low rates. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other wireless premises area networks, such as Wi-Fi. ZigBee networks are secured by 128-bit symmetric encryption keys. A typical ZigBee transmission range can be up to 100 meters depending on power output and environmental characteristics. This distance can be extended up to 1,600 meters with ZigBee-Pro.

Advantages of ZigBee include low power consumption, low implementation cost and provision of sufficient security. However, the low data processing capability, small memory size and easily being interrupted by other devices using same frequency bands are major drawbacks of ZigBee.

Wi-Fi is a high-speed wireless Internet and network communication technology. Its standard is based on the IEEE 802.11; and it can operate in 2.4 GHz, 3.5GHz and 5 GHz. Generally, Wi-Fi coverage is up to 100 meters with data rates from 2 Mbps to 600 Mbps. Wi-Fi provides reliable, secure and high-speed communications. The cost and power consumption of Wi-Fi products are also higher than other short-range wireless technologies such as ZigBee.

Ethernet is a most popular wired communication technology which is commonly used in the short-range network such as local area networks (LANs). Ethernet standard is based on IEEE 802.3. Ethernet implementation requires cables, which can be coaxial, twisted-pair or fiber optic, as well as a hub or a network switch. Ethernet can provide data rates ranging from 10 Mbps to 100 Gbps. Since Ethernet is a wired network, it is noise immune. However, once the network is placed, it is difficult to make changes.

4.4.2 Communication Schemes for HEM System

Communication schemes are designed for implementation of communication technologies in an HEM system. It is used to design the communication traffic, which can affect network latency, throughput and reliability. This Section discussed two different schemes: Always-on and Turn-on-in-loop.

In the Always-on scheme, an HEM unit and load controllers are turn on all the time. All load controllers send messages containing their electrical measurements to the HEM unit at the same time and continuously. That is, electrical measurements from each load controller are sent every one second. At every certain duration, e.g., one minute, the HEM unit broadcasts a confirmation message back to all load controllers. As needed, the HEM unit also sends ON/OFF control signals to selected load controller.

In the Turn-on-in-loop scheme, each load controller sends its electrical measurements to the HEM once every specified time intervals, e.g., 3, 5, 10 seconds. All load controllers must send their information sequentially in a loop fashion to the HEM. The duration of one loop, i.e., HEM receiving information from all load controllers, can be for example 60 seconds or more, depending on specifications of the HEM system. Once the load information is sent, the load controller listens to the HEM unit until the completion of one loop. After the HEM unit receives load information messages from all load controllers in the system, it broadcasts a confirmation message. At the end of one loop, the HEM unit sends ON/OFF control messages to selected load controllers as needed. In the Turn-on-in-loop scheme, the confirmation message is also used as the synchronous signal, which marks the beginning of the next loop.

4.4.2 Performance Comparison of the Selected Communication Technologies

Communication technologies for HAN may be evaluated using latency, throughput, and reliability, as described below for ZigBee, Wi-Fi and Ethernet.

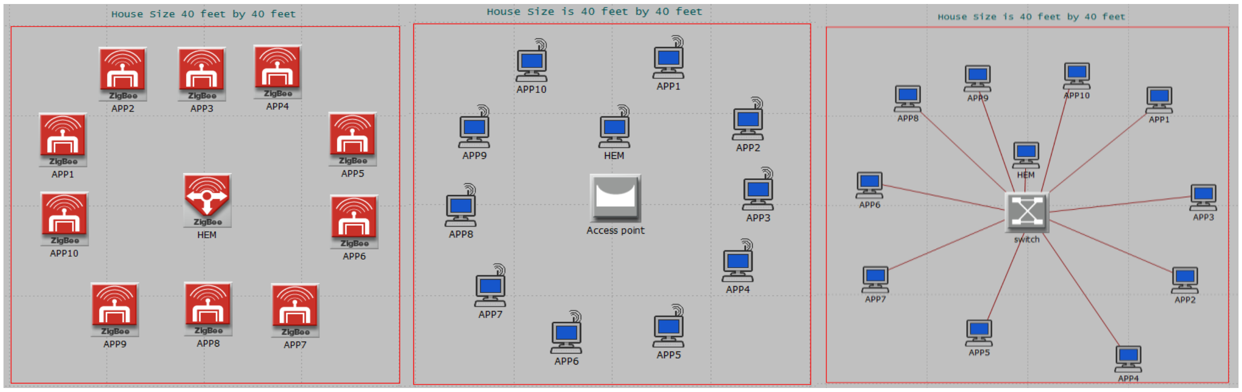
A) HEM Architecture Developed in OPNET

To enable performance comparison of ZigBee, Wi-Fi and Ethernet, the HEM architecture is developed in OPNET. This architecture is based on a premises area network inside a residential house. In this paper, a typical single story house in the U.S., 1,600-square feet, is taken as a case study. The HEM architecture includes an HEM unit and several load controllers for measuring and control of end-use appliances. It collects electrical data from load controllers, including voltage, current, real power, apparent power and power factor, and sends out control ON/OFF signals. A load controller can be connected to any kinds of electrical appliances, such as a water heater, an air conditioner, a clothes dryer, etc.

As shown in Fig. 4.17 (a), (b) and (c), the proposed HEM architecture consists of one HEM unit and ten load controllers utilizing ZigBee, Wi-Fi and Ethernet respectively. These architectures are built in OPNET. It can be seen that the ZigBee model is the simplest one among these three. There are only ten load controllers (APP1 to APP 10) and one HEM unit without a network switch or cables. The Wi-Fi model is the same as the ZigBee model except that it requires an access point. In the Ethernet model, there are ten load controllers, one HEM unit and one network switch. Red lines represent physical links between devices.

Two kinds of information messages in the HEM architecture are considered: control message and electrical data message. It is assumed that the size of each control/data message is 100 bytes, i.e., 800 bits. The maximum data rate of this network occurs when the HEM unit broadcasts in the Always-on scheme. This is 8,000 bps, considering the HEM's broadcasting data rate of 800 bits every one second to 10 devices. On the other hand, the total data rate (considering two-way traffic) of this architecture with the Always-on scheme is 16,000 bps. This is derived from the sum of the HEM's broadcasting data rate (i.e., 8,000 bps) and its information receiving data rate. The HEM's information receiving data rate is 800 bits/second from 10 devices.

Considering these HEM architectures as shown in Figure 4-13, performance comparison of ZigBee, Wi-Fi and Ethernet for HEM implementation in terms of their latency, throughput and reliability are discussed below.



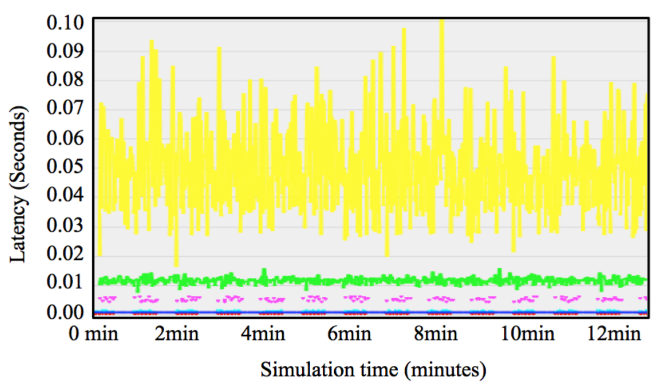
(a) (b) (c)

Figure 4-13. HEM architectures: (a) ZigBee; (b) Wi-Fi; (c) Ethernet.

B) Latency

Latency, also known as the End-to-End delay, refers to the time it takes for a message to be transmitted across a network from a source to a destination. Generally, it covers three kinds of delay: transmission delay, propagation delay and processing delay. The transmission delay is the amount of time required to push all packets into the channel. The propagation delay is the amount of time it takes for the signal to travel from a sender to a receiver. The processing delay is the amount of time it takes for a destination to receive all packets and store them in its storage/memory.

Simulation results are illustrated in Figure 4-14 showing the latency of ZigBee, Wi-Fi and Ethernet in seconds using two communication schemes (i.e., Always-on and Turn-on-in-loop). These are summarized in Table I. It can be seen that the Turn-on-in-loop scheme always has less latency than the Always-on scheme for all technologies. Using the same communication scheme, Ethernet has the least latency; while ZigBee has the highest latency. According to requirements specified in [6], latency of the three communication technologies using either of the two communication schemes is acceptable for the HEM application, which requires latency of less than a minute.



ZigBee Always-on; ZigBee Turn-on-in-loop;

Wi-Fi Always-on; Wi-Fi Turn-on-in-loop;

Ethernet Always-on; Ethernet Turn-on-in-loop;

Figure 4-14. Latency (seconds) of ZigBee, Wi-Fi and Ethernet using Always-on and Turn-on-in-loop schemes.

C) Throughput

The network throughput is the average rate of successful message delivery over a communication channel. Figure 4-15 (a) and (b) show the throughputs of the HEM system using ZigBee, Wi-Fi and Ethernet in the Turn-on-in-loop scheme and the Always-on scheme, respectively.

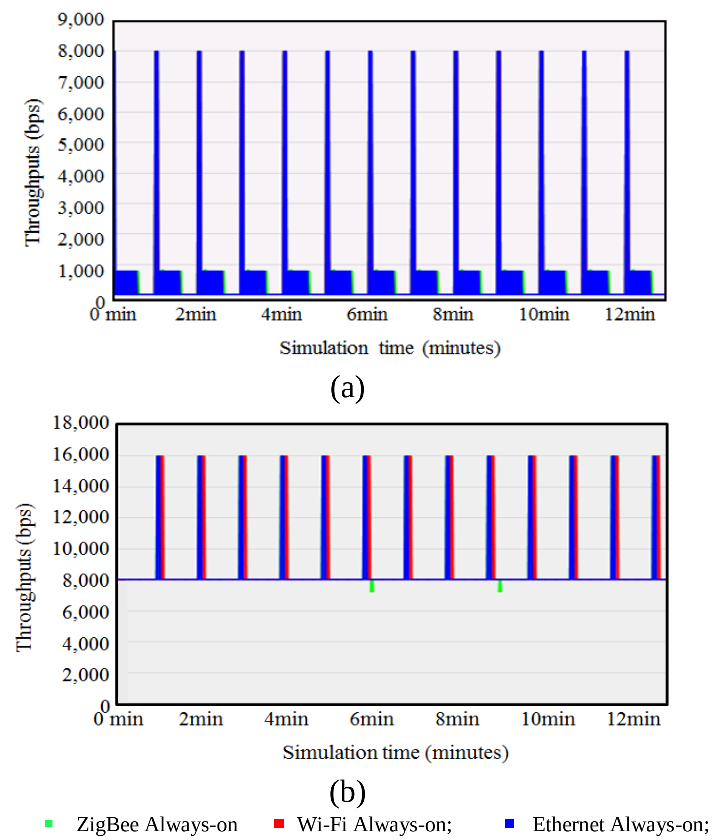


Figure 4-15. Throughputs (bps) of ZigBee, Wi-Fi and Ethernet using: (a) the Turn-on-in-loop scheme; (b) the Always-on scheme.

As shown in Figure 4.15 (a) for the Turn-on-in-loop scheme, there is only one device sending information during one time-slot. This can be either the load controller sends electrical measurement information (800bps) or the HEM unit broadcasts confirmation signals (10*800bps = 8,000bps). As shown, system throughputs are same regardless of the communication technology selected.

In Figure 4-15 (b), in the Always-on scheme, all load controllers send one message to the HEM unit every second. In this case, the HEM unit constantly receives 10*800 bps = 8,000 bps. A spike occurs, i.e., 16,000 bps, when the HEM unit broadcasts control signals to all load controllers. As shown in Figure 4-15 (b), throughputs are the same for Wi-Fi and Ethernet technologies (red and blue lines, respectively). However, the figure indicates some data drops when ZigBee is used (green line).

D) Reliability

Reliability is the characteristic showing how reliable a communication system is when performing a data transfer. Reliability can simply be calculated as a ratio of bits of data received correctly to bits of data sent. The most reliable network is the one with 100% reliability. Radio Frequency Interference (RFI) – the electronic noise produced by electrical and electronic devices, e.g., motors and personal computers – may affect the reliability of wireless communications. Since frequency ranges of these noises are between 10 kHz and 1 GHz [16], RFI on WiFi and ZigBee operated at 2.4 GHz can thus be ignored.

Overall simulation results indicate that the Always-on scheme has lower reliability than the Turn-on-in-loop scheme. The reliability of all communication technologies is 100% in the Turn-on-in-loop scheme in our simulation environment. Additionally, the reliability of Ethernet and Wi-Fi technologies are also 100% in the Always-on scheme as well with ten load controllers being considered. However, data drops occur when ZigBee is used in the Always-on scheme. See Figure 4-16.

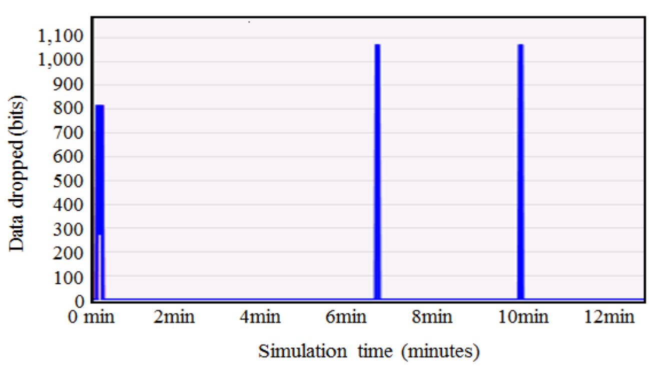


Figure 4-16. Data dropped (bits) using ZigBee (Always-on).

4.4.4 Impact of number of load controllers on communication performance

To analyze the impact of the number of devices on communication performance, HEM architectures with 5, 10 and 15 load controllers are simulated in OPNET for 30 minutes. Simulation results are summarized in Table I, which compare latency, throughput and reliability of three communication technologies of interest (i.e., ZigBee, Wi-Fi and Ethernet) using two communication schemes (i.e., Always-on and Turn-on-in-loop). According to Table I, it can be concluded that the latency and reliability delivered by the Turn-on-in-loop scheme are better than those offered by the Always-on scheme. All selected communication technologies can meet the latency requirement of the HEM application in the premises area network. Moreover, these three technologies can provide 100% reliability in the Turn-on-in-loop scheme.

Throughput ranges for three communication technologies are summarized in Table I. In the Turn-on-in-loop scheme, the minimum throughput is 800 bps for all cases as one load controller sends electrical measurement information to the HEM at a time. The maximum throughput is 800 bps * number of load control devices, as the HEM unit broadcasts confirmation signals to all load controllers. No data drop in the Turn-on-in-loop scheme. However, in the Always-on scheme, the minimum theoretical throughput is 800 bps * number of load control devices as all load controllers send their electrical data to the HEM unit at the same time. The maximum theoretical throughput is twice the minimum theoretical throughput as broadcasting confirmation messages from the HEM unit are also taken into account. As shown in Table I, with 10 or 15 load control devices with ZigBee communication, the actual minimum throughput appears lower than theoretical numbers due to data drops. With Wi-Fi, the simulation shows the data drop happens only once when the HEM unit broadcasts to 15 load control devices. However, since there is no other data drop during other times that the HEM unit broadcasts, the maximum throughput equals the theoretical maximum throughput.

Table 4-5 also summarizes power consumption of ZigBee, Wi-Fi and Ethernet, which are two important factors in selecting an appropriate communication technology in the premises area network. Apparently, ZigBee is the lowest power consumption device.

Typical implementation costs of ZigBee, Wi-Fi and Ethernet are also summarized in Table I, including chip, network switch/access point and cable costs. Since Ethernet is a wired communication technology, it needs extra cables and a network switch to connect to end-devices. Wi-Fi and ZigBee are wireless communication technologies. An extra network access point is required for Wi-Fi to set up a network.

Table 4-6. Summary of performance

	Number of Devices	**Communication Schemes**	**Typical Latency (second)**	**Throughput (bit/second)**	**Reliability**	**Power consumption [17, 18]**	**Implementation cost [19, 20, 21]**		
							Chip cost	**Cable cost**	**Network Switch**
ZigBee	5	Always-on	0.0093 - 0.1042	4000 - 8000	100%	~ 0.036 W	~ $2.75 - $3.5 /unit	$0	$0
		Turn-on-in-loop	0.0043 - 0.0062	800 - 4000	100%				
	10	Always-on	0.0164 - 0.1092	2400 - 16000	99.9518%				
		Turn-on-in-loop	0.0043 - 0.0062	800 - 8000	100%				
	15	Always-on	0.0249 - 0.1146	5600 - 24000	99.0747%				
		Turn-on-in-loop	0.0043 - 0.0062	800 - 12000	100%				
	5	Always-on	0.0046 -	4000 - 8000	100%	~ 0.210 W	~ $3 -	$0	$20 - $50

			0.0108				$20 /unit		
		Turn-on-in-loop	0.0008 - 0.0016	800 - 4000	100%				
	10	Always-on	0.0078 - 0.0166	8000 - 16000	100%				
		Turn-on-in-loop	0.0009 - 0.0016	800 - 8000	100%				
	15	Always-on	0.0107 - 0.0250	12000 - 24000	99.9451%				
		Turn-on-in-loop	0.0009 - 0.0016	800 - 12000	100%				
Ethernet	5	Always-on	0.0005 - 0.0007	4000 - 8000	100%	~ 0.300 W	~ $1 - $13.1 /unit	~ $1/meter	$20 - $50
		Turn-on-in-loop	0.0002 - 0.0002	800 - 4000	100%				
	10	Always-on	0.0005 - 0.0007	8000 - 16000	100%				
		Turn-on-in-loop	0.0002 - 0.0002	800 - 8000	100%				
	15	Always-on	0.0005 - 0.0009	12000 - 24000	100%				
		Turn-on-in-loop	0.0002 - 0.0002	800 - 12000	100%				

4.4.5 Summary

This section compares commonly used wired and wireless communication technologies for an HEM implementation in a premises area network. Simulation results from OPNET show the Turn-on-in-loop scheme always provides 100% reliability and provides better latency than the Always-on scheme. ZigBee has the highest latency while Ethernet has the lowest one using the same communication scheme. However, the latency of all three communication technologies is sufficient to support HEM system requirements. Ethernet always provides 100% reliability, while ZigBee and Wi-Fi have 100% reliability when the Turn-on-in-loop scheme is used; and both have data drops in the Always-on scheme. However, their reliability is still higher than 99%, which is sufficient to meet HEM system’s reliability requirements. Additional requirements of HEM applications in a premise area network are low power consumption and low implementation costs. ZigBee has the lowest power consumption and implementation costs, and can meet reliability and latency requirements for HEM applications. Therefore, ZigBee with the Turn-on-in-loop scheme is recommended as a potential solution for an HEM system. And the operation for the proposed demand curtailment allocation approach is under 0.05 second.

4.5 Conclusion

This chapter evaluates the performance of communication networks (WAN, NAN and premise area network) for the demand curtailment allocation approach which is proposed in chapter 3. This is to prove that the operation of the proposed approach can function quickly enough to avoid the operation of UFLS when using the ideal communication.

5. ANALYZE THE LIMITATION OF APPLYING CYBER SECURITY TECHNOLOGIES BASED ON DIFFERENT ENCRYPTION METHODS ON DEMAND CURTAILMENT ALLOCATION APPROACH

This chapter targets to address the knowledge gap discussed in Section 2.7.3. The proper operation of smart grid applications requires two-way communications that help transmit meter reading information from end-use customers to the control center and help transmit decisions and commands from the control center to field devices and customers. By integrating the communication system into the power system, security issues brought about by communication networks become a major concern in the smart grid environment.

To protect end-use customers' privacy and to maintain normal smart grid operation, a reliable and secure communication network is necessary. Applying cyber security technologies, such as encryption methods, to prevent adversary attacks can protect customers' privacy and allow the smart grid to operate reliably. Nonetheless, implementing encryption methods require extra software and hardware which increase complexity of the system. In addition, the processing of encryption/decrption also extends the system latency. Especially, by using strict cyber security standards, the operation of smart grid application may be negated. However, some smart grid applications have strict demands on fast operation speed. Therefore, it is necessary to analyze the limitation of using encryption methods on the smart grid operation.

The objective of this chapter is to analyze additional processing and transmission delays caused by implementing selected encryption methods on the proposed demand curtailment allocation strategy. In section 5.1, cyberattacks are classified into several types, and then some popular applied encryption methods which can be implemented onto smart grid communications are introduced.

Case studies in section 5.2 are demonstrated to compare the performance of proposed demand curtailment allocation (DCA) approach implemented with different encryption methods. Single DCA event is simulated in section 5.2.

In section 5.3, based on the analysis from the section 5.2, three proper encryption methods are implemented into the proposed demand allocation approach. Cases studies are presented to show the capability of the novel DCA approach when facing sharp decrease of renewable energy during the whole day. Multiple demand curtailment allocation events are simulated in each case study.

5.1 Cyberattacks and Encryption Methods

In the first part of section 5.1, cyberattacks are classified based on sources of security attacks and security objectives. In the second part, several popular encryption methods which can be implemented onto smart grid communications are introduced.

5.1.1 Classification of Cyberattacks

In general, the cyberattack is any type of offensive maneuver implemented by individuals or whole organizations which targets to malfunction computer information systems, infrastructures, computer networks, or individual's computer devices, by various means of malicious acts. Sources of security attacks can be classified into two types, which are misbehaving users and malicious users. Misbehaving users are those selfish users who attempt to obtain more network resources than legitimate users by violating communication protocols [89]. Differently, malicious users aim to illegally acquire, modify or disrupt information in the network. Security attacks from malicious users are more damaging to the network and drawing more attractions to be prevented.

Be implemented with communication network, the smart grid faces more cyber security problems than the traditional power system. In order to keep the normal operation of the smart grid, there are three high-level cyber security objectives: availability, integrity and confidentiality. According to smart grid's cyber security objectives, cyberattacks in a smart grid can be classified into three types [90]:

(1) attacks targeting availability, also called denial-of-service (DoS) attacks, is an attempt to delay, block or corrupt the communication in the smart grid;
(2) attacks targeting integrity aim at deliberately and illegally modifying or disrupting data exchange in the smart grid;
(3) attacks targeting confidentiality intend to acquire unauthorized information from network resources in the smart grid.

5.1.2 Encryption Methods

Introduce Encryption Methods:

Cyber security technologies are needed to guarantee the normal operation of the smart grid. On the other hand, proper cyber security technologies from various types which can be applied into smart grid need to satisfy three major requirements: having attack detection and resilience operations; having identification, authentication and access control; having secure and efficient communication protocols. Strict cyber security technologies always need additional software and hardware to realize. As a result, extra processing time and cost are added. As mentioned before, smart grid application, especially the proposed demand curtailment allocation approach, is strict with operation speed. So, it is necessary to choose the security methods with high operation speed and easy implementation.

Since its easy application and low cost, the data encryption is the most widely used among many kinds of cyber security technologies applied in the smart grid environment. Generally, the encryption algorithm is a mathematical function used in the encryption and decryption process.

In an encryption process, the supplied key is used to protect the information. To the opposite, the encrypted information is decrypted using the supplied key at the receiving end. The aim of an encryption method is to make the encrypted information as complex as possible, making it difficult to decipher. Nonetheless, the complex encryption method may be time consuming to transmitted and decrypted. As a result, it is important to choose proper types of encryption methods.

Hashing, symmetric cryptography and asymmetric cryptography are three major types of encryption methods.

The hashing encryption turns a piece of information (usually a key or a password) into a fixed length string of characters. It is great for usage when comparing a value with a stored value, especially for short piece information.

Different from the hashing encryption method, both symmetric and asymmetric encryption methods rely on supplied keys. Symmetric cryptography, also called private-key cryptography, is the one of most traditional and secure encryption methods. In the symmetric encryption method, the same key is applied at both encryption and decryption processes. Besides, anyone who has the key can decryption coded messages.

More secure than the symmetric encryption method, the asymmetric encryption method uses two different keys. The public key is used to encrypt messages and is available for everyone. At the decryption side, each receiver has a different private key to decrypt the coded messages. Timing costing is asymmetric encryption method's disadvantage.

Most popular encryption methods are listed and introduced below.

Digital Encryption Standard (DES): In 1977 the Data Encryption Standard (DES), a symmetric algorithm, was adopted in the United States as a federal standard. DES encrypts and decrypts data in 64-bit blocks, using a 56-bit key. It takes a 64-bit block as an input and the encrypted block is a 64-bit block.

Triple DES (3DES): Since DES can be vulnerable in some cases, the Triple DES (3DES) has emerged as a stronger method. Triple DES encrypts data three times and uses a different key for at least one of the three passes. The common key size is 112-168 bits.

Advanced Encryption Standard (AES): AES is a symmetric key encryption technique. It is used to replace DES and 3DES. It was the result of a worldwide call for submissions of encryption algorithms issued by the US Government's National Institute of Standards and Technology (NIST) in 1997 and completed in 2000 [95]. Although the key of 128 bits is efficient, AES also uses keys of 192 and 256 bits for heavy-duty encryption purposes.

Blowfish Encryption Algorithm: Bruce Schneider designed the Blowfish (a symmetric encryption algorithm) in 1993. Blowfish has a 64-bit block size and a variable key length - from

32 bits to 448 bits. It is a 16-round Feistel cipher and uses large key-dependent S-boxes. [95]

Rivest-Shamir-Adleman Encryption Algorithm (RSA): Ron Rivest, Adi Shamir and Leonard Adleman designed the RSA in 1978. [104] It is an asymmetric cryptosystem based on number theory, which is a block cipher system. Two prime numbers are used to generate the public and private keys which are used for encryption and decryption purpose. Operation of RSA can be decomposed into three major steps: key generation, encryption and decryption. Finding the compatible keys is time costing.

Choosing Encryption Methods:

In last section, five popular encryption methods are introduced: DES, 3DES, AES, RSA and Blowfish. To choose proper encryption methods, both security and efficiency need to be considered.

For many years, the DES encryption method is widely applied since its easy application. However, in July 1998 a team of cryptographers cracked a DES-enciphered message in 3 days, and in 1999 a network of 10,000 desktop PCs cracked a DES-enciphered message in less than a day. As a result, DES encryption method is not considered in the case study.

Asymmetric encryption techniques are almost 1000 times slower than symmetric techniques, because they require more computational processing power [110, 111]. Considering the efficiency, RSA, which is an asymmetric encryption method, is also removed from the case study.

In summary, 3DES, AES and Blowfish encryption methods are simulated in the case study.

Parameters of Encryption Methods:

As symmetric encryption methods, choosing proper parameters can affect the security and efficiency. In this section, the parameters for each type of the encryption method are listed in Table 5-1.

Table 5-1. Parameters of encryption methods

	3DES	AES	Blowfish
Block Size (bit)	64	128	64
Key Size (bit)	128	128	64

The processing speed of the encryption method is another important factor. According to [112], the encryption and decryption processing speed on a PC with CPU (2.4 GHz and 2 GB RAM) are listed in Table 5-2:

Table 5-2. Processing speed of encryption methods

	3DES	AES	Blowfish
Encryption (Mbytes/Second)	3.450	4.174	25.892
Decryption (Mbytes/Second)	5.665	6.452	18.72

5.2 Case Study: Performance of Encryption Methods

Single DCA event is simulated in this section. Case studies are demonstrated to compare the performance of proposed DCA approach implemented with different encryption methods. The IEEE 14-bus system model is simulated in PowerWorld simulator. And the data used in case studies are derived from distribution feeders in a service area of an electric utility in Virginia. The data is available every one minute interval, and the day selected for the case study is a hot summer day in August. The solar energy output data is derived from solar panels on one building in Virginia. The data is available every 15 seconds interval, and the day selected for the case study is the same day in August.

Before introducing the case study for the single DCA event, the system model and some concepts used in this section are listed below.

IEEE 14-bus System

The IEEE 14-bus system model built using PowerWorld simulation tool is shown in Figure 5-1.

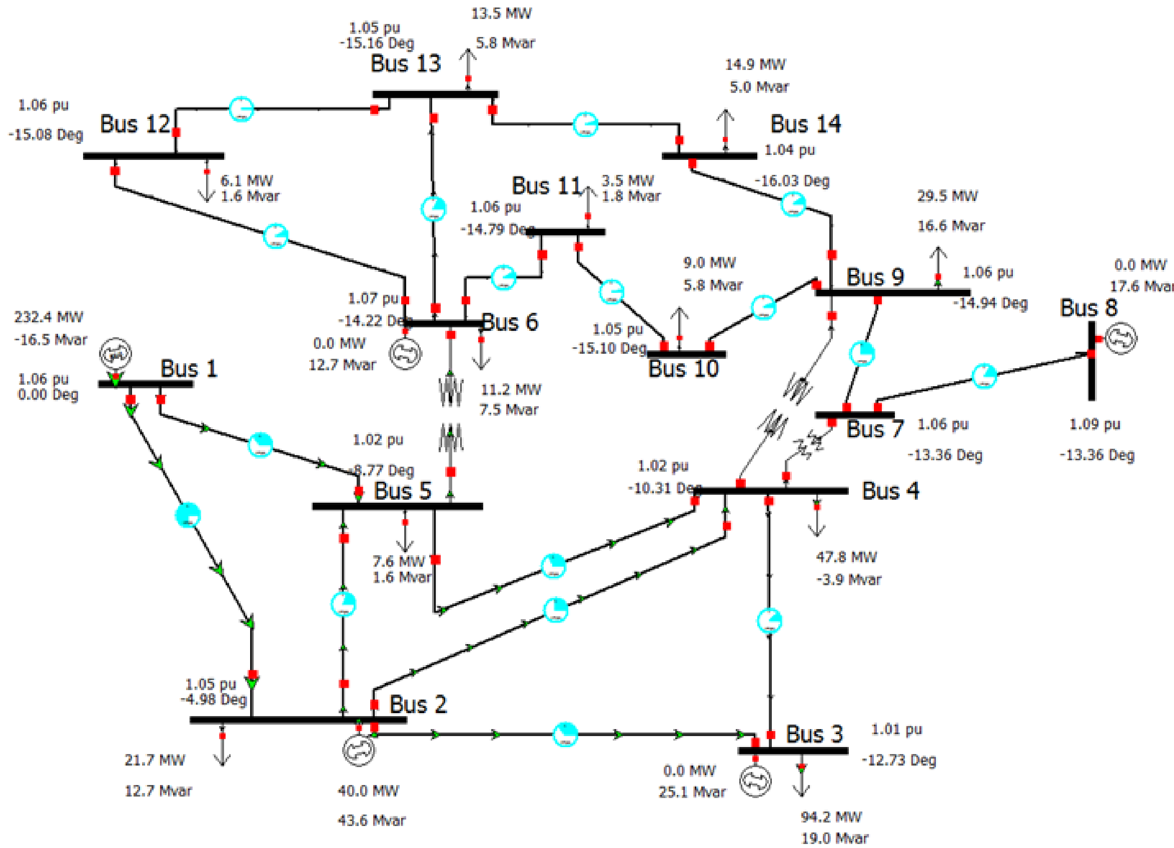


Figure 5-1. The IEEE 14-bus system model

This system consists of five synchronous machines with IEEE type-1 exciters, three of which are synchronous compensators used only for reactive power support. There are 11 loads in the system totaling 259 MW and 81.3 MVar. Its normal operation frequency is at 60 Hz which is shown in Figure 5-2.

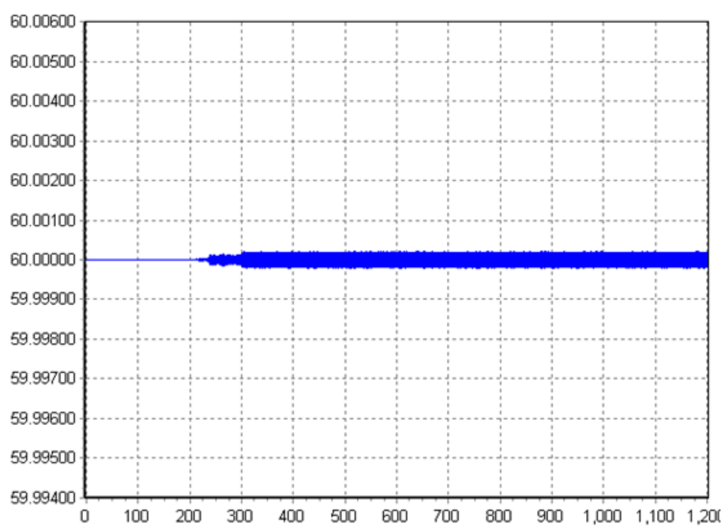


Figure 5-2. The operation frequency of IEEE 14-bus system

Photovoltaic (PV) Penetration Level

The rapid progress in technologies in the last few years decreased the price of PV panels significantly. This increased the penetration of photovoltaic panels in the smart grid. However, the high penetration of the PV panels may bring the grid to its operation limits. Grid operators also have concerns about the voltage and current violations in the grid as the number of PV panels increasing.

As a result, the PV penetration level is defined to evaluate the effects of the PV panels on the grid. There are couple definitions for the PV penetration level. In this section, the PV penetration level is defined as the ratio of total peak power generated by PV panels to the peak load apparent power on the feeder:

$$\text{PV Penetration} = \frac{\text{Peak PV Power}}{\text{Peak Load Apparent Power}}$$

Ramp Rate

The average ramp rate is the load change divided by the amount of time required to move from the initial load to the final load.

Ramp rates of most industrial frame gas turbine models are advertised as 10 MW/min up to 100 MW/min, with an average of about 25 MW/min [113]. For example, GE 7F.05 Gas Turbine (60Hz) has ramp rate of 40 MW per minute. GE 7FA gas turbine has 30 MW per minute [114]. Siemens SGT6-5000F gas turbine has up to 40 MW per minutes [115] and Siemen's H class CCGT (combined-cycle gas turbine) has 25 MW per minutes [116]. Traditional generation (coal/steam): based on different unit sizes (76, 155, 350MW), the ramp rate varies from 2 to 4 MW/minute [117].

In this section, the major generation is assumed as traditional generation (coal/steam). Besides, based on the size of generation in IEEE 14-bus system, the ramp down rate is set as 3.5 MW/minute. The gas turbine's ramp rate is set as 25 MW/minute.

Western Electricity Coordinating Council (WECC) Category B/C Standard

WECC is geographically the largest and most diverse of the eight regional entities with delegated authority from the North American Electric Reliability Corporation (NERC) and Federal Energy Regulatory Commission (FERC). It provides an environment for the development of reliability standards.

WECC category B frequency monitors all load buses for a frequency dip below 59.6 Hz for duration of 0.1 second. Similarly, WECC category C frequency monitors all load buses for a frequency dip below 59.0 Hz for duration of 0.1 second.

In this section, the proposed demand curtailment allocation method is triggered when the grid's frequency falling into the WECC category B frequency monitoring condition. If the DCA is not able to draw the frequency back to its normal range and the frequency drops into the WECC category C frequency monitoring condition, the UFLC (under frequency load control) program is triggered.

Latency

In this part, the latency for a command send from the control center to smart appliances in a house is calculated/simulated.

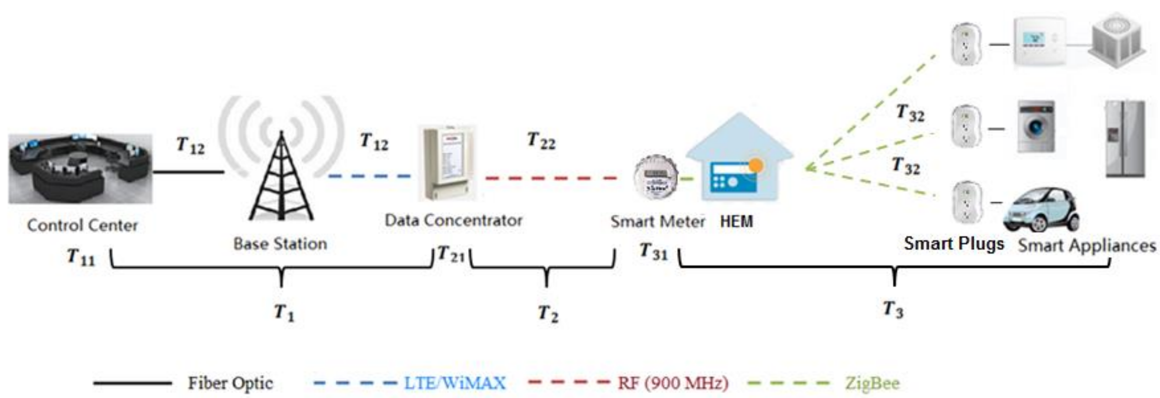


Figure 5-3. The network structure of DCA

As discussed in the chapter 4, the network structure for the DCA is shown in Figure 5-3. The total latency for a command transmitted from the control center to the smart appliance includes two parts: the communication delay and the algorithm processing delay.

$$T_{total} = T_{algorithm} + T_{communication}$$

The communication delay can be further divided into three parts: transmission delay, propagation delay and processing delay.

$$T_{communication} = \sum (T_{transmission} + T_{propagation} + T_{processing})$$

$T_{transmission}$ - the amount of time required to push all packets into the channel;

$T_{propagation}$ - the amount of time it takes for the signal to travel from a sender to a receiver;

$T_{processing}$ - the amount of time it takes for a destination to receive all packets and store them in its storage/memory.

To calculate the overall latency, the network can be divided into three layers: WAN (wide area network), NAN (neighborhood area network) and HAN (home area network). And the latency of each layer is calculated/simulated by two parts: the communication delay and the delay from the algorithm.

$$T_{total} = \sum (T_1 + T_2 + T_3)$$

T_1 - latency in WAN
T_2 - latency in NAN
T_3 - latency in HAN

Part 1: Control Center to Data Concentrator: T_1

$$T_1 = T_{11} + T_{12}$$

T_{11} - Algorithm Processing Time;

T_{12} - Communication Latency

The DCA algorithm proposed in chapter 3 is simulated on one PC with CPU of 3.3 GHz and 6 GB RAM. The simulated latency of this algorithm processed in the control center is under 0.1 seconds. The communication latency is simulated using the OPNET. The communication technologies are Optic Fiber and WiMAX/LTE. The simulated results are discussed and shown in Section 4. The total communication latency for this part is also under 0.1 seconds.

$$T_{11} \ll 0.1 \text{ second}$$

$$T_{12} = \sum (T_{transmission} + T_{propagation} + T_{processing}) \ll 0.1 \text{ second}$$

$$T_1 = T_{11} + T_{12} \ll 0.2 \text{ second}$$

Part 2: Data Concentrator to Home (Smart Meter): T_2

$$T_2 = T_{21} + T_{22}$$

T_{21} – Algorithm Processing Time;

T_{22} – Communication Latency.

Similarly, the DCA algorithm proposed in Section 3 is simulated on the same PC with CPU of 3.3 GHz and 6 GB RAM. The simulated latency of this algorithm processed in the data concentrator is under 0.1 seconds.

The communication latency for this part is based on RF network using 900 MHz. The data rate of 900 MHz is up to 13.5 Mbps. The coverage is around 25 miles. For each base station, 300-1000 customers can access.

$$T_{22} = \sum (T_{transmission} + T_{propagation} + T_{processing})$$

Using the data from in chapter 4, each data concentrator is connected with 423 smart meters. And the radius of hexagonal area is 4 miles. For each customer, the size of data package is 100 bytes. To calculate the latency, it is assumed that the smart meter and data concentrator have the same access speed.

$$T_{transmission} = T_{processing}$$

$$= \text{Package size} * \text{Number of Customers} / \text{Data Rate}$$

$$= 800 * \frac{423}{10*10^6} = 0.03 \text{ second}$$

To calculate the propagation delay, the distance between each access points and the base station is assumed to be Gaussian distribution between 0 and 4 miles. And the propagation speed of signal in free space is as same as the light which is 3*10^8 m/s.

$$T_{propagation} = \frac{\text{Distance}}{\text{Propagation Speed}} = \frac{D}{S} \ll 0.01 \text{ second}$$

$$T_2 = T_{21} + T_{22} \ll 0.2 \text{ second}$$

Part 3: Smart Meter to Appliance: T_3

$$T_3 = T_{31} + T_{32}$$

T_{31} – Algorithm Processing Time;

T_{32} – Communication Latency

Same as previous cases, the DCA algorithm proposed in chapter 3 is simulated on one PC with CPU of 3.3 GHz and 6 GB RAM. The simulated latency of this algorithm processed in the HEM is under 0.1 seconds.

$$T_{31} \ll 0.1 \text{ second}$$

The communication latency is simulated using OPNET. The communication technologies are ZigBee, Wi-Fi and Ethernet. The simulated results are discussed and shown in Chapter 4. The total communication latency for this part is also under 0.1 second.

$$T_{32} = \sum (T_{transmission} + T_{propagation} + T_{processing}) \ll 0.1 \text{ second}$$

$$T_3 = T_{31} + T_{32} \ll 0.2 \text{ second}$$

In summary, the total latency for a command sending from the control center to the smart appliance without encryption method is under 0.6 second.

$$T_{total} = \sum (T_1 + T_2 + T_3) \ll 0.6 \text{ s}$$

Frequency Response

Power system frequency is a continuously changing variable and it is determined and controlled by the balance between system demand and total supply. The frequency falls when the demand is greater than the supply. In order to keep the system's frequency within its normal operation limits, it is necessary to be aware of the system's frequency response (MW/0.1 Hz). Frequency Response is a measure of a system's ability to stabilize frequency immediately following the sudden loss of generation or load. It is defined as sum of the change in demand, plus the change in generation, divided by the change in frequency, expressed in megawatts per 0.1 Hertz (MW/0.1 Hz). [118]

In practice, the amount of frequency decline depends on characteristics of the load and generators available at the time. [119]

To calculate the frequency response of a system, the most popular method is by observations of frequency decline events. For example, the NERC Resources Subcommittee occasionally requests Frequency Response Characteristic Surveys for specific events [120].

To estimate the frequency response ratio of the IEEE 14-bus system model used in this section, several frequency decline events are simulated. For example, the frequency of the system decreases from 60 Hz to 58.5 Hz when the load increased 40 MW. Using the formula 5-1, the IEEE 14-bus system's frequency response is 27.1 MW/0.1 Hz.

$$k_p = -\left(\frac{f_1 - f_0}{L_1 - L_0}\right) \qquad (5\text{-}1)$$

5.2.1 The data for case study

In this part, a case study of the single demand curtailment allocation event is simulated. In the case study, the solar energy is assumed involved and located at Bus 2. The data of solar energy used in this case study is derived from actual data of PV panels for a building located in north Virginia. The solar energy in a typical summer day is picked and used in this case study. The data is available for every 15 seconds. It is assumed that the solar energy during the whole day is shown in Figure 5-4.

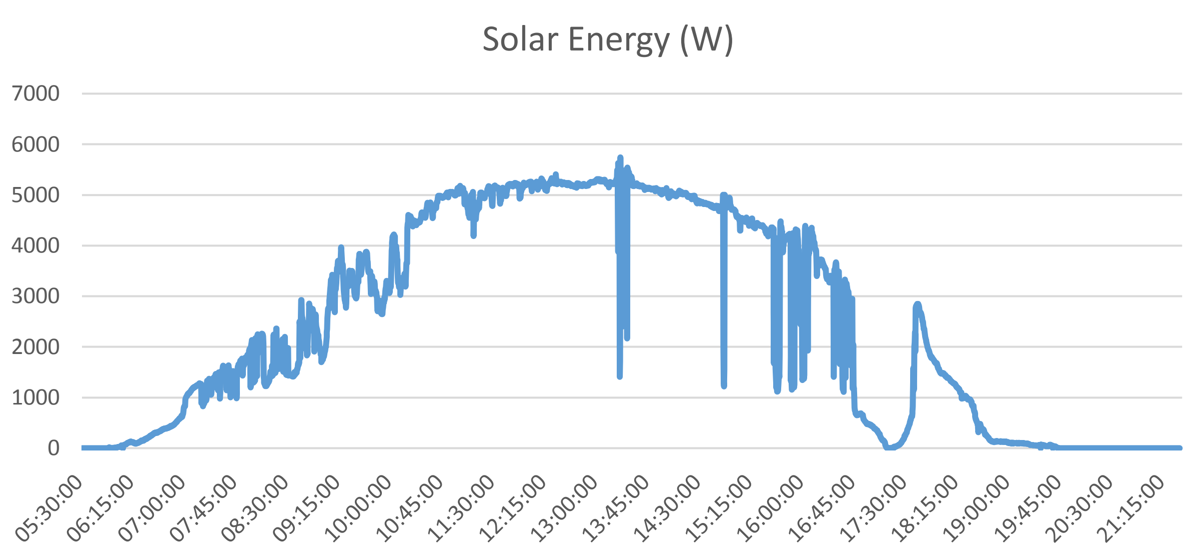


Figure 5-4. The solar energy for the whole day

The data of load used in this case study is derived from distribution feeders in a service area of an electric utility in north Virginia. The maximum load during the whole day is scaled up to 259 MW which is the standard load of IEEE 14-bus system. The derived load data for a typical summer day on IEEE 14-bus system is shown in Figure 5-5.

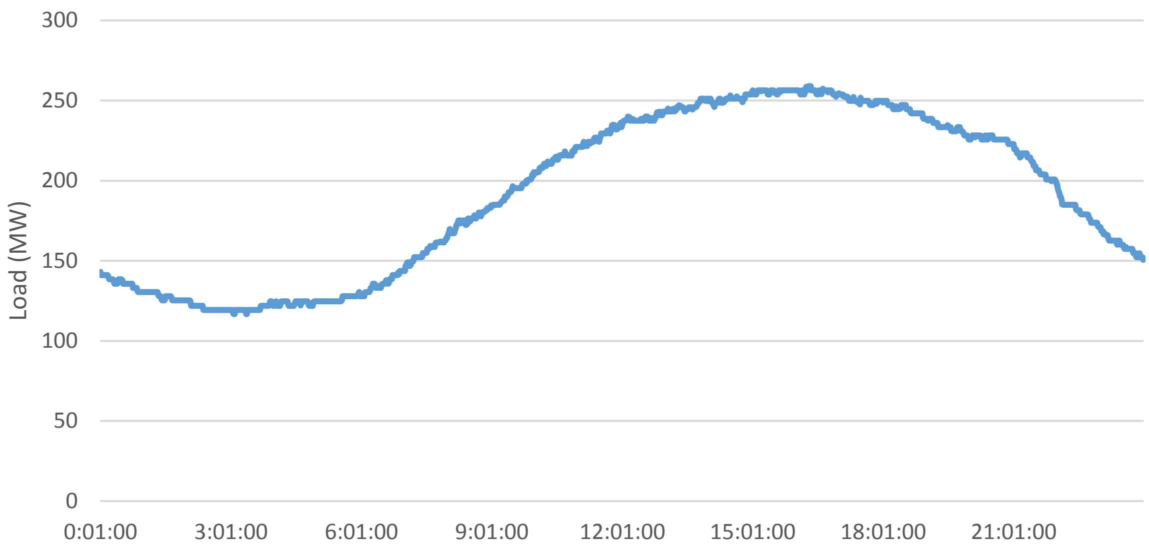


Figure 5-5. The load of a typical summer day

In this case study, it is assumed that solar penetration level is 10%. Base on the definition, the solar energy in the IEEE 14-bus system is modified and shown in Figure 5-6.

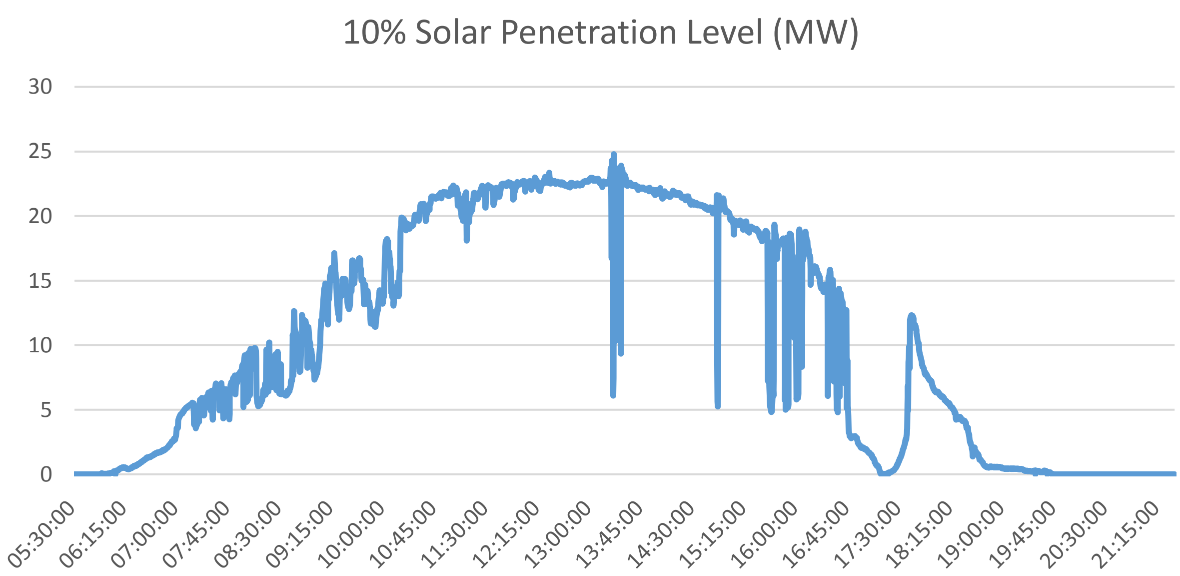


Figure 5-6. Modified solar energy (10% solar penetration level)

5.2.2 The Operation of Case Study

During peak hours of the typical summer day, it is assumed that the gas turbine turned on. During the normal operation period, total load of the system is covered by total outputs from traditional generations, gas turbines and PV panels. And the frequency of this system operation is around 60 Hz.

The control center monitors the frequency of the system constantly. Once its frequency is out of its normal operation range, either the operation of DCA or gas turbines are triggered. If the frequency is higher than 60.1 Hz and lasts longer than 0.1 second, the gas turbine is turn down accordingly.

On the other hand, if the frequency of power system decreases and keeps lower than 59.6 Hz for 0.1 second, the DCA strategy is triggered. Base on decisions of the DCA strategy, customers are requested to curtail their load accordingly. If the system’s frequency is still lower than 59.6 Hz after the operation of DCA, gas turbines are requested to ramp up in order to increase system’s frequency.

Instead, once the frequency is higher than 59.6 Hz after the DCA’s operation, any customers who accepted the load curtailment requests need to keep their load equally or lower for 15 minutes. If the solar energy comes back during this 15-minute gap, gas turbines are requested to ramp down in order to avoid high frequency of the system. The flow chat of the DCA operation is shown in Figure 5-7.

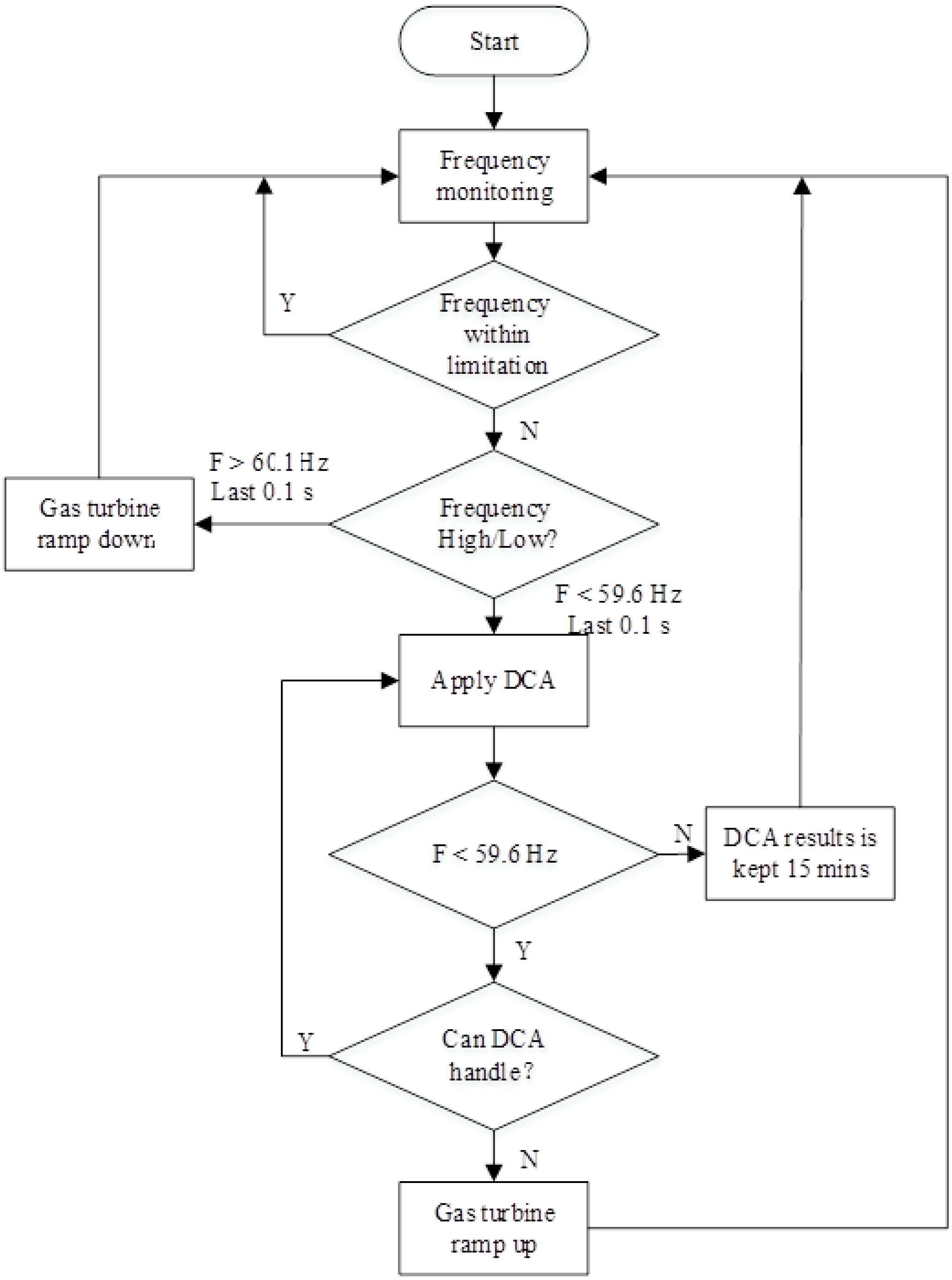


Figure 5-7. The operation of the DCA

5.2.3 Results of the Case Study

In this part, case study for a single DCA event is simulated to compare the performance of proposed DCA approach implemented with different encryption methods. Four case studies are compared: DCA with non-encryption method, DCA with 3DES, DCA with AES and DCA with Blowfish.

During one day, solar energy output has several sudden decreases. In this section, the chosen decrease happens at around 14:45 pm is used for the single DCA event case study. The solar energy output for the whole day and the DCA event period are shown in Figure 5-8.

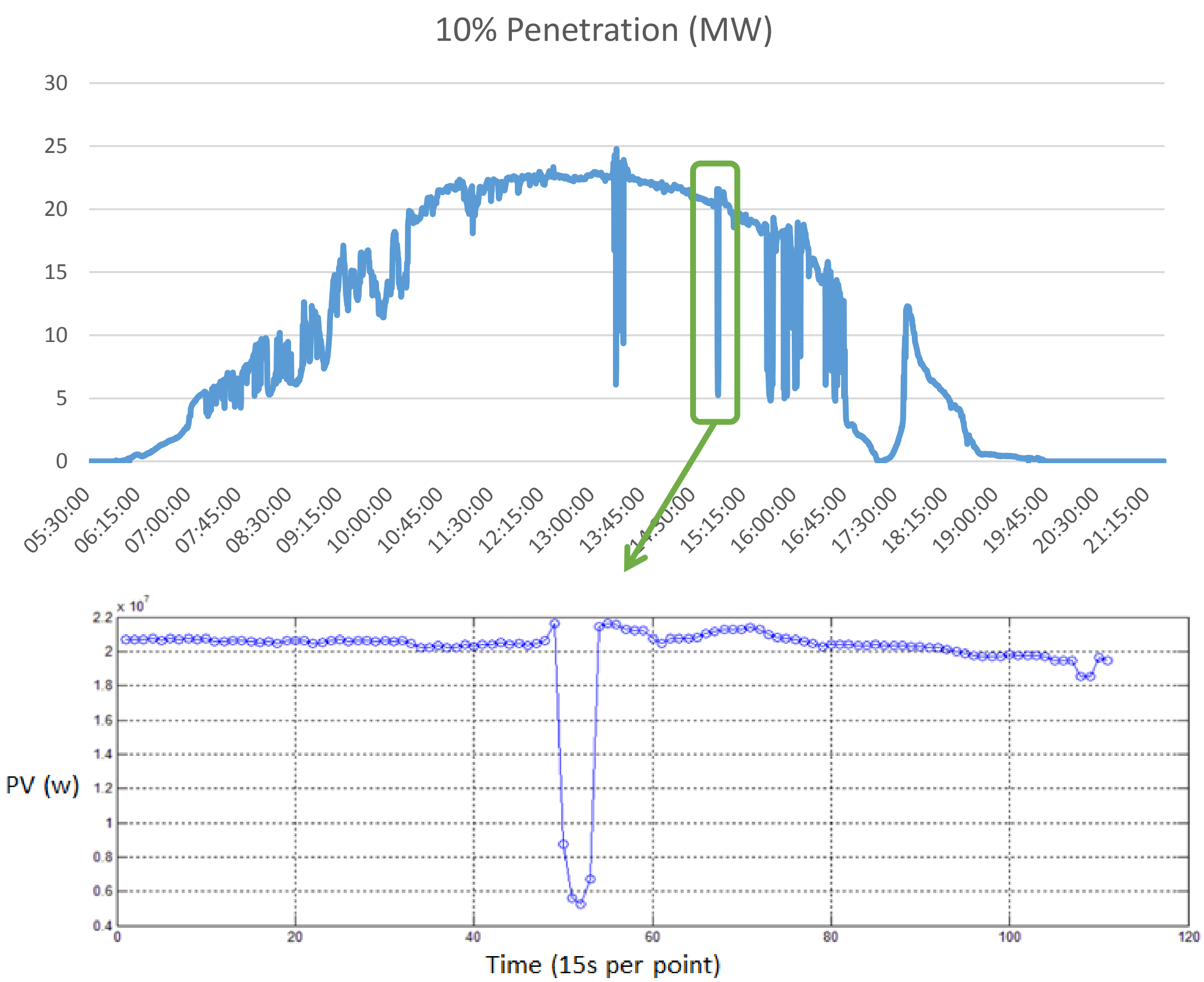


Figure 5-8. The drop of the solar output

The data for solar energy output is available every 15 seconds interval. As a result, it is assumed that the solar output is constant during the 15-second gap. The solar energy output is summarized in Table 5-3. The load during this period is 252 MW.

Table 5-3. The solar output

	Solar Output (MW)	Difference (MW)
14:49:45	21.89	N/A
14:50:15	8.72	13.17
14:50:30	5.61	3.11
14:50:45	5.25	0.36
14:51:00	6.88	-1.63
14:51:15	21.88	-15

Non-encryption method

In the first case study, DCA's commands are implemented without any encryption method. The latency includes three parts. First, it is the observation period. Once the frequency is lower than 59.6 Hz, it needs to last 0.1 second to trigger the DCA. Second, it is the communication latency which is assumed as 0.6 second without encryption method. The detailed calculation and simulation are shown in previous sections. Third, it is the function latency of the relay. Once the command is received by smart appliances at home, the relay takes around 0.1 second to realize its function, such as shutting down or turning down appliances. The total operation latency is shown in Figure 5-9.

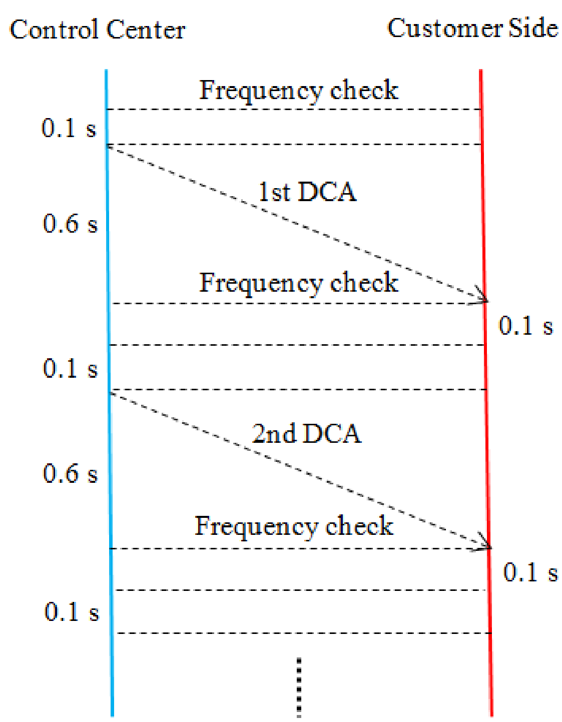


Figure 5-9. Operation latency for DCA without encryption method

The simulation result is shown in Figure 5-10. At 14:50:00, the solar output lost 13.17 MW and then, another 3.11 MW is lost within 30 seconds. As a result, the frequency is lower than 59.6 Hz at round 14:50:22. The observation takes 0.1 second. The DCA is triggered since the frequency is still lower than 59.6 Hz at 14:50:23. Based on the droop slop rate of the system, the 14-bus system needs to curtail 10.505 MW. After the first step of the DCA requirement, the frequency is still lower than 59.6 Hz. Another step of DCA requirement is needed at 14:50:27. Similarly, another 10.07 MW is required to be curtailed based the system's droop slop rate. After two steps of DCA requirements, the frequency increases and is higher than 59.6 Hz which is within its normal operation range.

At 14:51:15 PM, the solar energy output increases to 21.88 MW. In order to keep the frequency back to its normal range, the gas turbine begins to ramp down at ramp down rate of 25 MW per minute. In total, 15 MW are ramped down within 30 seconds. Finally, the frequency of the system is stable at around 60 Hz.

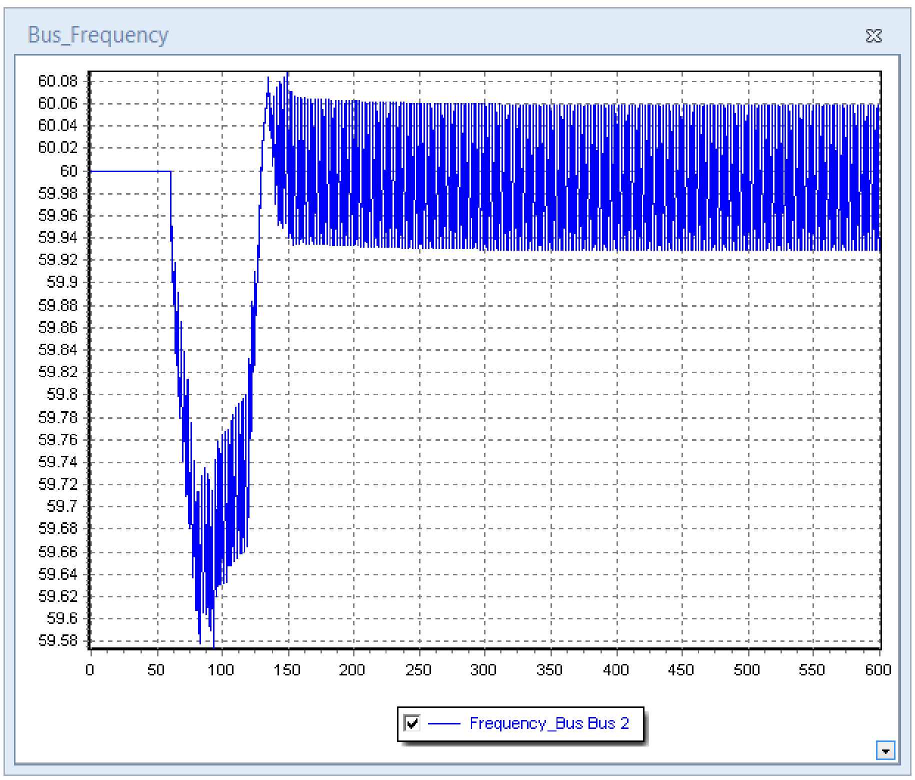


Figure 5-10. The simulation results without encryption method

With encryption methods: 3DES, AES and Blowfish

Different from the previous case study in which the DCA implemented without encryption method, the total latency in this section needs to add extra time delayed by processing time of encryption method: encryption processing time and decryption processing time.

As summarized in chapter 4, the overall network is controlled by the only one control center. The whole network includes 15 cellular cells. There are 46 data concentrators in each cellular cell. Each data concentrator is connected by 423 smart meters. Besides, it is assumed that each information packet has 100 bytes.

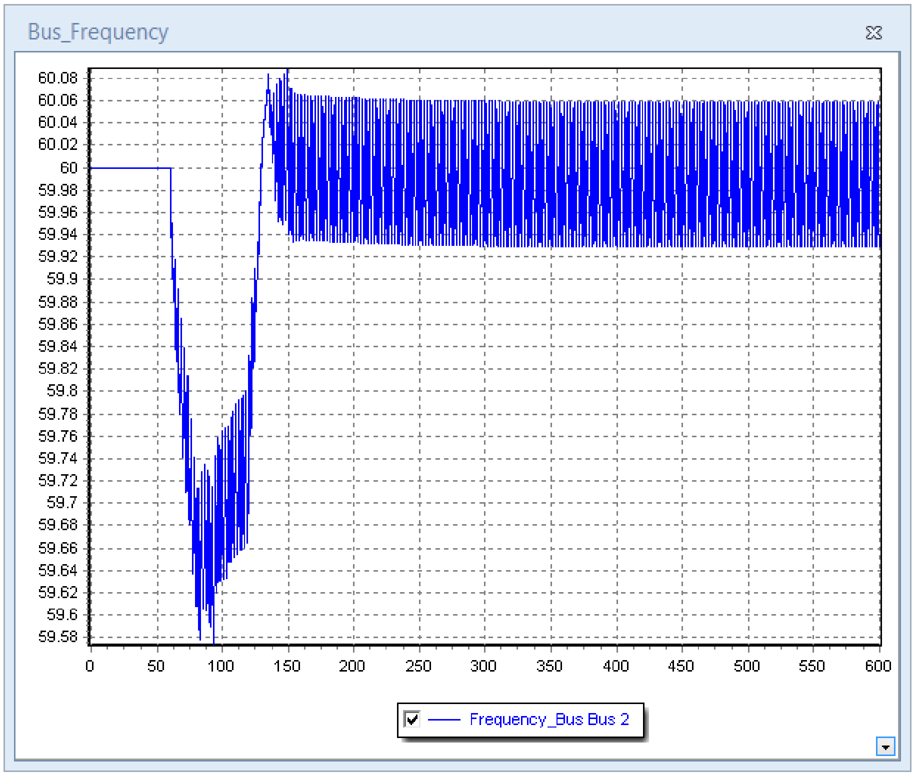
For DCA operation, the total data throughput is around 50 Mbits. As a result, at the control center, the encryption throughput is considered as 50 Mbits. At the data concentrator, the decryption throughput for the received information from the control center is around 1.08 Mbits. To forward the information, another encryption processing is needed. And the encryption throughput is 423*100 bytes. And the decryption throughput at home site is around 100 bytes.

The encryption methods' processing latency is calculated and summarized in Table 5-4.

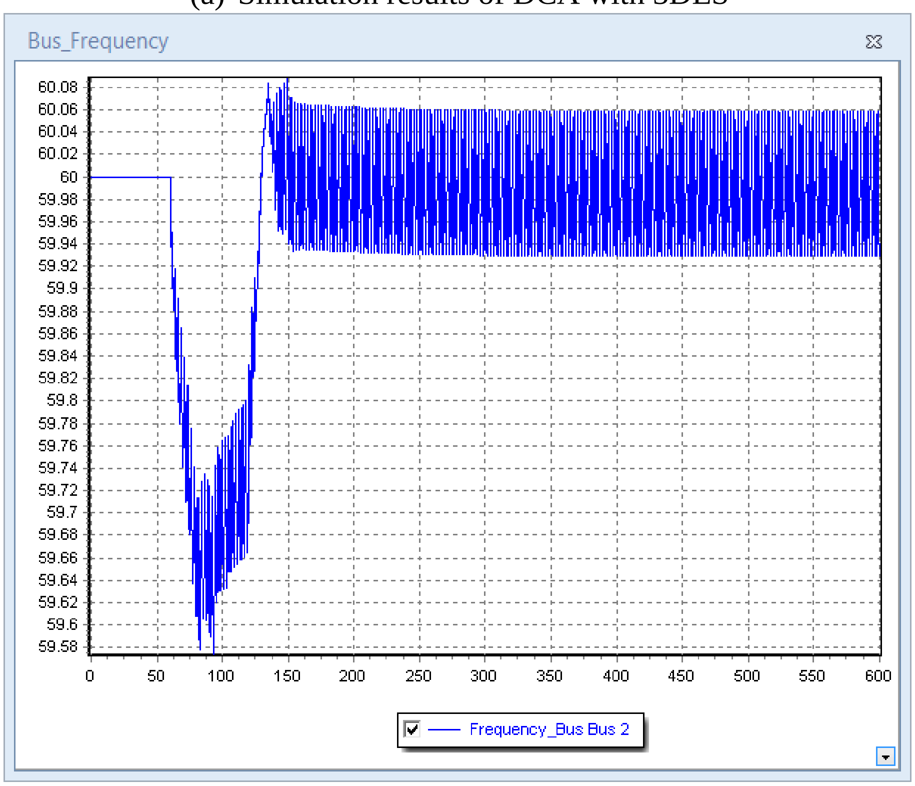
Table 5-4. Processing latency for three encryption methods

	Unit	3DES		AES		Blowfish	
		Encryption	Decryption	Encryption	Decryption	Encryption	Decryption
T1	Mbyte	6.25	0.136	6.25	0.136	6.25	0.136
	Mbyte/s	3.45	5.665	4.174	6.452	25.892	18.72
	second	1.8116	0.0240	1.4974	0.0211	0.2414	0.0073
T2	Mbyte	0.0423	0.0001	0.0423	0.0001	0.0423	0.0001
	Mbyte/s	3.45	5.665	4.174	6.452	25.892	18.72
	second	0.01223	1.765E-05	0.0101	1.549E-05	0.0016	5.341E-06
Total	second		1.8479		1.5286		0.2503

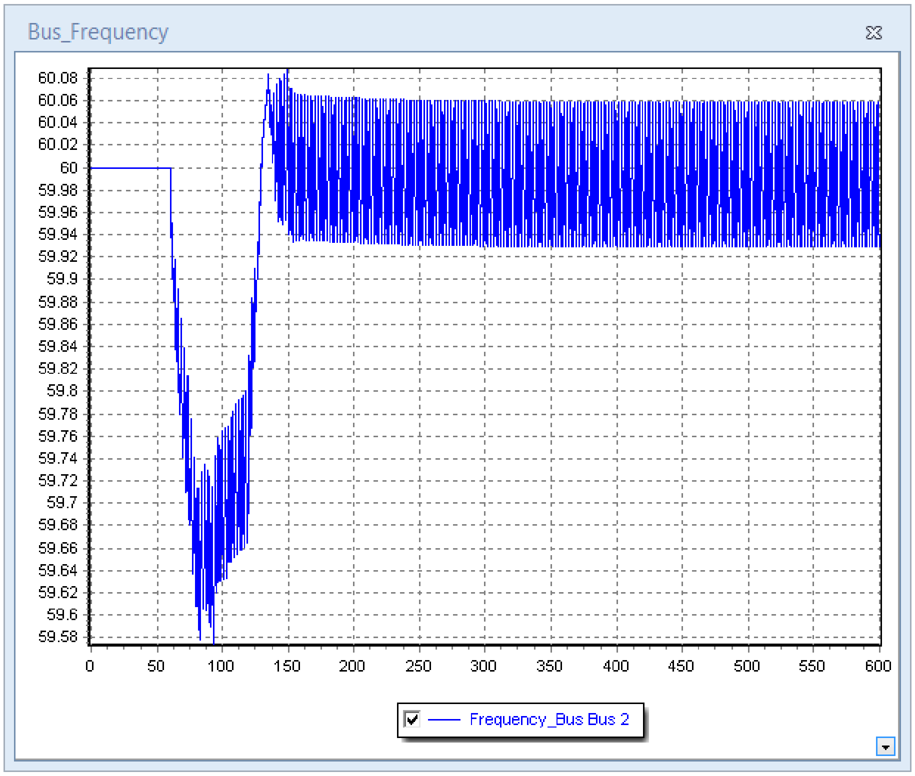
Simulation results for case study using 3DES, AES and Blowfish are shown in Figure 5-11.



(a) Simulation results of DCA with 3DES



(b) Simulation results of DCA with AES



(c) Simulation results of DCA with Blowfish

Figure 5-11. The simulation results using 3DES, AES and Blowfish

From case study results, the performance of DCA with different encryption methods is summarized in Table 5-5. In all four cases, operations of the DCA can keep the system operation frequency within its normal range during the sudden change of solar energy output. The slower the encryption processing speed is, the larger the amount curtailment is requested. In this single DCA event, DCA's operation can function normally with different encryption methods implemented.

Table 5-5. DCA performance with different encryption methods

	Non-encryption	3DES	AES	Blowfish
Steps of DCA	2	2	2	2
First step DCA (MW)	10.25	10.25	10.25	10.25
Second step DCA (MW)	10.25	10.50	10.60	10.28
Total curtailment (MW)	20.50	20.75	20.55	20.53

5.3 Case Study: Whole Day

In this section, performances of DCA with different encryption methods (3DES, AES and Blowfish) during the whole day are compared. In the first part, the sudden significant changes of solar energy output during the whole day are summarized. And then, case studies about DCA's operation under two different PV penetration levels (10% and 20%) are simulated. At last, the effects from encryption methods on the performance of DCA are compared and summarized.

5.3.1 Summary of the Solar Energy Output

In this section, the solar energy output used in the case study is from the same day in previous case. During normal hours, the total load of the system is balanced by total outputs from traditional generators, gas turbines and the solar PV. The frequency of the system is around 60 Hz. Only if the solar energy output decreases significantly and suddenly, the system needs DCA strategy, gas turbine or ULFC to keep its frequency within its normal working limitation.

The solar energy output during the whole day and the zoomed solar dropping periods are shown in Figure 5-12. Starting points for each event and amount of load at those periods are summarized in Table 5-6.

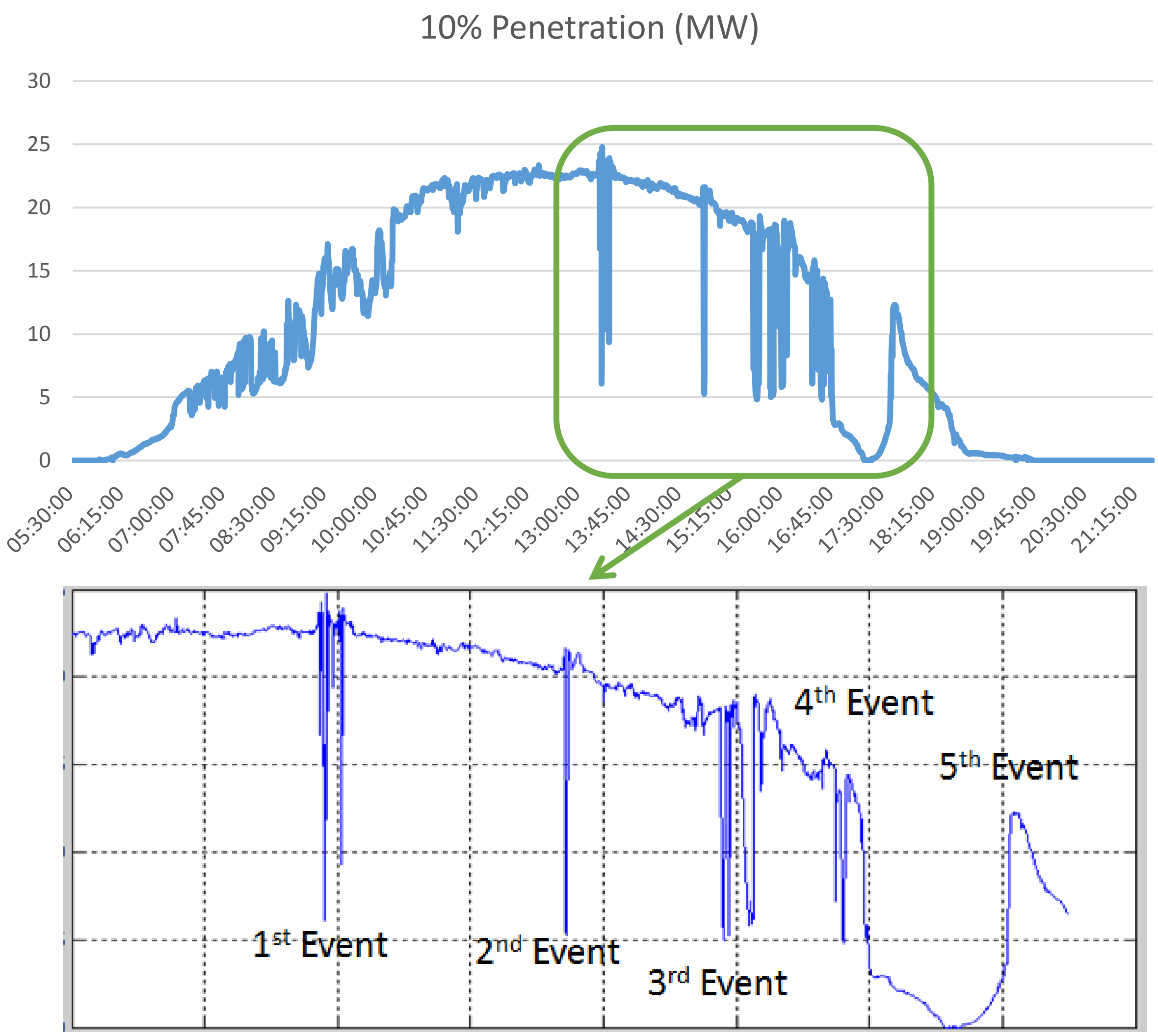


Figure 5-12. Solar energy output

Table 5-6. Starting point of each event and sized of load

	1st Event	2nd Event	3rd Event	4th Event	5th Event
Time	13:17:30	14:49:00	15:48:00	16:31:00	17:36:00
Load (MW)	238	249	249	246	246.7

5.3.2 **Case study: 10% and 20% of PV Penetration Level**

In this part, the simulation lasts the whole day with five significant and sudden changes of solar energy outputs. Case studies (3DES, AES and Blowfish) are simulated with different PV penetration levels (10% and 20%).

The first event

The first event happens at 13:17:30 PM. The solar energy output drops from 23.69 MW. At the meantime, the system load is around 238 MW. The detailed solar energy output is shown in Figure 5-13. Simulation results of DCA with different encryption methods under two PV penetration levels are shown in Figure 5-14.

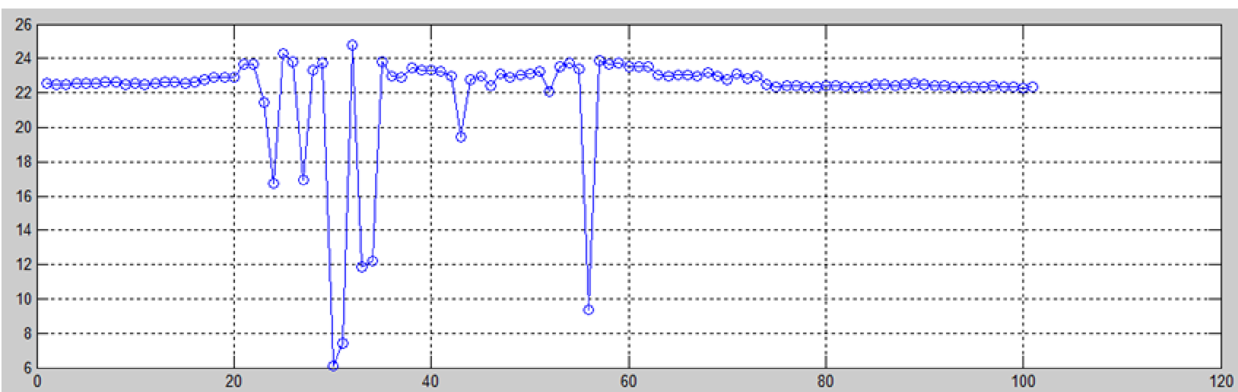
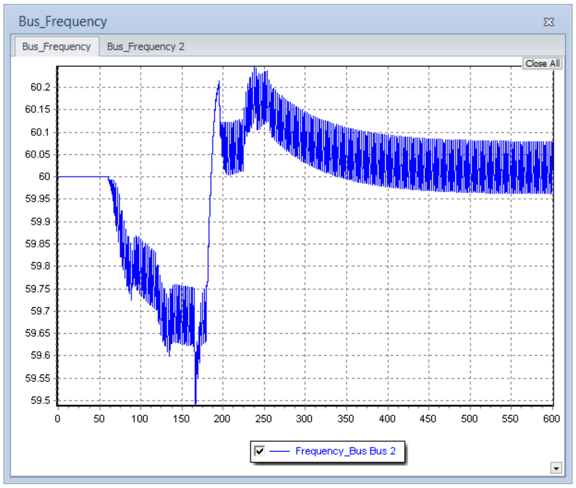
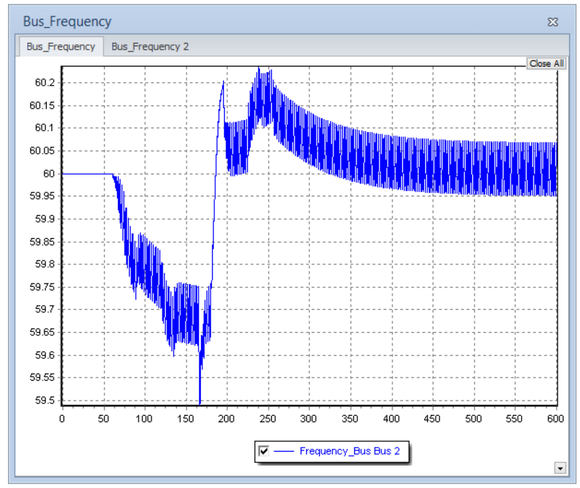


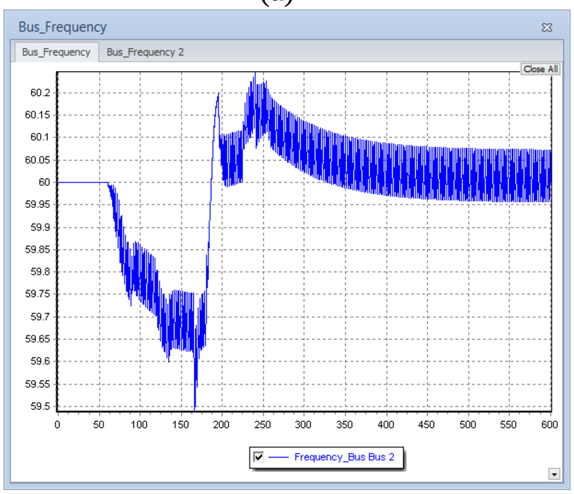
Figure 5-13. The solar energy output for the first event



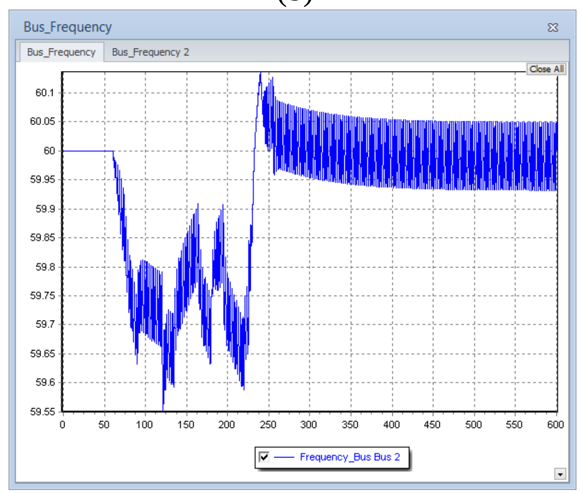
(a)



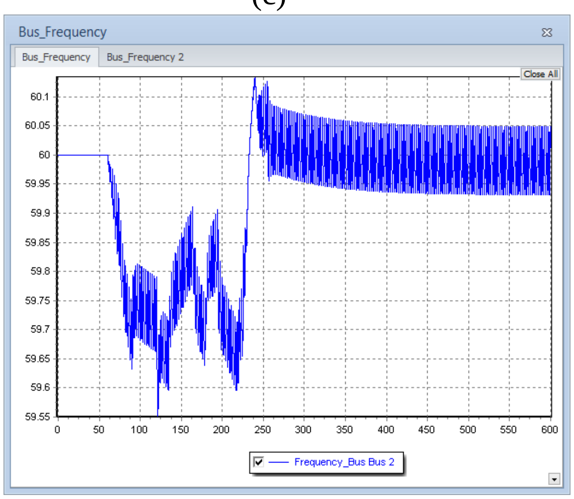
(b)



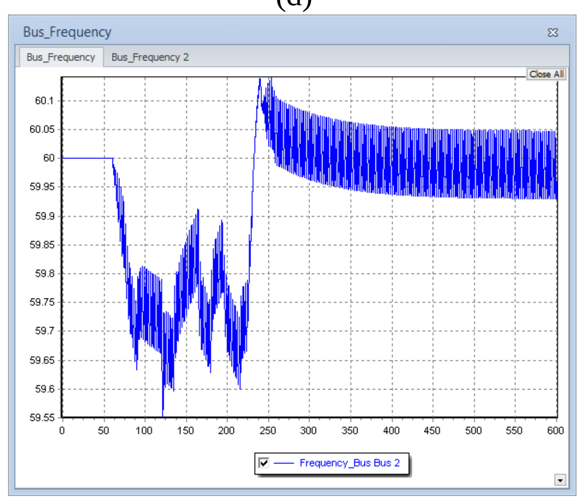
(c)



(d)



(e)



(f)

Figure 5-14. Simulation results for the first event

(a) DCA with 3DES under 10% PV penetration level; (b) DCA with AES under 10% PV penetration level; (c)DCA with blowfish under 10% PV penetration level; (d)DCA with 3DES under 20% PV penetration level; (e)DCA with AES under 20% PV penetration level; (f) DCA with Blowfish under 20% PV penetration level.

The second event

The second event happens at 14:49:00 PM. The solar energy output drops from 22 MW. At the meantime, the system load is 249 MW. The solar energy output is shown in Figure 5-15. Simulation results of DCA with different encryption methods under two PV penetration levels are shown in Figure 5-16.

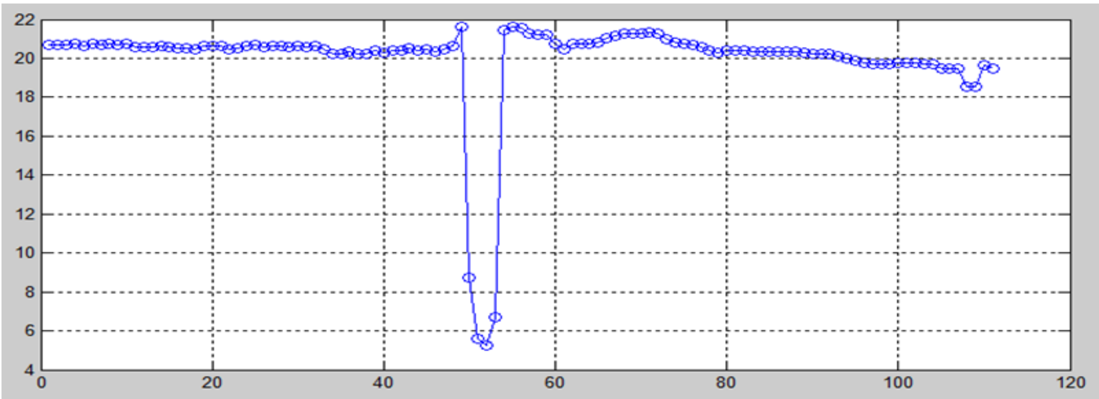
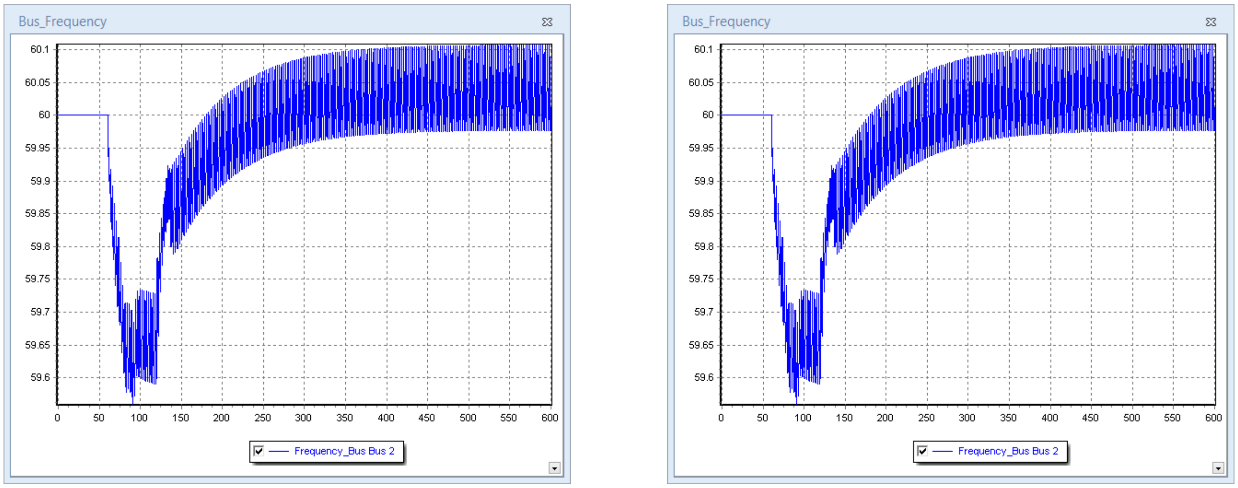
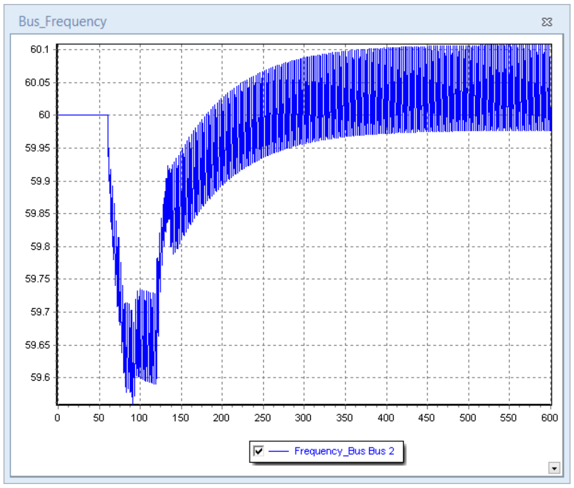


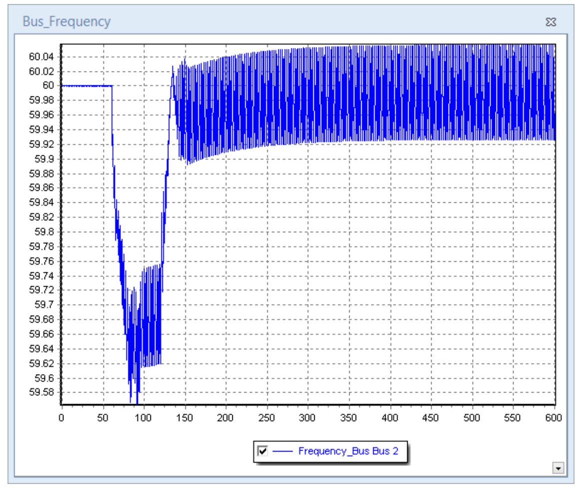
Figure 5-15. The solar energy output for the second event



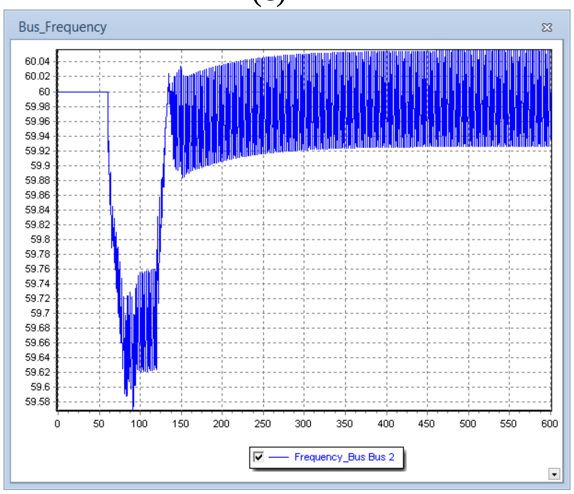
(a) (b)



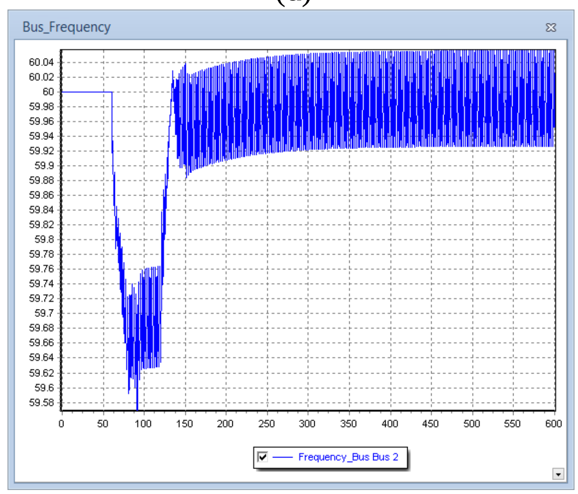
(c)



(d)



(e)



(f)

Figure 5-16. Simulation results for the second event
(a) DCA with 3DES under 10% PV penetration level; (b) DCA with AES under 10% PV penetration level; (c)DCA with blowfish under 10% PV penetration level; (d)DCA with 3DES under 20% PV penetration level; (e)DCA with AES under 20% PV penetration level; (f) DCA with Blowfish under 20% PV penetration level.

The third event

The third event happens at 15:48:45 PM. The solar energy output drops from 18.22 MW when the system load is 249 MW. The third event can be further divided into two parts. In the first part, the solar energy output drops suddenly and comes back within 5 minutes. In the second part, the solar energy output begins to decrease smoothly at around 15:53:00 PM. It is assumed that the decreased solar output is covered by outputs of traditional generators and gas turbines. The frequency is still around 60 Hz. At 16:00:00 PM, the solar energy output increases suddenly. The gas turbines ramps down in order to keep the frequency within its normal operation limitation. In the second part, since the operation of gas turbine is controlled by the control center directly and

DCA doesn't execute, simulation results won't be affected by encryption methods and are same for different encryption methods.

The solar energy output is shown in Figure 5-17. Simulation results of DCA with different encryption methods under two PV penetration levels are shown in Figure 5.18 and Figure 5.19.

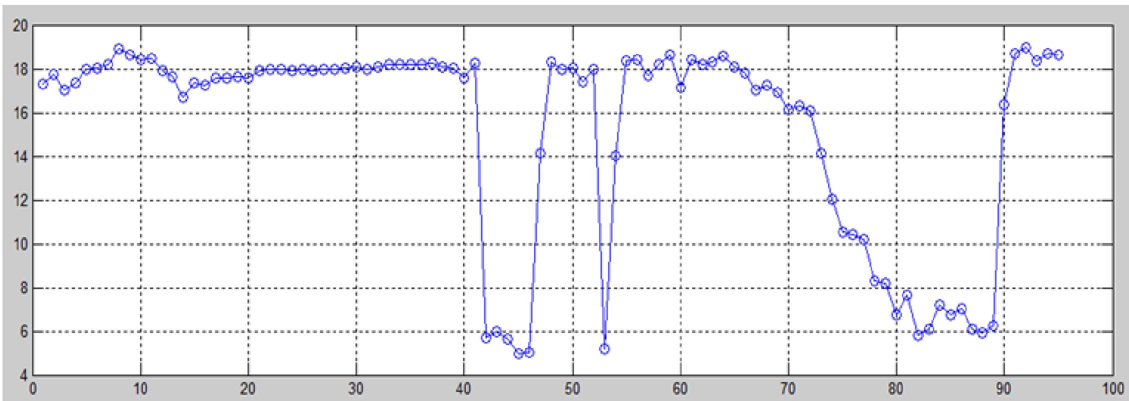
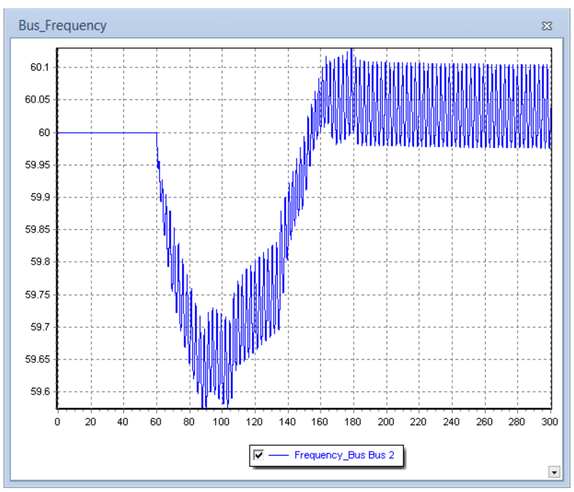
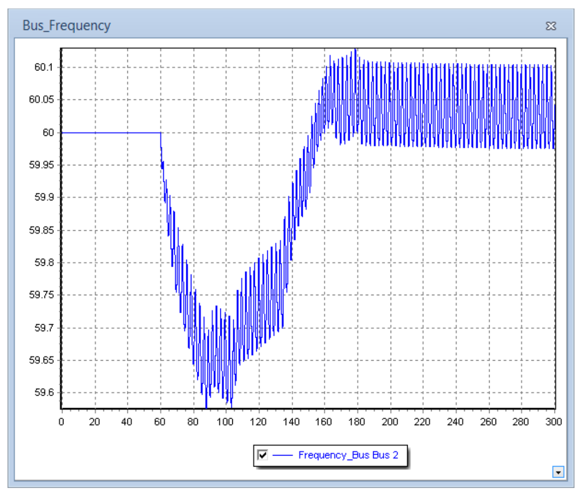


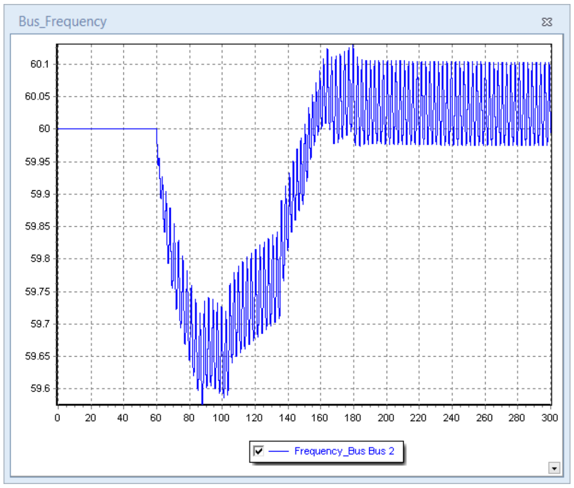
Figure 5-17. The solar energy output for the third event



(a)



(b)



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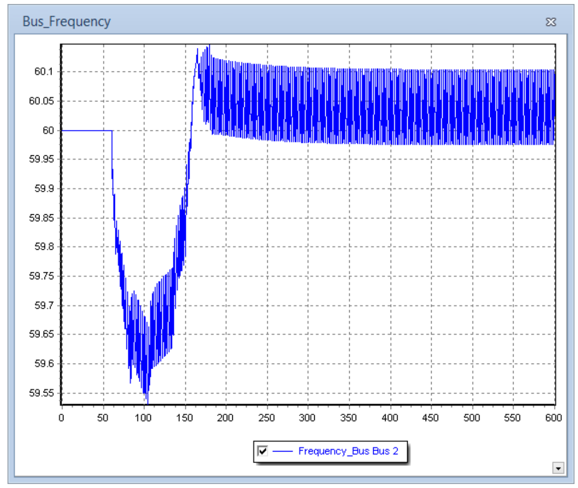

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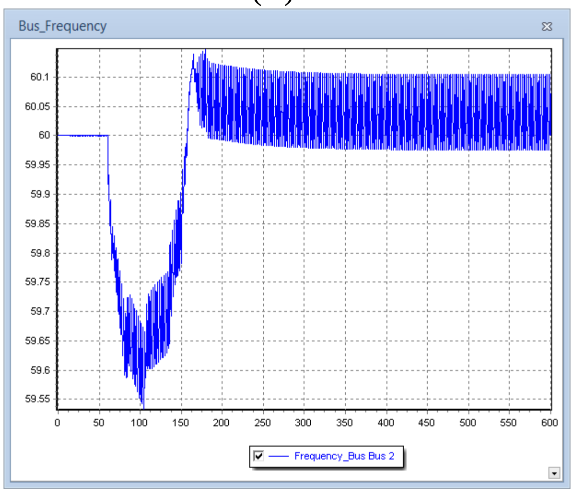

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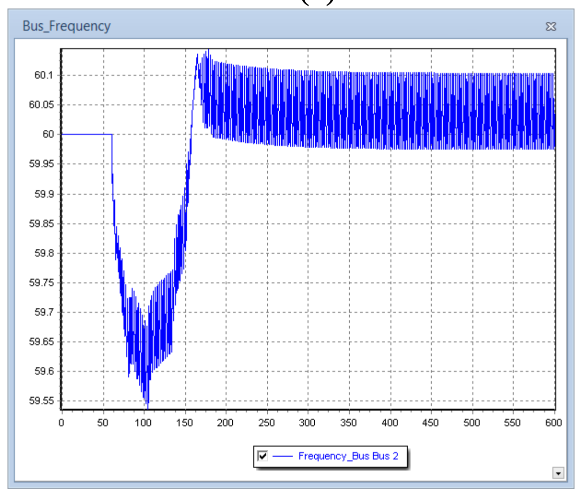


(f)

Figure 5-18. Simulation results for the third event (part 1)
(a) DCA with 3DES under 10% PV penetration level; (b) DCA with AES under 10% PV penetration level; (c)DCA with blowfish under 10% PV penetration level; (d)DCA with 3DES under 20% PV penetration level; (e)DCA with AES under 20% PV penetration level; (f) DCA with Blowfish under 20% PV penetration level.

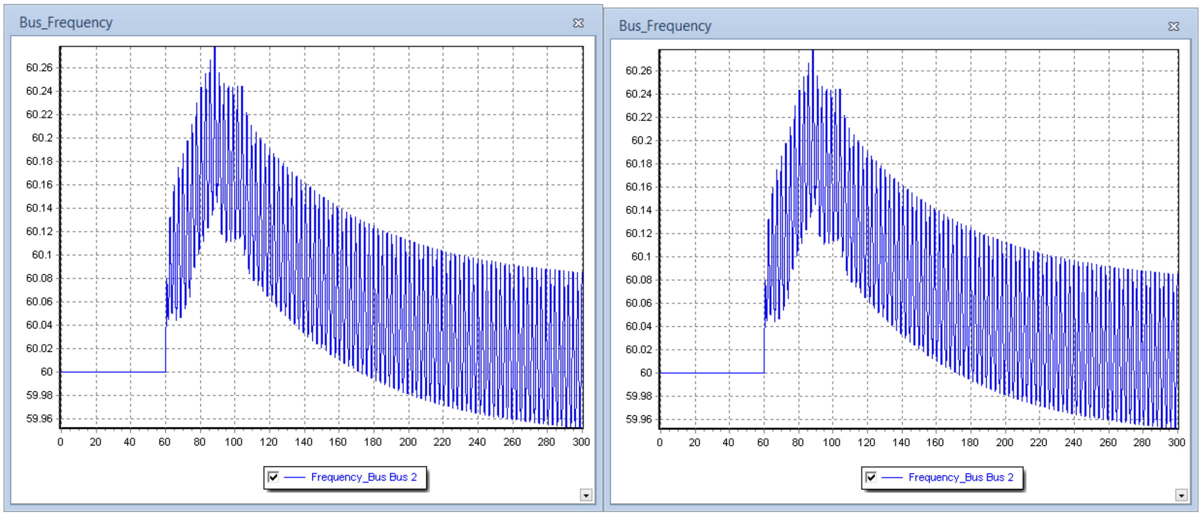


Figure 5-19. Simulation results for the third event (part 2)

The fourth event

The fourth event happens at 16:31:15 PM. The solar energy output drops from 15 MW. And the system load is 246 MW. The solar energy output is shown in Figure 5.20. Simulation results of DCA with different encryption methods under two PV penetration levels are shown in Figure 5-21.

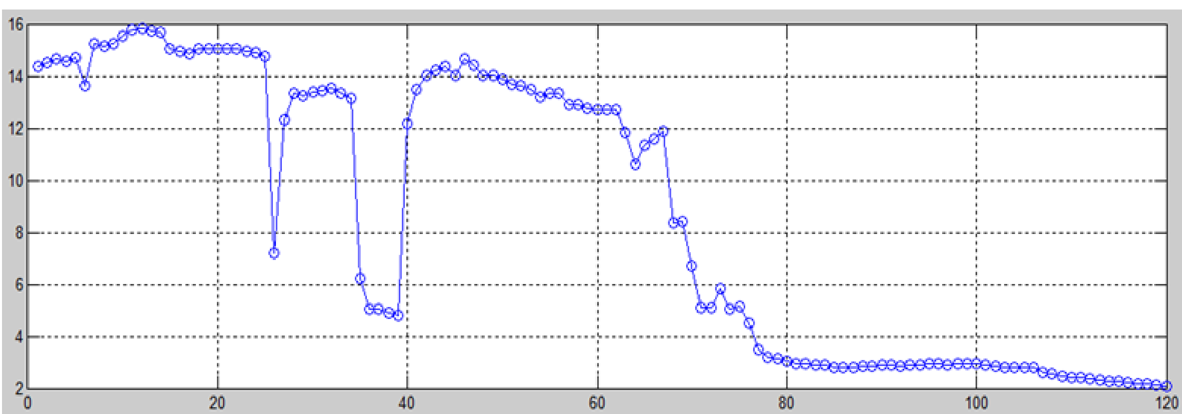
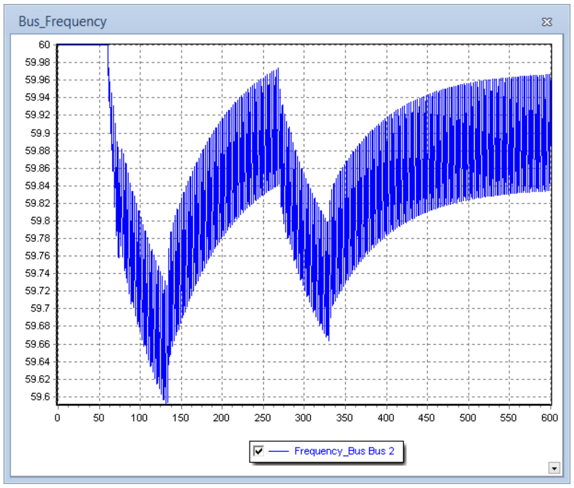
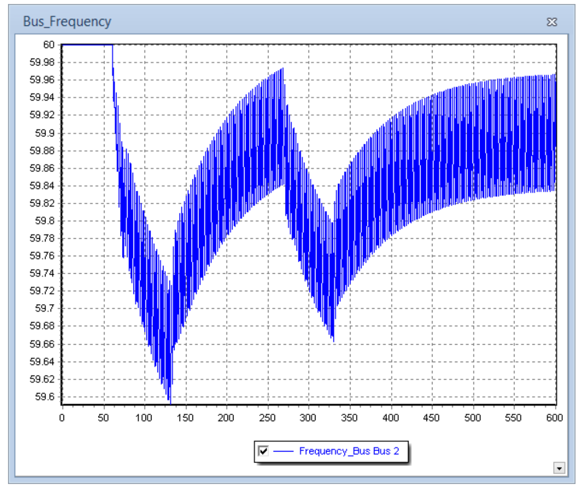


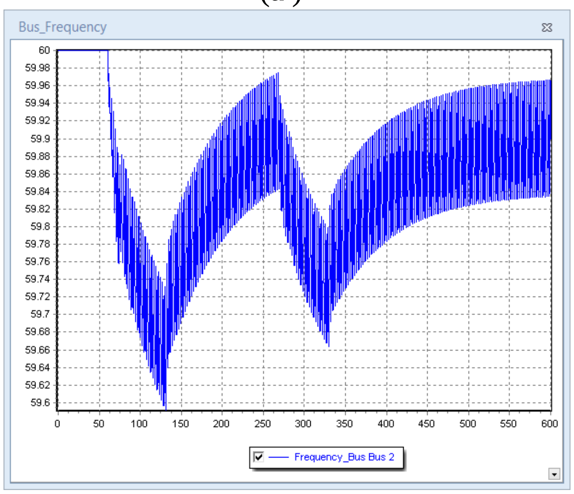
Figure 5-20. The solar energy output for the fourth event



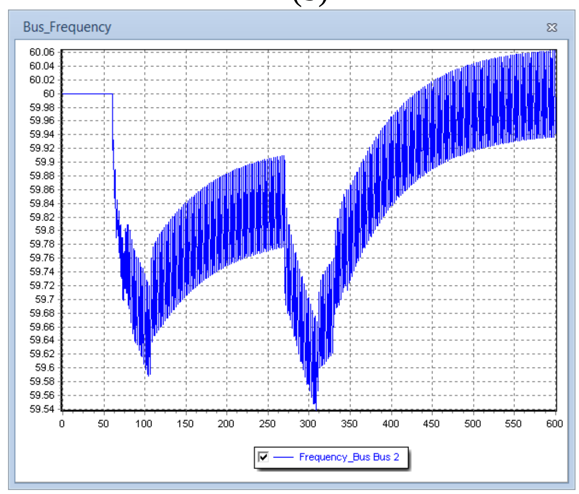
(a)



(b)



(c)



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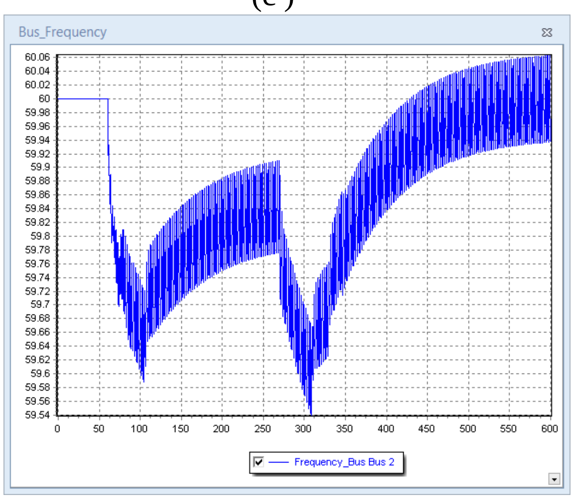

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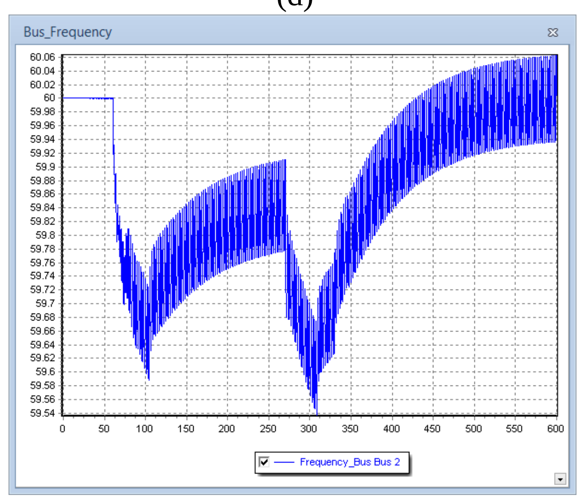

(f)

Figure 5-21. Simulation results for the fourth event
(a) DCA with 3DES under 10% PV penetration level; (b) DCA with AES under 10% PV penetration level; (c)DCA with blowfish under 10% PV penetration level; (d)DCA with 3DES

under 20% PV penetration level; (e)DCA with AES under 20% PV penetration level; (f) DCA with Blowfish under 20% PV penetration level.

The fifth event

The fifth event happens at 17:36:45 PM. The solar energy output is 3.6 MW when the system load is around 246.7 MW. The solar output is zoomed and shown in Figure 5-22. Same as the second part of the third event, since the operation of gas turbine is controlled by the control center directly and DCA doesn't execute. Simulation results are not affected by encryption methods and are same for different encryption methods. Simulation result is shown in Figure 5-23.

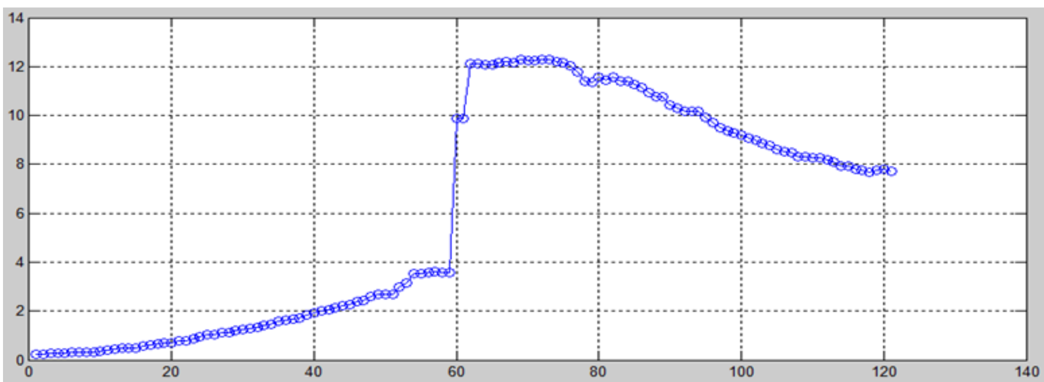

Figure 5-22. The solar energy output for the fifth event

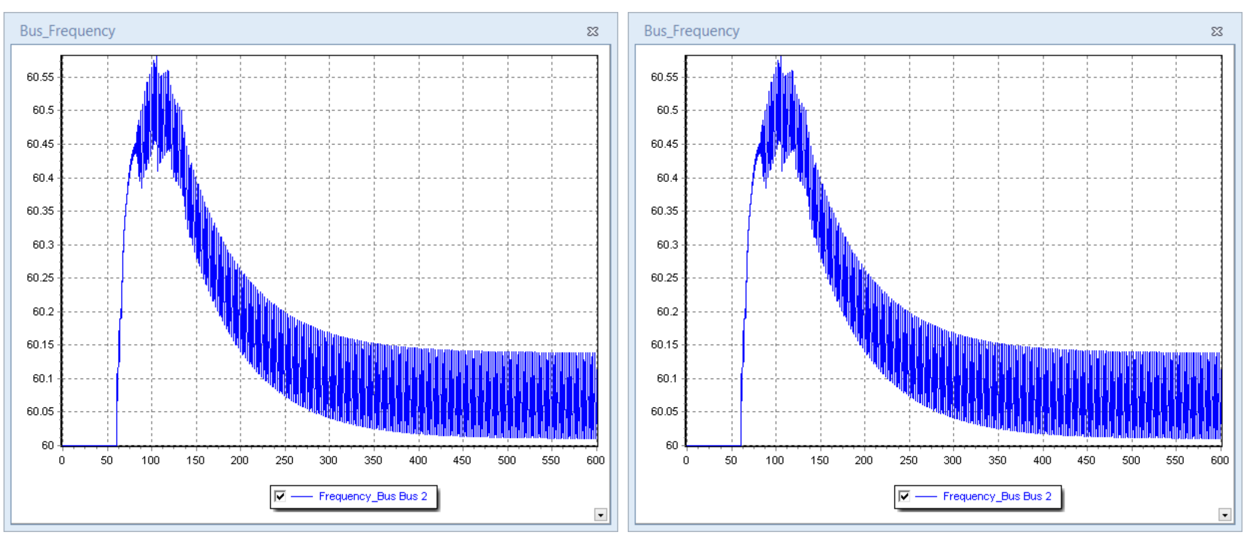

Figure 5-23. Simulation results for the fifth event (10% and 20% PV penetration level)

5.3.3 Summary

In the last section, case studies for the whole day with different encryption methods and two PV penetration levels are simulated. The total amount of curtailment or the amount of gas turbine ramping down for each case study is summarized in Table 5-7 and Table 5-8.

Table 5-7. Simulation results with 10% PV penetration level

WM	1st Event	2nd Event	3rd Event (1)	3rd Event (2)	4th Event	5th Event
3DES	21.150	20.750	20.492	-10.5	10.259	-6.1
AES	20.912	20.558	20.475	-10.5	10.256	-6.1
Blowfish	20.815	20.525	20.465	-10.5	10.250	-6.1

Table 5-8. Simulation results with 20% PV penetration level

WM	1st Event	2nd Event	3rd Event (1)	3rd Event (2)	4th Event	5th Event
3DES	20.452	20.503	20.513	-12.5	20.558	-11.5
AES	20.431	20.433	20.506	-12.5	20.555	-11.5
Blowfish	20.407	20.430	20.503	-12.5	20.548	-11.5

In all case studies, implementing with DCA, the system frequency can be kept within its normal operation range when facing the significant decreasing of solar energy output. In this chapter, three commonly applied encryption methods are simulated with the operation of DCA. As the simulation results shown, applying encryption methods (3DES, AES and Blowfish) don't have effects on the operation of DCA.

5.4 Conclusion

In this chapter, case studies are presented to show the performance of the novel DCA approach when facing sharp decrease of renewable energy during the whole day. Multiple demand curtailment allocation events are simulated in the case study. The performance of the proposed demand curtailment approach is evaluated considering the implementation of cyber security technologies. The performance of encryption methods, e.g., 3DES (Triple Data Encryption Standard), AES (Advanced Encryption Standard), Blowfish, etc. are compared taking into account extra data rates and the processing time. At last, the limitation of applying different encryption methods to secure the proposed demand curtailment allocation approach is analyzed.

6. CONCLUSION AND FUTURE WORK

6.1 Conclusion

In order to provide a remedy for the sudden loss of generations such as generator trips, failure of transmission lines and sudden drop in renewable energy outputs, this dissertation proposes an expert-based demand curtailment allocation approach, which is pre-calculated but dynamically readjusted, if needed. It can curtail end-use loads faster than traditional DR programs and prevent UFLS operations. Specifically, it is an approach to manage the electrical demand using inputs from experts and information about DR potential and load curtailment priority level. The proposed approach takes into account the DR potential (according to different load classifications) and load curtailment priority (using an AHP method) of each distribution substation (DS). AHP criteria contains DS loading ratio, DS capacity, load type (deferrable, interruptible and critical), and customer types (residential and commercial).

The performance of the communication network supporting the demand curtailment implementation is evaluated to determine how rapidly the proposed demand curtailment strategy can be implemented. Since a number of smart grid applications share the same communication network, the performance of this communication network is also evaluated considering simultaneous operation of popular smart grid applications.

Lastly, this dissertation also analyzes additional processing and transmission delays caused by implementing selected encryption methods (3DES, AES and Blowfish encryption methods) on the proposed demand curtailment allocation strategy.

6.2 Future Work

The proposed demand curtailment allocation strategy is proved can be implemented to balance the sudden loss of energy outputs. And it can prevent UFLS operation due to its fast operation. Nonetheless, this dissertation assumed the ratio of capacity change (MW) to frequency change (0.1Hz) is well-estimated. Besides, the performance of communication network and the power system are simulated and analyzed separately using different software packages. This work can be extended by using a co-simulation platform which can lead to a more in-depth analysis for both the power system and the communication system working together. As a result, there are two possible future work paths.

Dynamic sensitivity factor

In this dissertation, the frequency response of the IEEE 14-bus system is estimated at 27.1 MW/0.1Hz by simulating frequency decline events.

However, the frequency response for a large power system is difficult to estimate as it dynamically changes during a day. It also changes when different types of power generating sources involved. Different types of load also impact the frequency response. A future work can be to study and provide accurate estimation of frequency response throughout a day given detailed characteristics of system's loads and generation.

Setting up a real-time co-simulation platform

PowerWorld, MATLAB/Simulink, GridLAB-D, RT-LAB are popular power system simulation tools. OPNET, NS2/ NS3 and OMNeT++ are popular communication and network simulators. Nonetheless, neither simulation tools for power system analysis consider the impact from communication systems, nor can communication system simulators provide power system analysis. By combining both power system and communication network simulators, a co-simulation platform can be developed that enables simulations of electric power systems that take into account communication network properties, such as Quality of Service (QoS), latency, etc. It allows realistic studies of smart grid operations integrated with communication systems.

A real-time co-simulation platform needs an interface that can enable the information exchange between two simulators. The synchronization of two simulators relies on this interface, which serves as a data buffer that allows real-time packet exchanges using protocols, like TCP or UDP. In a real-time co-simulation platform, two simulators run synchronously. As an advantage, a real-time co-simulation platform can handle large and complex systems without manual intervention. Figure 6-1 shows an example real-time co-simulation platform using Java, OPNET and OPAL-RT.

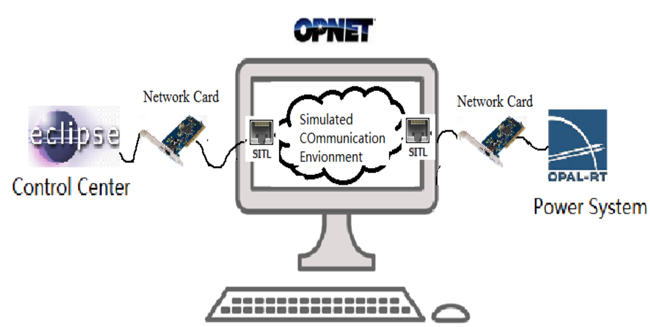

Figure 6-1. Connection among OPAL-RT, OPNET and Java Eclipse.

Reference:

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