AN EFFICIENT DEMAND-SIDE LOAD SHEDDING ALGORITHM
IN SMART GRID

By

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Abstract

Rapid advances in the smart grid technology are making it possible to tackle a lot of problems in the aged power systems. High-speed data acquisition system, high-voltage power electronic equipment, advanced utility and customer interaction technologies, as well as distributed renewable generation are enabling the revolution in the electric power generation, delivery and distribution. Through the implementation of ubiquitous metering and communication networks, the customers would no longer be a passive receiver of the electrical energy, but instead, an active participant in the power system and electricity market. They can not only sell their own energy to the utility, but also take part in the emergency restoration in the power grid. Nonetheless, some technical barriers are encountered during this revolution, such as difficulties in integrating home automation, smart metering, customer interaction and power system operation into the whole system.

This thesis proposes a customer involved load shedding algorithm for both the power system frequency control and the micro-grid islanding. This new algorithm possesses the features of centralized load control and distributed load control, which fully utilizes the advantages of hierarchical communication networks along with the home automation. The proposed algorithm considers the reliability of the power grid as well as the comfort of the electricity users. In the power distribution system, the high-level control centre is responsible for coordinating the local load controllers, whilst the local controller takes charge of frequency monitoring and decision making. In the micro-grid, a centralized control strategy is adopted to better serve the system with the wide set of information available at the micro-grid control centre. The simulation results have demonstrated the correctness and feasibility of the proposed algorithm. Finally, the hardware implementation further tests the validity of the wireless sensor networks serving as the system’s monitoring and communication technology.
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Chapter 1

Introduction

Conventional power systems are huge energy generation, transmission and distribution networks. Given the critical role of electrical energy in the daily activity of human beings, maintaining the reliable operations of these power networks is essential. Nonetheless, in the aged power systems, the monitoring and protection apparatus is mostly mechanical device and usually out-of-date, which cannot provide guaranteed reliability for energy delivering and flow control. In addition, the system measurements are gathered from a low-speed communication network, called SCADA (Supervisory Control and Data Acquisition) system. Due to the technology constraint of SCADA system, only a limited amount of measurements can be gathered to perform regional sub-optimized control decisions. Under emergency situations, like over voltage or over current in the transmission lines, protection mainly depends on the action of protection relays to cut off fault lines; however, this kind of protection method may not only induce a large-area blackout, but also trigger further serious problems to the rest of the system. The 2007 North American blackout has already sounded the alarm for this aged system [1].

In light of this, now researchers are trying to construct a more intelligent system that incorporates the advanced techniques in control and communications, which is called smart grid [2]. A proposed infrastructure of the smart grid is shown in Fig. 1.1.
1.1 Motivation

In conventional power systems, out of the limitations of the communication infrastructure, the electrical measurements are only collected from some power plants and distribution substations through low-speed SCADA system. No detailed customer level measurements are available through these communication networks. On the other hand, the control of the power flow and emergency protection relies basically on mechanical equipment, such as under-frequency relays, tap-changers and circuit breakers. Problems associated with this kind of mechanical equipment
are low intelligence, low flexibility; and sometimes these may lead to complicated control analysis and design issues.

To deal with the problems in the aged power system, the smart grid concept is proposed that can incorporate a variety of technologies from various fields to enhance the intelligence and reliability of the system. One of the critical issues is to utilize modern wide-range communication networks to involve electricity end users in the power system emergency restoration activities, which is called demand-side load control. To do so, a two-way communication network and a reliable interaction mechanism between utilities and customers are indispensable. In addition, the design of new control algorithms to facilitate these interactions is equally important which needs to meet the requirements of corresponding power system operations, and meanwhile minimize customer discomfort. A number of studies have already been proposed for demand-side load control in the past few decades, although none of them have been applied to real systems. There are several reasons behind that: (a) some techniques are too complicated to incorporate into the current systems; (b) some techniques need a lot of support from the communication infrastructure, thus realizing it needs high-cost dedicated communication networks; (c) other techniques expose too much power consumers’ private information, making it hard to accept for the customers; (d) it is hard to test the performances and effects of these techniques in the huge power systems, which involves both the power grid and the end users’ behaviors.

In this thesis, we will propose a new load shedding algorithm that fully utilizes the advantages of modern communication networks so that power consumers could be involved in the emergency control activities, and at the same time, we try to overcome the problems in the previous studies as listed above.
1.2 Thesis Contribution

To deal with the problems associated with previous demand-side load control and to make the proposed load control algorithm practical, this thesis tries to cite a thorough study of the demand-side load control, from the customer side to the system side, from the control systems to the communication technologies, from the system simulation to the hardware implementation. The main contributions of this thesis are listed as following: We

1. Propose a new demand-side load shedding algorithm. It is the focus of this thesis. The proposed algorithm combines the features of centralized load control with distributed load control to achieve a good system performance and enough flexibility. It accommodates the applications in both bulk power grids and small micro-grids. Meanwhile, it has a low system complexity and thus easy to realize in power systems.

2. Take into account the home energy management in end user’s houses. In this thesis, we will exemplify a simple home energy management method that not only has a low complexity, but also protects customers’ privacy very well.

3. Simulate the algorithm on both the IEEE 14 bus test system and a small micro-grid. We establish the models of the end users’ power consumption as well as the communication and control network delay to make the simulation approach the reality. In the IEEE 14 bus simulation, the proposed algorithm is fully verified under system frequency drop; while in the micro-grid simulation, it is tested for its ability to stabilize the system voltage when islanding takes place. Those two scenarios are the most probable applications for the proposed algorithm.

4. Experimentally implement the smart metering networks with wireless nodes. We interface the power meters with the CC2530 wireless nodes to remotely acquire the
measurements from the output port of the AC load and solar converters. Given the limitations of the equipment in the lab, we are unable to construct a real micro-grid system to verify the algorithm, but the basic technologies and ideas remain unchanged.

1.3 Thesis Outline
As an overview of the thesis, in chapter 2, a literature review of the previous studies will be given. It explains the modern smart grid concept and the demand-side load control, as well as comparing other researchers’ work of centralized and distributed load control. In chapter 3, the proposed demand-side load shedding algorithm will be presented. Then the simulation results and analysis on IEEE 14 bus test system and the micro-grid will be given in chapter 4. Chapter 5 will explain the hardware and software implementation of the smart metering network, including the application realization on the ZigBee software stack, the interfacing between the wireless nodes and the power meters, and the measurement-exhibition GUI on the PC. Finally, chapter 6 will conclude the thesis with summary and recommended future work.
Chapter 2

Literature Review

In this chapter, some basic concepts of the smart grid and load control will be discussed, as well as the current research progress in these related areas. Indeed, a significant amount of research on demand-side load control has already been done; nonetheless, these techniques experience the practical problems we mentioned in the last chapter. The main purpose of this chapter is to clarify these problems and shortcomings and to concatenate different concepts and techniques.

2.1 Smart Grid System

This section will give an overview of the basic smart grid concept that contains the development in the demand-side response, micro-grid and communication in modern power systems.

2.1.1 Modern Smart Grid Concept

As we discussed in the beginning of the thesis (Section 1.1), those problems arise in the aged power systems when power systems have been growing to fairly large scales as the population grows and the technology develops. It makes the conventional information collection and control methods hard to meet the current system requirements, calling for much more efficient and reliable monitoring & control technologies in power systems.

The smart grid converts the aged central power generation system into a more flexible and reliable distributed generation system through the smooth integration of smart metering infrastructure, advanced control system, renewable energy generation and advanced power electronic facilities [2]. The ultimate goal is to construct a more reliable, convenient and customer- and environment-friendly power grid.
One of the basic tasks for the smart grid is to improve power system reliability in order to supply the customers with high-quality and uninterrupted electrical energy. Reliability involves almost every aspect of power system operation, and it is palpable that as the grid expands tremendously nowadays, ensuring system’s normal functioning is becoming harder and harder. In terms of this, the smart grid intends to incorporate advanced monitoring and communication infrastructure to make the grid informed of the current state from every corner of the system, based on which it can make well-informed control decisions. This advanced monitoring and communication infrastructure would be enabled by large numbers of sensors, smart meters and PMUs (Phasor Measurement Units) \[3\] in the transmission and distribution networks. System operators or automatic control centers can make optimized control and emergency countermeasures with the view and knowledge of the whole system, which will increase the
system reliability to a higher level. The smart metering network in the smart grid is shown in Fig. 2.1.

2.1.2 Demand-Side Response
More customers’ involvement is an important way to provide advanced system control and optimization at distribution levels when the power system evolves from centralized grids all the way to distributed systems. To facilitate this, the concept of demand response is proposed 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” [5]. By reflecting the fluctuation of the cost of electricity supply, the varying electricity price gives the utility companies and end users a way to interact with each other. This method can help shave peak load and reduce the total energy consumption. But for system reliability maintaining, such as load following, spinning reserve and frequency restoration [6] it needs much faster load response than peak shaving. This imposes more demanding requirements on the response speed, communication bandwidth, power system control support, and customer support, etc.

2.1.3 Micro-Grid
As the penetration of distributed generation increases, the consequent reliability problems also arise, such as large energy transmission loss, negative effects on system reliability, generation intermittency, etc. Because of these, it is better to put distributed generation units close to the local load and control them locally. In view of this, a new concept named micro-grid, has been brought forward, which is a local subsystem that owns local load and self-sustaining local generation and functions like a mini power system [7], as shown in Fig. 2.2. This micro-grid is
capable of islanding itself from the main grid when there is a disturbance on the transmission lines, as well as reconnecting itself to the main grid when the fault is eliminated. The prevalence of micro-grids distributes the central control into small local areas, thus increasing system flexibility and reliability.

![Micro-grid schematic diagram](image)

**Figure 2.2 Micro-grid schematic diagram [8]**

### 2.1.4 Communication in Smart Grid

The smart grid interlinks data sensing, collection and communication, aiming at optimizing control of the whole system. From this point of view, one of the most critical features of smart grid is that it is tightly bonded with its communication infrastructure. The aim of this communication infrastructure is to realize the reliable bi-directional information exchange among numerous sensors, electric machines and control centers. They together form a tightly connected entity to facilitate the interaction and automation in the smart grid, which lays the groundwork for ubiquitous smart metering to monitor every corner of the system.
A number of communication technologies have already been proposed and tested for applications in the smart grid, such as optical fibers, power line communication (PLC) and wireless communication. They all have their own advantages and limitations which would fit themselves in different application fields in the smart grid. In [9], it comprehensively analyzed the advantages and disadvantages of different communication techniques in smart grid, including PLC, satellite communication, optical fiber communication and wireless communication. Through this analysis, it drew a conclusion that although fiber optics is excellent in transmission capacity and security, its high installation cost makes it less attractive to be used as a low-level communication tool, but more appealing as a backbone communication technique. To the contrary, PLC compensates some of the limitations of fiber optics, such as installation difficulty and high cost, but suffers from large noise, signal distortion, attenuation and limited transmission bandwidth. In addition, wireless communication is a flexible, low-cost, easy-setup technique that offers a very good choice for the last-mile communication [10], but some very popular wireless communication technologies might not be suitable for the smart grid, e.g. cellular networks and WiMax. Because for the cellular networks, the channels for telecommunication are too crowded to allocate them specifically for power systems; and for the WiMax, the cost of installing WiMax base station is too high.

Among all the communication technologies, wireless sensor network (WSN), which is set up on the top of IEEE 802.15.4, can be a very promising technology to provide a reliable two-way communication in the last miles, because it is easy to deploy, and efficient to expand into large areas [10]. The graph describing the WSNs in smart grid is shown in Fig. 2.3. Due to its ad hoc nature, WSN is also a very robust network form in which end devices can always easily find and maintain their way to the sink node [11]. Even if several nodes in the network collapse during
an emergency, other healthy routes can still be found to guarantee reliable communication. In addition, WSN protocols are designed to be low-cost and energy-efficient, which makes it consistent with the smart grid’s goal of being “green”. All these features make WSNs a good fit for serving as the last-mile communication infrastructure in the smart grid.

Figure 2.3. WSNs in the smart grid

2.2 Power System Frequency Control
This section will give an overview of the frequency stability problems in power systems and further compare the pros and cons of different frequency control methods.

2.2.1 The Concept of Frequency Stability
Definition of Power system stability was given by IEEE in [12] as “the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium
after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact”. Specifically, frequency stability refers to the system’s ability to regain steady-state frequency after a significant imbalance between the generation and the load.

2.2.2 Conventional Frequency Control Methods

Frequency in the bulk power system is a direct reflection of the balance between power generation and load demand, thus normally it can be controlled by generation and flow control. But when a relatively severe disturbance results in a significant imbalance between load and generation, corresponding countermeasures need to be taken to restore system equilibrium. Classical frequency control mainly lies on generation side. Usually generators will continuously monitor the system frequency deviation. When there is a frequency bias beyond a certain threshold, the primary frequency control will be triggered trying to halt the frequency deviation within tens of seconds. Then the secondary frequency control will act to restore the frequency into nominal range in tens of minutes [13]. Therefore the whole frequency stabilizing process is very slow and demands large spinning reserve on the generation side. Besides, the frequency restoration on the generation side will also consume quite an extra amount of energy, as a result of the frequent adjustments of the set points of generators. Meanwhile, as the whole power system is decentralized, primary and secondary frequency control will further become difficult to achieve in the micro-grids where electronic converters interfaced generators dominate.

On the load side, customers can also be forced to participate in the frequency response when serious under-frequency problem occurs. Load shedding is triggered manually or through under-frequency relays when there is a big imbalance between generation and load and the spinning reserve in the system is not enough to fill the gap. Under this situation, the under-
frequency relays will act to cut whole areas off the grid [14] and thus lot of customers will suffer from sudden blackout. Undoubtedly, this method will lead to high customer discomfort.

### 2.2.3 Modern Demand-Side Frequency Control

Instead of bulk load shedding, many researchers now turn their focus onto designing a much subtler customer-side frequency response mechanism. As discussed in the previous section, there is a new customer-participated power grid control method called demand response which uses dynamic pricing to stimulate customers’ willingness to actively take part in a series of grid maintaining and restoration activities, such as, dynamic pricing, load following and frequency control. Generally speaking, two types of controls are included, i.e. the centralized load control and distributed load control, which are classified based on whether communication with a high-level central controller is present to facilitate the control.

#### 2.2.3.1 Centralized Frequency Control

For the centralized load shedding, an earlier example was the intelligent load shedding (ILS) proposed in [14]. Still using load circuit breakers, it collects measurements from all the meters at the ILS server and uses them to train its system knowledge base. From this knowledge base, the ILS server generates dynamic load-shedding tables and distributes them to the distributed controllers to control all the circuit breakers. This technique has a good system performance and a very short response time, but it still relies on relay load shedding and thus it would trigger discomfort among end users. Recent development in smart metering technology enables two-way direct communication between energy suppliers and power consumers, which leads to the emergence of direct load control (DLC) where a central controller can switch the loads on and off to balance supply and demand in real time [15], [16], [17], [18]. [17] proposed a DLC taking thermal comfort level as one of the criterions. An online optimized load shedding with direct
feedback through Internet to minimize the difference between required shedding load and actually shedding load was suggested in [18]. However, the DLC is initially designed for peak load shaving which has a relatively loose delay requirement, so it is unlikely that DLCs can meet the demanding requirements of the short response time of load shedding.

In [19], [6], [20] the authors showed us a central frequency control strategy in a micro-grid which uses an adaptive hill climbing algorithm and a step-by-step algorithm to control the responsive loads to respond to frequency deviation. The simulation results are promising; however, those papers fail to give detailed analysis about the realization of the responsive load in the system, i.e., how to control customers’ home appliances, which is a critical part of demand-side frequency control.

2.2.3.2 Distributed Frequency Control

On the other hand, for the distributed frequency control, the basic concept was first proposed in [21] in the form of Adaptive Power Energy Scheduler (FAPER) which is a distributed load controller with the capacity to respond to the frequency change in the system. Most of the later papers on distributed frequency control try either to demonstrate the efficiency of FAPER or to realize similar controllers as FAPER. Authors of [22] developed a frequency and voltage measuring algorithm, along with a fuzzy control algorithm for the distributed load controller. Authors of [22], [23] analyzed the effects of distributed intelligent loads on the grid frequency fluctuation and demonstrated its ability to increase fixed generation and line loading capacity. Ref. [24] carried out a detailed model for the refrigerator and its dynamic demand controller. It further studied the influence of using large numbers of refrigerators as spinning reserve when there was a frequency dip and when there was large wind power generators in the grid. In [25], the authors brought out a new controller model that reacts to not only the frequency deviation but also the
frequency evolution over a time window. This provides a more flexible control for distributed controllers.

As an alternative to FAPERs, authors of [26] proposed a frequency controller at the home level. It uses in-home smart meters to monitor the frequency and make control decisions to switch on and off all the home appliances. Although it needs communication between controllers and home appliances, the communication is limited in the home area networks; therefore the communication delay is negligible. But the coordination and control of the appliances need further study to minimize the customer discomfort.

As a summary, both of the centralized and distributed load control schemes have their advantages and intrinsic flaws. The centralized frequency control faces the challenge of communication delay and failure; while the distributed frequency control, like FAPER, is only fit for several energy consuming appliances, like refrigerators, air conditionings and heaters and lacks an efficient way to coordinate and optimize the energy solutions among appliances.

2.3 Stability in Micro-Grid Islanding

Micro-grid is a crucial part in the smart grid decentralization, and it is distinguished by some unique technical features, such as micro-grid islanding and reconnection, micro-grid fault ride-through and micro-grid self-operation, etc. In this section, stability issues during the micro-grid islanding process will be brought out, and corresponding electronic-interface control and load shedding methods during islanding will also be discussed. It lays the groundwork for my later discussion and simulation in the demand-side load shedding algorithm in micro-grid islanding. The layout of the micro-grid is exhibited in Fig. 2.4, in which VSC is short for voltage source converter, and MGCC is micro-grid control center. PCC (Point of Common Coupling) breaker is a three-phase electric breaker used for islanding the micro-grid from and reconnecting it to the
main power system. Several distributed generators and local loads constitute the main electrical part of the micro-grid, which are controlled by their local controllers and further coordinated by the MGCC.

![Micro-grid schematic diagram](image)

**Figure 2.4. Micro-grid schematic diagram**

### 2.3.1 Micro-Grid Islanding

The basic concept of micro-grid is already introduced in section 2.1.3. Among all the pivotal techniques in the micro-grid, micro-grid islanding, as an efficient control strategy to disconnect the micro-grid from the main power systems so that the quality of the electricity power delivered within the micro-grid is guaranteed, is generally categorized in to two types: intentional islanding, which refers to the islanding process executed by switching off the circuit breaker at the PCC or at the feeder line to disconnect the micro-grid from the main power grid [27], and unintentional islanding, which happens out of system fault or emergency without system operators’ awareness and may lead to serious network instability and personnel injuries and death [28]. Unintentional
islanding is the phenomenon that system operators should try to avoid, and fortunately, it is very rare in the grid. While intentional islanding is a flexible system operation method that can be utilized to greatly improve the micro-grid reliability and electricity quality. Furthermore, the intentional islanding is categorized into preplanned switching events and fault switching events. The former operation is usually out of system maintenance, and the latter operation is to ensure the power quality within the micro-grid when electric fault occurs on the transmission lines [27].

In the islanding process, how to coordinate all the VSCs’ behavior and how to shed local load when necessary determine the performance of the micro-grid islanding. The two consequent sections will give an introduction to these two aspects, especially load shedding, which is the focus of this thesis.

2.3.2 Control of the Power Electronic Converter Interfaced Distributed Generators in the Micro-Grid Islanding

In the modern distributed generation systems, power electronic devices, taking advantages of their rapid adjustments of the output power characteristics, are usually adopted as the interface between the grid and the distributed generators, such as solar converters and wind generator converters. A lot of control algorithms, e.g. P-ω, Q-V droop control, master/slave control, hybrid control, are developed for paralleled electronic interface control [29], [30], [31]. When micro-grid is islanded from the main power system, the electronic interfaces within the micro-grid have to turn their control into islanding mode to accommodate self-sustaining operation, so it is very important to carefully handle the transfer of these control algorithms in order to smooth out the transient state in the micro-grid.

2.3.3 Load Shedding in the Micro-Grid Islanding
When there is a fault occurring on the distribution feeder, the micro-grid may have to open its central breaker to island itself from the main power grid. This islanding process probably would lead to a sudden generation-load imbalance. In the bulk power system, due to the large inertia of all the generators and the other equipment, the transient due to the load-generation mismatch is slow which gives system operators enough time to react [32]. However, in the relatively small-size micro-grid, because of its small inertia, dramatical frequency drop may occur after islanding which leads to system instability. Therefore, micro-grid poses a higher requirement on the response speed of the load adjustment.

During islanding, if there is a great imbalance between load and generation within the micro-grid, load shedding has to be taken to prevent the system from collapse [31]. The amount of load to be shed should be carefully manipulated to minimize the cost of this process. Apparently, conventional load shedding with mechanical relays cannot meet this demanding requirement. In the future, quite a number of micro-grids would be residential systems in which electrical end users are directly involved, so ensuring the comfort of these customers during a system transient process is very important. Otherwise, frequent islanding and reconnecting operations would probably irritate them.

Besides this, load shedding should be handled according to the different priorities of the load. In the bulk power system, priority is easy to handle considering the diversity of the load in the whole system, e.g., some residential load can be shed to protect the sensitive industrial load, while in the micro-grid, because of the limited scale, the load type is usually singular, e.g., all are residential loads, so more subtle load shedding method considering the power supply priority should be designed.

Below, we will discuss and compare different load shedding methods in the micro-grid.
2.3.3.1 Conventional Load shedding

Conventional load shedding technique surely can be applied in micro-grid islanding process, but they will introduce a number of problems. For instance, although the common interlock breaker can respond very swift, it usually disconnects more load than necessary [33], the same feature as under-frequency relays as shown in Fig. 2.5. With communication network available among the breakers and the PCC, a more comprehensive load control strategy is possible to improve the load shedding performance. Still using circuit breakers and static switches, the author of [34] tried to fuse load shedding into the concept of micro-grid protection which deploys interactive protection devices all over the sensitive parts with high-quality communication among micro-grid system to construct a more comprehensive and reliable protection infrastructure.

Figure 2.5. Load Shedding with Under-frequency Relays at Each Local Load

2.3.3.2 Load shedding with local measurements

For modern advanced load shedding schemes, some researchers try to carry out the algorithms which allow load controllers to calculate the minimum load shedding based on local
measurements [35]. This kind of strategy is swift, while, because of the limited information available, it cannot provide comprehensive or optimized solution. Like in [36], a load shedding method was proposed whose shedding quantity is calculated out of the local voltage and voltage derivative. The final results obtained are as follow:

\[
R_{1_{pu}} = \frac{R_{I_{pu}} R_{2_{pu}}}{R_{2_{pu}} - R_{I_{pu}}} \tag{2.1}
\]

\[
R_{2_{pu}} = \frac{1}{\sqrt{\frac{I_{d_{pu}}^2}{Z_{cpu}}}}
\]

where, \( R_{I_{pu}} = R_{1_{pu}} / R_{2_{pu}} \), \( R_{1_{pu}} \) is the per unit load to be disconnected, \( R_{I_{pu}} \) is the resistive load in the system before load shedding, \( I_{d_{pu}} \) is the load current before load shedding which can be calculated from the local voltage measurements, and \( Z_{cpu} \) is the capacitor impedance value in the system.

From (2.1) we can see this method only considers the resistive load but ignores inductive and capacitive load in the system, and in order to precisely determine the load shedding quantity, accurate system impedance measurements are indispensable, but in reality, they are hard to obtain in common scenarios. In [37], a comprehensive islanding strategy taking into accounts both DGs’ maximum output ability and system load shedding capacity was carried out. The frequency and voltage measurements collected at the PCC are used to initialize the islanding; and the local measurements at the load controller is used to evaluate the load shedding quantity. Under some emergencies, like communication network failure, these load shedding methods with only local data become very convenient for system continuous functioning.

As mentioned above, before the intentional islanding, the distributed system probably undergoes electrical faults. Some FACTS (Flexible AC Transmission System) devices are
necessary for DGs, especially for wind turbines’ low voltage ride through. Sometimes, under severe emergencies, load shedding should be coordinated with FACTS devices to provide support for reliable islanding. Authors in [34] pointed out that in this scenario, the dynamic behavior of wind turbines should be thoroughly studied when sheds the load to prevent their tripping due to frequency decay. Therefore, the minimum load shedding is calculated according to both feeder line loading and wind speed before the moment of islanding; however, this is a very empirical strategy, which is unlikely to achieve in practice because of the big amount of DGs in the system and their unpredictable diverse dynamic behaviors.

2.3.3.3 Load shedding with energy support

Another interesting study in [38] uses communication among PCC, DGs and load controller to coordinate the islanding process, through which the amount of load to be dropped can be accurately and directly calculated in PCC through its local measurements. The authors further tried to compensate the extra load demand by temporarily exploiting the kinetic energy of wind turbines and generators for the micro-grid’s energy reserve. Nonetheless, this support can only last for several seconds, and after that the wind turbines have to draw their deficient kinetic energy from the micro-grid for continuous normal operation, which probably again jeopardizes the frequency stability of the grid unless more load is being shed. Of course, if energy storage equipment is available in the grid, it can better assume the responsibility of this temporary energy support during islanding [39].

2.3.3.4 Prospective modern load shedding scheme

No matter how intelligent and comprehensive these load shedding strategies are, as long as they are designed with circuit breakers and switches, inevitably, they will turn off bulks of customers or devices when act. This will be especially annoying for residential customers, and in
some of the small micro-grids, the power consumers may all be residential customers. Frequent islanding processes probably will induce frequent load shedding, which undoubtedly will lead to customers’ discomfort. Therefore, more intelligent demand-side load shedding would be the trend of the future technologies.

As discussed previously, demand-side distributed frequency control, such as FAPER, is swift, efficient and relatively oblivious for customers, thus promising to be used in micro-grid islanding process. However, it originally uses frequency dip as the indication of load reduction, which is efficient in the bulk power system, but unsuitable for the micro-grid islanding, because the frequency and voltage measurements in the micro-grid may fluctuate wildly and irregularly during islanding. In addition, the distribution nature makes it lack a mechanism to interact with the PCC and the load controller. Therefore, more research is necessary for its application in the micro-grid islanding.

2.4 Summary and Conclusions

In this chapter, we first introduced the basic concepts of the smart grid, micro-grid, demand-side load control, and communication in the smart grid. Then we compared different load control methods in both bulk power system frequency control and micro-grid islanding load shedding. We found out that, as power systems evolve, the conventional load shedding with mechanical relays can no longer meet the demanding requirements of the power systems and consumers; therefore, researchers have proposed some advanced load shedding methods that involve the individual power consumer in the load shedding process, including the centralized load shedding and distributed load shedding. The centralized load shedding manipulates the load remotely at the central controller; while the distributed load shedding controls the switch-on and -off of the individual home appliance locally. Nonetheless, these two types of load control
methods both have their own flaws. For the centralized load control, it poses a demanding requirement on the communication delay; and for the distributed load control, it lacks a mechanism to interact with the central controller or other home appliances; thus, hard to apply into other areas where the central information is indispensable, such as in micro-grid islanding. The new demand-side load shedding algorithm proposed in this thesis will try to combine the advantages of the centralized load control with the distributed load control to better serve the load control applications in the smart grid.
Chapter 3

The Proposed Demand-Side Load Shedding Algorithm for Smart Grid

In this chapter, the detailed explanation of the proposed demand-side load shedding algorithm will be presented. Firstly, for simulation and modeling purpose, the characters and requirements of the modeled system will be discussed, including the requirements of the power system and the micro-grid, as well as the communication networks. Then the details of the proposed algorithm in both the power distribution system and the micro-grid will be explained.

3.1 System Model and Requirements

This section will establish the system models of the power system and micro-grid, along with the characters of the layered communication networks, which serves as the groundwork for the later discussion of the proposed algorithm.

3.1.1 Power System Model

In the model, it is presumed that power utilities and end users have signed contracts with each other to allow the utilities to control the power consumption in each house during emergency. The proposed algorithm makes this process easier for the end users; because in this algorithm, end users do not need to expose too much private information; indeed, only their reducible power consumptions are reported to the utilities.

In the power grid, a three-level hierarchical control system is employed to conduct the system monitoring and control, as shown in Fig. 3.1. At the highest level, a substation central
controller (SCC) resides in each distribution substation and takes responsibility to coordinate all the residential load controllers (RLCs) within its distribution network. At the second level, each RLC monitors an area that contains around 1000 houses. The number varies according to the population density of the area. This design limits the communication distance on the second level to a reasonable range so that the load shedding commands could reach each house after a very short communication delay. Later in this section, from the algorithm, readers will see that the communication delay at this level is a very critical influence factor on the algorithm’s performance, so if the residential control areas have independent neighborhood communication networks, the performance of this algorithm could be improved. Finally, on the lowest level, the HEMEs would monitor and manage all the home appliances and keep the RLCs updated with the real-time power consumption information.

Fig. 3.1. Three control and communication levels in the system
3.1.2 Micro-Grid System Model

The micro-grid system contains distributed generation and local loads, the main power grid, and the distribution feeders, as shown in Fig. 3.2. The distributed generation can be in the form of either traditional energy or renewable energy. In our model, it includes solar generation and wind generation. The main power grid is treated as an entity possessing enormous capacity, so if it is connected with the micro-grid, the micro-grid can operate in constant power mode to leave the duty of frequency and voltage regulation to the main power grid. The main grid is coupled with the micro-grid at the PCC through a micro-grid central breaker.

**Figure 3.2. Micro-grid system model**

The control system is the same as in Fig. 3.1, except that in the micro-grid the SCC is substituted by a micro-grid control centre (MGCC) which is responsible for monitoring and coordinating all the controllers and smart meters. Normally, the micro-grid central breaker is
closed to allow bi-directional electrical energy flow between the micro-grid and the main grid. When a fault occurs at the feeder, in order to ensure the power quality in the micro-grid, the micro-grid central breaker would be opened by the MGCC and an island system is formed. In the island, the paralleled converters have to cooperate to regulate the system voltage and frequency [31].

Design of the transfer from the grid-connected mode to the island mode is very important for the micro-grid. Quite an amount of research on islanding mode switching can be found in literature [31], [40], [41]. In our system, a smooth transient control is employed in islanding; otherwise, even if the load is shed in time, the micro-grid may still end up with serious instability problems.

In contrast to the bulk power systems, voltage and frequency in the micro-grid can no longer serve as a precise indicator of generation-load imbalance in the micro-grid during islanding. Therefore, in terms of the small geographical area and specific requirements of islanding in the micro-grid, load shedding commands are made centrally at the MGCC and sent directly to all the RLCs.

3.1.3 Communication Networks

Tens of communication technologies emerged in the past few decades fulfilling the specific requirements in different fields, from high-speed broad band communication like fiber optics, to low-speed narrow band monitoring like ZigBee [42]. A lot of these technologies are good candidates for certain applications in the smart grid environment.

In our application the three different control layers impose different requirements on the networks. At the SCC or MGCC level, relatively large coverage area, high speed and wide bandwidth are desired to give the central controllers enough supports to manage all the local
controllers in real-time. For this application, with their broad bandwidth and wide coverage range, fiber optics and WiMax can be good candidates.

The RLC, HEME levels, and for some small micro-grids, the MGCC level as well, cover relatively small areas and demand a lower communication bandwidth. For these control levels, some small-range communication techniques are enough, such as power line communication, ZigBee and Ethernet. In [43] and [44], two spectrum-efficient communication protocols, cognitive radio and ZigBee, are refined to offer QoS for smart grid last-mile networks. With the less demanding delay and bandwidth requirements in our algorithm, those low-cost communication technologies can serve the lower control layers very well.

3.2 Proposed Demand-Side Load Shedding Algorithm

In this section, the proposed algorithm will be explained. The functions and features of the three control and communication levels will be expounded one by one from the lowest to the highest.

3.2.1 Home Energy Management Algorithm (HEMA)

One of the advantages of the proposed algorithm is that, instead of interfering with the ways HEMEs manage their home appliances, it defines the form of their local information being updated at the RLCs. As long as the RLCs get the desired reducible power consumption information from all the HEMEs, it does not matter how these HEMEs monitor and manage their loads. This mechanism gives a great freedom to the customers for them to choose their preferred HEMAs.

As an illustration, we are going to give an example of a simple HEMA that is a good fit for our load shedding algorithm. In this HEMA, we categorize loads into two types: reducible loads, whose power consumption can be decreased for some time periods, such as air conditioning and
refrigeration units, and deferrable loads, whose operation or charging time can be deferred, such as washing machines and electrical vehicles. For reducible loads, the HEME can function like a FAPER to reduce their power consumptions [24]. For deferrable loads, they can postpone the operation of the appliances under customer premise. We can calculate the total reducible power, using:

\[
\Delta P_{total}(t) = \sum \Delta P_n(t) + \sum P_m(t)
\]  

(3.1)

where, \(\Delta P_{total}(t)\) is the total reducible power at time \(t\), \(\sum \Delta P_n(t)\) is the reducible power consumption of the \(n\)-th reducible load, and \(P_m(t)\) is the power consumption of the \(m\)-th deferrable load because the reducible power consumptions of the deferrable loads equal to their current power consumptions.

To release the communication burden and, on the other hand, to protect power consumers’ privacy, the total reducible power consumption of a house is reported to the load controller only on change. Difficulty arises when we need to know how long the load can be shed. This is necessary because the load shedding has to be maintained for a certain time period to allow the primary and secondary frequency control to take full actions. In contrast to demand response of dynamic pricing, where the load reduction usually needs to be cut for hours in the rush hour, the emergency load shedding usually needs to last for only several minutes, after which the secondary frequency control would function. Here, we assume the secondary frequency control requires the support from the load shedding for 10 minutes. For this very reason, when the reducible power changes, we have to know how long it can last. Only the loads with reducible power lasting for over 10 minutes are considered.
Another problem is how the HEME gets to know this time information. For intelligent controllable load, they should know how long their operation time would be according to the preset time value or by forecasting. For instance, the washing machine can precisely know how long it would take to finish the laundry. The electrical vehicle can calculate its charging time based on the remained energy value and its charging character curve. The air conditioning can predict the maximum switch-off time using the outdoor temperature, along with its power rating and the cooling factor. This time information is then transmitted to the HEME, which guarantees the HEME has a good knowledge on the operation times of all the home appliances.

As an example to this HEMA, assuming at this moment, four appliances are running in a house among which two are reducible loads whose power consumptions can be decreased by 0.10 kW for 20 minutes and 0.25 kW for 30 minutes, respectively, and the other two are deferrable appliances each with a power consumption of 1.1 kW and 0.3 kW and can be deferred to operate 70 minutes and 125 minutes later, respectively. After 120 minutes, the two reducible loads regain their previous state and their power consumptions can be decreased by the same quantity again. To guarantee the 10 minutes shedding time, when the reducible power is going to decrease, the HEME has to report this change 10 minutes in advance. Therefore the current reducible power in this house is calculated using (1) as 0.10+0.25+1.10+0.30=1.75 (kW), and this value varies in the subsequent 120 minutes as depicted in the time coordinate in Fig. 3.3. The reducible power information is reported from this HEME to its residential load controller at the five time points, a, b, c, d, e, during the next 2 hours. After load shedding, the HEME would turn on the home appliances randomly one by one to avoid an abrupt demand increase. This method can also be used to facilitate in-home renewable energy generation. The available renewable power generation can be treated as negative reducible power consumption.
3.2.2 The Reducible Load Table at the RLC

![Diagram of the Reducible Load Table at the RLC]

Figure 3.3 The variation of the reducible power in a house

3.2.2 The Reducible Load Table at the RLC

- SCC
- RLC
- HEME

Normal Scenario

- Total Reducible Loads Update Frame
- $\eta$, Update Frame

Load Shedding Control

Home Reducible Power Update Frame

Load Reduction Commands

Control Frame
Fig. 3.4 The information exchange among the three control levels: (a) in power distribution systems; (b) in the micro-grid

The RLC is the most critical one among the three control entities. It takes responsibility to update and maintain the reducible power consumption information in the normal scenarios, while making load shedding decisions when frequency emergency occurs.

In the normal scenario, only the lower two layers are activated. The information exchange is illustrated in Fig. 3.4. Fig. 3.4(a) shows the data communication in the power distribution system, while (b) shows that in the micro-grid. As you can see, the communication processes in the lower two levels of the two systems are the same, the main difference lies on whether the high-level controller is involved in the load shedding control. Therefore, according to this, this load shedding algorithm is a half-centralized control in the power distribution networks; while it is a centralized control in the micro-grid.

The HEMEs would automatically send the reducible power information along with their home numbers to the load controller whenever there is a state change as discussed in section
3.2.1. The residential load controller keeps a reducible load table which is a two-column information table showing the reducible power consumption along with the home number of each house (Table II). Upon receiving the new state information from any HEME, the load controller would correspondingly update its reducible load table. At the same time, the residential load controller would communicate with its SCC to report the total reducible power consumption in the local area.

Meanwhile, the residential load controller continuously monitors the system frequency and voltage. When a frequency emergency occurs, it would use predefined algorithm to calculate the load shedding quantity. Normally, in power system, frequency is a good indication to show the load and generation balance. That is because the frequency in the system is proportional to the rotational speed of the generators’ rotators. When the load increases or the generation decreases, the generated power cannot meet the demand of the load, so the generators have to draw their kinetic energy to compensate this imbalance. In this way, the rotational speed of the stator would decrease, thus leading to the decrease of the system frequency. The same reason applies to the scenario when frequency arises out of decreasing load.

In this study, a simple algorithm based on initial frequency gradient [45], [46] is adopted:

$$P_{shed,ki} = \eta_{ki} \frac{2H_{eq}}{f_N} \cdot \frac{df}{dt} \cdot P_k$$  \hspace{1cm} (3.2)

where, $P_{shed,ki}$ is the required shedding load at the $i$-th RLC controlled area in the $k$-th SCC distribution network; $H_{eq}$ is the equivalent system inertia of the whole power grid [46]; $f_N$ is the nominal frequency (60 Hz); $\frac{df}{dt}$ is the initial frequency gradient; and $P_k$ is the rated power of the $k$-
th SCC distribution network. In addition, $\eta_{k_i}$ is called the area load ratio which is calculated using:

$$\eta_{k_i} = \frac{\Delta P_{k_i}}{\Delta P_k}$$

(3.3)

where, $\Delta P_k$ is the total reducible power in the $k$-th SCC distribution network, and $\Delta P_{k_i}$ is the current reducible power at the $i$-th RLC controlled area in the $k$-th SCC distribution network. $\Delta P_{k_i}$ can be calculated locally at each RLC, and $\Delta P_k$ can be updated periodically at the SCC. When load shedding happens, $\eta_k$, $P_k$, and $H_{eq}$ are all ready to use at the RLC.

In the model, for simplicity, we assume that 90 percent of the loads are all constant power loads, thus variation of the system voltage has little influence on load power. However, in reality, most of the loads fluctuate due to the voltage variation, so the algorithm in [46] that takes into account the voltage modulation effect on the loads needs to be adopted.

The frequency gradient may be measured differently at different locations, but collectively, they would give a relatively precise average value [46]. In the system, the RLC continuously monitors the local frequency measurements. Whenever the frequency gradient $\frac{df}{dt}$ goes beyond the predefined threshold, the load controller would calculate $P_{shed,k_i}$ according to (3.2), and then scans the reducible load table to select a group of houses whose total reducible power equals to $P_{shed,k_i}$:

$$\sum_{n=1}^{M} \Delta P_n \geq P_{shed,k_i}$$

(3.4)

$$\{\Delta P_1, \Delta P_2, \ldots, \Delta P_M\} \subseteq \{\Delta P_1, \Delta P_2, \ldots, \Delta P_N\}$$
\[ \Delta P_1 \geq \Delta P_2 \geq \cdots \Delta P_N \]

where, \( \Delta P_n \) is the reducible home power consumption of the \( n \)-th house. As (3.4) shows, the RLC selects a group of houses which have the highest reducible power and their total value is greater than or equal to the required load shedding quantity in this area. This method ensures the number of the selected houses is minimized so that the number of commands needed to be sent is decreased, thus reducing the communication burden and delay in the emergency phase. But if we always shed houses with the highest reducible power, the possibility exists that some of the houses with high power consumptions may always be selected, while some other houses may never be. This can be solved by introducing a fairness mechanism in the decision making process in RLCs. Some frequent participants may be disabled for some time periods to leave the chance to other less frequent users.

If the frequency drop continues until below a predefined load shedding threshold, the load shedding is triggered by the RLC. Then the RLC would send a command to each of the selected houses to request a power reduction. Those houses would decrease their power consumptions by the predetermined quantity. The control command transmission during load shedding phase in the power distribution network is illustrated in the lower part of Fig. 3.4(a).

If it is in the micro-grid, the RLC does not need to monitor the frequency and make the shedding decisions, because these tasks are accomplished centrally at the MGCC. Therefore, the RLC waits for the load shedding commands from the MGCC and processes them, and then sends the power reduction command to each house. The house selection algorithm is the same as (3.4), the only difference is that \( P_{\text{shed,k}} \) is not calculated from (3.2), but directly received from the MGCC. The information updating and control commands transmission process in the micro-grid is shown in Fig. 3.4(b).
3.2.3 Supervision and Coordination at the SCC and MGCC

As explained before, the control at the lower two levels are very similar for both the bulk power systems and the micro-grid, but at the highest level, it is different between them two, which depends on whether or not they are centralized control. At the highest level, for the power distribution system, an SCC is located at each distribution substation to coordinate all the local RLCs; while an MGCC is located at each micro-grid to control and monitor the functioning of all the controllable units within the micro-grid. Therefore, below we divide this part into two subsections to expound the functions of the SCC and MGCC respectively.

3.2.3.1 SCC in the Power Distribution System

The SCC does not need to be involved in the information updating and emergency decision making process. It is only responsible for receiving the reducible power consumption information from each RLC and correspondingly updating its reducible load table, and then calculating the RLC’s residential load ratio \( \eta_{ki} \) using (3.3). This can be done periodically on an hourly basis, because the distribution of the residential reducible loads would not vary frequently, which reflects the assembly electricity consumption behavior of a large number of houses.

The \( \eta_{ki} \) is then divided to each RLC by the local SCC according to their load reduction ability. Therefore, although the SCC functions as a central controller in the normal phase, during the frequency restoration, it is not involved so that the whole system still keeps the advantages of the distributed load control.

To summarize, normally, the lower two control layers in the power distribution system would take responsibility of monitoring the system frequency and voltage measurements, coordinating the home appliances and updating the state information. The SCC would periodically update and distribute the load ratio \( \eta_{ki} \) to each RLC. When frequency emergency
happens, the RLC would detect the frequency abnormality and calculate the necessary shedding quantity. Then it would select a group of houses whose total reducible power is equal to the required quantity, and send them load shedding commands. Upon receiving this command, the HEME would reduce its domestic power consumption according to the schedule.

3.2.3.2 MGCC in the Micro-Grid

As mentioned above, the MGCC does not need to be involved in the information updating process in the normal scenarios when it continuously monitors the whole grid and collects the state information from all the meters and controllers. If a fault is detected at the PCC, it may need to open the micro-grid central breaker to disconnect the micro-grid from the main power system. Meanwhile, it would use the measurements collected previously from all the distributed generator controllers and the meter at the PCC to calculate the quantity of the load needs to be shed as:

\[ P_{\text{Shedding}} = P_{\text{PCC,flowin}} - \sum P_{\text{a.margin}} + P_{10\%} \]  \hspace{1cm} (3.5)

where, \( P_{\text{Shedding}} \) is the total load needs to be shed, \( P_{\text{PCC,flowin}} \) is the current power flow from the main power system to the micro-grid. If the direction of the current power flow at the PCC is from the micro-grid to the main system, then it means the micro-grid has redundant power generation and thus it does not need to cut off its load during islanding. \( \sum P_{\text{a.margin}} \) is the sum of the generation margins of all the generators in the micro-grid, i.e., the maximum extra power they can generate beyond current output. \( P_{10\%} \) is a stability margin of 10\% of the total DGs’ capacity, which is kept to accommodate the variation of the load and renewable generation. The data transmission of load shedding commands in islanding control is illustrated in the lower part of Fig. 3.4(b).
It is worth mentioning that these measurements are all collected in the last sampling time and stored in the MGCC’s memory, so no further information needs to be collected at this point in emergency. But the measurement sampling rate should be high enough so that we can ignore the error introduced by measurements variation between two consecutive sampling points. With these measurements available, the load shedding quantity can be calculated very swift at the MGCC using (3.5). Then it would send the shedding command to the residential load controller which contains the \( P_{\text{shedding}} \) in the data frame. If there is more than one residential load controller, it will divide \( P_{\text{shedding}} \) into several pieces according to the ratio of the local load to the total micro-grid load in each area. From the operational process in the MGCC, we can predict it would consume a very small amount of computation and communication resources, leaving space to other functions and entities.

To summarize, normally when the micro-grid is connected to the main power system, the lower two control layers are running to update the reducible power consumptions of all the houses. When an islanding happens and the total generation cannot meet the load within the micro-grid, the MGCC would calculate the quantity of load that needs to be shed and send corresponding commands to all the RLCs. Upon receiving this command, the RLC would select a group of houses whose total reducible power consumption matches the required quantity, and send them load reduction commands. Any HEME that receives this command would decrease its domestic power consumption according to the schedule.
Chapter 4
Simulations and Results

4.1 Introduction to the Simulations
To verify the correctness of the proposed load shedding algorithm, we have performed two simulations in two different systems, i.e. the power distribution system and the micro-grid. The simulated power distribution network is IEEE 14 bus system, and the micro-grid is a small residential system. Both of these simulations are executed on Matlab/Simulink platform. The subsequent sections will further show the simulation results and analysis. The purpose of these simulations is to demonstrate that the proposed algorithm has a comparable performance as the fast-response relay load shedding during system restoration. For this reason, both the proposed algorithm and the relay shedding are simulated in the same systems.

4.2 Simulation on IEEE 14 Bus Test System
Simulation on the IEEE 14 bus test system is used for verifying the application of the proposed algorithm in the power distribution system. In the subsequent sections, we will first give a brief introduction to the test system and the simulation tool. Then the residential load model will be established. Finally, the simulation results and analysis will be exhibited.

4.2.1 IEEE 14 Bus Test System and Power System Toolbox 2.0
The simulation system is IEEE 14 bus power system, which is modeled by IEEE PES according to the real parameters from part of the American national power grid. A single line diagram of the IEEE 14 bus test system is shown in Fig. 4.1. It consists of 5 generators and all of them are operated with constant mechanical power input and constant excitation, three of which are
synchronous compensators used only for reactive power support. The total rating of the 5 generators is 685 MVA. The generator and power line parameters are from [47], as shown in appendix A.

![IEEE 14 bus test system](image)

**Figure 4.1 IEEE 14 bus test system [47]**

The reason we choose this system is because it is a sub-transmission network with the ability to test the frequency variation in the grid. Compared to other big transmission networks, it has a relatively small capacity that reduces the simulation burden for the residential loads.

To save the simulation time and resources, the simulation on the IEEE 14 bus test system is executed with the power system toolbox [48] developed by Graham Rogers, K.W. Cheung, and Joe H. Chow under MATLAB environment which is designed exclusively for simulating power
transmission and distribution system transient states. This toolbox is easy to use and consumes a limited amount of computing resources. More importantly, it allows us to modulate the active and reactive power on the load buses in real time.

4.2.2 Residential Load Model

One of the most critical parts in this simulation is to model the residential loads. If we model the residential house individually using the detailed algorithm in section 3.2.1, it is impossible to simulate the hundreds of thousands of houses in the whole system. Because in our simulation, the houses only need to provide the reducible power information, we can greatly simplify the load model by just considering the aggregate power reduction curves on the load buses.

We assume the loads on bus 2, 3, 4, 5, 6, 9, 10, 13 and 14 are all controllable residential loads where, through the variation of the home power consumptions, the load curves on these buses could fluctuate accordingly. To model the home power consumptions, we have made two Gaussian distribution assumptions, one for the reducible loads, and the other for the communication and control delays.

Further to approach the reality, the reducible load model is established based on the statistics of Canadian residential power consumption. The paper [49] gives the statistics of the yearly average power consumption curve for low, average and high energy houses, as shown in Fig. 4.2.
Figure 4.2 Average power consumption curves for high, medium and low energy consumption families in Canada [49]

From the figure, we can see the valley, average and peak load for a Canadian house are around 500 W, 1 kW and 1.5 kW respectively. Then according to report [50], around 81% of the residential load is for heating, hot water, ventilation and cooling. These loads can be turned down for a while in emergency situations without drawing consumers’ attention. Assuming the average house consumption in the simulation is 1 kW and those reducible loads in the houses can be turned down by 20~ 30% for several minutes, the average reducible power consumption in a house would be $1 \text{ kW} \times 81\% \times 25\% = 0.2025 \text{ kW}$ with a variance of $\sigma^2 = (0.3)^2 \ (kW)^2$. Because the reducible power cannot be a negative quantity, clipped Gaussian distribution is used whose part below zero on x-axis is dropped. The final distribution curve of the reducible load is shown in Fig. 4.3(a).
Because of the diversity of the communication technologies in the last miles, it is difficult to specify an exact mean and variance for the delay distribution model. Considering the execution delay and communication retransmissions, three different means, 0.4 s, 0.8 s, 1.5 s, with the same variance, $(700)^2$ ms$^2$, are assigned to the delay model. The three distribution curves for the communication and control delays are shown in Fig. 4.3(b). With the three different delays, the
influence of the variation of the communication and control delay on the system performance can be shown in the simulation results.

Based on these two models, the simulator would first generate a load reduction table, and then according to the algorithm, choose a group of houses. Each of these houses carries its own communication delay and reducible load information. With this information, a local load reduction curve at the RLC level is obtained by aggregating the delay and reducible power of all the selected houses. Next, all the RLCs’ load reduction curves are aggregated at the SCC level and then the final load reduction curve is generated on each bus. Finally, the current load curve is evaluated by subtracting the reduction load curve from the original load curve.

The SCC and RLC controlled areas are predefined in the form of load rated power and number of houses. The bus-RLCs mapping is shown in Table I.

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Regional Rated Load Power (MW)</th>
<th>No. of Houses</th>
<th>No. of RLCs</th>
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<td>21.7</td>
<td>20000</td>
<td>20</td>
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<td>3</td>
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<td>5</td>
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<td>7</td>
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<td>9000</td>
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<td>13</td>
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<tr>
<td>14</td>
<td>14.9</td>
<td>15000</td>
<td>15</td>
</tr>
</tbody>
</table>

4.2.3 Simulation Results and Analysis
In order to highlight the effect of load shedding, the power rating of the generator on bus 1 in [47] is decreased from 615 MVA to 300 MVA to make the total spinning reserve in the system
limited. During the simulation, at 0.2 s, the generator on bus 2 with a power rating of 60 MVA is tripped, so after this point, the system suffers from a large generation and load imbalance.

The proposed load shedding is compared with the relay load shedding, which uses similar estimation algorithm as (3.2) while sheds load step by step at several specific frequency points. The under-frequency relay will disconnect its load when it detects a large frequency deviation, so the relay on the particular bus that has the fastest frequency drop will react first. In practice, due to the predefined load mapping, the under-frequency relays often shed more loads than necessary. But in this simulation, in order to compare the performances of the proposed load shedding with the conventional load shedding under the same conditions, we ignore the over shedding character in the relay load shedding.

To get the frequency in the system, we calculate it using the voltage angle in the system:

$$\frac{\theta_i(t_k) - \theta_i(t_{k-1})}{t_k - t_{k-1}} = f_i$$  \hspace{1cm} (6)

where $\theta_i(t_k)$ is the voltage angle of the $i$-th bus at the $k$-th time sample, $t_k$ is the time of the $k$-th time sample, $f_i$ is the frequency of the $i$-th bus. In this way, we can calculate the frequency fluctuation on each bus separately and use them as the measured frequency values at the RLCs.
Figure 4.4 System responses to generator tripping without turbine governor control: (a) Frequency responses, (b) Voltage responses
Figure 4.5 System responses to generator tripping under turbine governor control: (a) Frequency responses, (b) Voltage responses

Fig. 4.4 and Fig. 4.5 demonstrate the simulation results of two scenarios: the former is simulated without the turbine governor control while the latter is under turbine governor control.
As shown in Fig. 4.4, without governor control and load shedding, frequency cannot recover and
the voltage recovers very slowly. In Fig. 4.4(b), the frequency hits 57.5 Hz which is not allowed
for normal power system operation. If the relay load shedding is added, the frequency and voltage
can recover quickly as the figures show. Compared with the conventional relay load shedding, the
proposed algorithm exhibits the same steady state value and a very similar performance. For the
frequency response, it responds slightly quicker than the relay load shedding because it doesn’t
need to shed the load step by step to avoid overshoot. Instead, the proposed load shedding
algorithm sends the load shedding commands all at once but the actual loads are shed gradually
due to the distributed delays introduced by the diverse communication networks and control
equipment. The generated load reduction curves on all the controllable load buses are displayed
in Fig. 4.6. Due to the gradual shedding behavior, the voltage response of the proposed load
shedding is smoother than the relay load shedding.

In addition, we also simulated the scenario when the communication and control delay in
the proposed load shedding is increased or decreased. In the figures, the yellow curve depicts the
response of the proposed load shedding when the mean of the communication and control delay is
increased from 0.8 s to 1.5 s; while the brown curve is that when the mean of the communication
and control delay is decreased from 0.8 s to 0.4 s. Comparing all the response curves in the
figures, we can see increasing the delay would worsen the performance of the algorithm and vice
versa. However, this influence is not very significant so that the proposed load shedding
algorithm can still function well even in large communication and control delay.
Figure 4.6 Load reduction curves on the controllable load buses

When the turbine governors are enabled, the resulting voltage and frequency responses are shown in Fig. 4.5, where the relay load shedding and the proposed load shedding still possess similar performances. They both eliminate the steady state error introduced by the generator secondary control. However, because of the slower response of the turbine governors and the collectively longer delay of the proposed load shedding, the proposed load shedding displays a slightly higher overshoot than the relay load shedding in the frequency response. But it still exhibits a smoother transient than the relay load shedding in the voltage response.

In the next test, the time constants of all the turbine governors in the system are reduced. The results are shown in Fig. 4.7. In the figure, the proposed load shedding possesses almost the same frequency and voltage response as the relay load shedding. This is reasonable because by reducing the governors’ time constant, they respond faster to small changes of the load and thus follow the load variation more tightly. From this test we can conclude that by adapting the time constant of the turbine governors, the performance of the proposed load shedding can approach that of the relay load shedding. Therefore, this proposed load shedding can benefit from the
evolution of the power grids, because with the growing number of distributed power generation along with their power electronic converters, the power system time constant would decrease. In the future smart grid, the time constant of the generation units could be very small.

Figure 4.7 System responses to generator tripping when the time constants of turbine governor are reduced: (a) Frequency responses, (b) Voltage responses
It is worth mentioning that, in our simulations, we did not try to control the voltage at the distribution networks, thus reactive power is also not under our control. The reason is that the reactive power only occupies a very small portion of the load in the residential area, and it is unlikely to directly control the residential reactive power, because, for the home appliances, the reactive power is usually a byproduct of their power consumptions and thus tightly coupled with the real power consumption. Therefore, changing the real power consumption would also change the reactive power consumption. Because of the uncontrollability of the local reactive power, large series or paralleled compensators at the distribution level, or STATCOM devices should be installed to protect the system from reactive power emergencies.

4.3 Simulation of Micro-grid Islanding

In this section, as another demonstration, we will show the simulation we performed on the small micro-grid developed on the Matlab/Simulink platform. Before showing the simulation system and results, a discussion of the micro-grid islanding control will be given to show the different control strategies for the electronic converters and the transient state of islanding in the micro-grid. This discussion lays the groundwork for the latter modeling of the micro-grid system. After the discussion, the variable load model on the Simulink platform is demonstrated. Finally, the simulation results are shown along with the performance analysis.

4.3.1 Control of Power Electronic Converters in the Micro-Grid

Conventional rotational machines interfaced micro-sources are connected to the grid directly by generators, like diesel-based synchronous DGs and some squirrel-cage induction generator based wind turbines [51]. These generator interfaces along with their mechanic accessories have a high inertia, resulting in a slow transient response, for which it is not very attractive in stabilizing of the micro-grid islanding transient. On the contrary, power electronics interfaced renewable
generations, such as solar arrays and some wind turbines, produce very fast and accurate transient response, making it a perfect choice to stabilize the transient state right after the islanding.

The islanding and reconnecting behavior of the micro-grid proposes unique requirements on its power electronic converters. When the micro-grid is connected to the main power system, the voltage and frequency are regulated by the main grid, and the converters in the micro-grid should output constant real and reactive power to the grid. After islanding, the regulation of the main power system is lost, so the converters have to control the frequency and voltage locally. The control of the electronic converters in the micro-grid should have a fast and smooth switch between grid-connected mode and island mode.

As discussed in the section 2.3.2, there are a lot of converter control methods in the micro-grid. The most frequently used control methods include droop control, master/salve control and hybrid control. Among them, droop control inherits the characters of the governor droop control in the rotational machines, which are easy to design and does not need communication signals for paralleled converter coordination. Adopting master/slave control, in island mode, master unit regulates the micro-grid voltage & frequency and generates slave converter P & Q references; meanwhile, slave converters try to output constant real and reactive power based on the P & Q references from the master units. Hybrid control combines two or more different types of control strategies to achieve a better performance.

Since master/slave control is easy to implement and has a smooth transient in mode switch. In our simulation, we adopt the master/slave control technique proposed in [52] where the converter of the wind generation system functions as a master unit while the converter of the solar generation system functions as a slave. Therefore, before islanding, both of the converters function in constant power mode to output desired power to the grid. No voltage or frequency
regulation is needed under this scenario. After islanding, the converter of the wind generation system will assume the responsibility to generate the desired voltage and frequency based on the local reference; and the converter of the solar system functions at the constant power mode and follows the commands from the wind converter to output the desired real and reactive power.

4.3.2 Micro-Grid Islanding Transient

For micro-grid islanding, there are two categories, intentional islanding, which refers to the islanding process executed by intentionally switching off the circuit breaker at the PCC or at the feeder line to disconnect the micro-grid from the main power grid [53], and unintentional islanding, which happens without system operators’ awareness and may lead to serious system instability and personnel injuries and death [28]. Unintentional islanding is the phenomenon that system operators should try to avoid, and fortunately, it is very rare in the grid. While intentional islanding is a flexible system operation method that can be utilized to greatly improve the system reliability and electricity quality. Furthermore, the intentional islanding is categorized into preplanned switching events and isolation of micro-grids due to faults in the distribution networks. The former operation is usually out of system maintenance, and the latter operation is to ensure the power quality in the micro-grid during the fault [53]. In our simulation, both of two scenarios of the intentional islanding will be studied.

During the islanding transient, the converters will automatically detect and switch their operation mode from grid-connected mode to island mode. In this way, micro-grid will be smoothly transferred into island mode if the current load is not beyond the maximum generation power which depends on the wind speed, irradiance, temperature etc. at the renewable energy generation units. If this condition is not satisfied, timely load shedding should be taken so that system stability is not jeopardized. If wide-area or layered communication is available in the
system, like in [31], comprehensive central control can be used to coordinate the VSCs, islanding detection and load shedding long with other system operations, such as charging and discharging of energy storage units. Through this kind of comprehensive communication and control network, great reliability is achievable in micro-grid islanding process. As pointed out in [52], because of the low data rate requirement and small geographical span, some low-cost communication approaches can satisfy this need. However, high dependency on communication may also endanger system reliability when communication networks fail [54], so backup local control methods become necessary in these systems.

4.3.3 Micro-Grid System Model

![Figure 4.8 System model of the micro-grid in Matlab/Simulink](image)

54
The topology of the system is the same as in Fig. 3.2, and the Simulink model snapshot is shown in Fig. 4.9. As exhibited, in the micro-grid, there is a solar generator with its converter, two wind generators with their converters, a residential load, a WSN, an MGCC and a micro-grid central breaker. Each of the wind generators is a double-fed induction generator and has a power rating of 275 kW; while the solar generator has a power rating of 100 kW. The main power grid is simulated after an infinite capacity system, and the micro-grid is connected to the bulk power system through its central breaker at the PCC which makes it convenient to island and reconnect.

The solar and wind converters regulate the magnitude and phase of their modulation signals with their PWM generators to output desired power and voltage. In grid-connected mode, the power references are constant, so the converters adjust the current-loop to control the output current. While in the island mode, the voltage and frequency need to be regulated in the master unit, so the wind converter uses the internal voltage wave reference as the modulation wave of the PWM generator to output desired voltage. The solar converter still works in the constant power mode, but receives the real and reactive power reference from the master unit controller.

Because the islanding transient is very short, during this time period, the wind speed and solar radiation fluctuation has little impact on the output power of the wind and solar generators, so we set the wind speed and the solar radiation constant. The red wireless smart meter module simulates the behavior of the smart meters with wireless transmitters. We will show their hardware implementation in chapter 5. The module can measure the local frequency and voltage and then transmit them wirelessly to the other meters and the MGCC. Considering the simulation time, we don’t model the wireless channel in the simulation, but only introduce transmission delay for the wireless communication channels.

**4.3.4 Variable Residential Load Model**
The variable load model is used to model the power variation of the residential load. It receives the simulated power curves from the simulator and generates corresponding output power.

To get full control over the load’s real and reactive power, we transform the coordinator into d-q rotational frame. On the d-q frame, the desired real and reactive power of the responsive load can be written as:

\[
P(t) = \frac{3}{2} (v_d(t)i_d(t) + v_q(t)i_q(t)) \quad (4.1)
\]
\[
Q(t) = \frac{3}{2} (-v_d(t)i_q(t) + v_q(t)i_d(t)) \quad (4.2)
\]

where \( v_q \) and \( v_d \) are the load voltage in the d-q frame, and \( i_d \) and \( i_q \) are the load currents in d-q frame.

From the above equations we can get

\[
i_d = \frac{2}{3} \frac{v_d}{v_d^2 + v_q^2} P + \frac{2}{3} \frac{v_q}{v_d^2 + v_q^2} Q \quad (4.3)
\]
\[
i_q = \frac{2}{3} \frac{v_q}{v_d^2 + v_q^2} P - \frac{2}{3} \frac{v_d}{v_d^2 + v_q^2} Q \quad (4.4)
\]

Equation (4.3) and (4.4) establish the relationship between the desired real/reactive power and the d-q currents. The \( v_q \) and \( v_d \) can be calculated from the three-phase voltage using Parker transformation [55]. Since we only intend to control real power, the desired reactive power is set to 0. Then (4.3) and (4.4) are simplified to represent the relationship between the desired real power \( P \) and the \( id/iq \). By controlling the d-q currents, the desired power can be obtained. This variable load model is constructed based on [19], as shown in Fig. 4.10. In the model, the d-q currents are first calculated from the desired real power, and then they are further transformed
into three-phase currents. The current values are used to modulate the output of the three-phase controllable current source from the Simulink library.

![Diagram of variable residential load model](image)

**Figure 4.9 The variable residential load model [19]**

### 4.3.5 Simulation Results and Analysis

When micro-grid islanding occurs, there is possibility that the local generation cannot meet the demand of the local load. In this situation, an appropriate amount of load has to be shed. We use the load shedding algorithm we proposed to facilitate this process.

The MGCC continuously monitors the state information of all the equipment in the micro-grid and make optimization when necessary. Therefore in this system, centralized control is adopted to better manage all the equipment scattered in a relatively small area. Due to this feature of micro-grid control, instead of executing local frequency monitoring and load shedding as in the simulation on the power distribution system in section 4.2, the shedding commands here would be made centrally at the MGCC and then sent to all the RLCs through WSNs to realize the proposed load shedding algorithm.
Figure 4.10 (a) Histogram of reducible power (b) Histogram of communication and control delays of all houses in the micro-grid

The residential load is simulated as a three-phase controllable current source that can adjust its output power according to the load curve generated from the load controller. For simplicity, we assume the local loads are all residential loads and there is only one RLC in the micro-grid.
The reducible power and delay distribution models are the same as that in section 4.2. The distribution of the reducible power stays the same; however, considering the relatively small geographical area the micro-grid covers, the mean and variance of the delay distribution model are decreased to 200 ms and $(700)^2$ ms$^2$ respectively. 600 houses are covered in the residential areas. Fig. 4.11(a) and Fig. 4.11(b) show the histograms of all the houses’ reducible power and delays respectively, which closely follow their distribution models.

In the first scenario, the preplanned islanding is simulated. Initially, the micro-grid is connected to the main grid. The output power of the two wind generators and the solar generator stays constant. At 2 s, the MGCC opens the micro-grid central breaker according to the command from the operator. Before islanding, the micro-grid imports power from outside the system whose quantity is beyond the generation margin of the total distributed generation in it. Therefore, during the islanding, the MGCC starts the load shedding process and it goes exactly as the algorithm describes.

As a comparison to our new algorithm, the conventional load shedding by relays is also simulated in the same system. Since we want to compare the performance of these two methods, we assume that the relay load shedding method would shed exactly the same amount of load as our new method. However, in reality, relays often shed more loads than necessary due to their pre-assigned load-relay mapping.

Tab. II shows the part of the reducible load table generated during the simulation that includes the houses which would participate in the load shedding. Totally, 94 out of 600 houses take part in this operation.
Table II
Reducible Load Table

<table>
<thead>
<tr>
<th></th>
<th></th>
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</table>

Figure 4.11 The voltage responses in micro-grid during islanding
The converter of the wind generation system is the master device, so after islanding, it transforms into islanding mode and regulates the system voltage and frequency using the internal voltage and frequency references. In contrast to bulk power systems, the micro-grid has a much smaller inertia, so the parameters in it can vary wildly out of disturbance. If the generation can meet the load in the micro-grid, the voltage would remain stable. On the contrary, if this precondition cannot stand, the voltage would drop to compensate the overload (we keep the frequency relatively stable in the simulation). The simulation results of the voltage responses in Fig. 4.12 show that after the islanding at 2 s, there is a sharp voltage drop in the system due to the imbalance between the system load and generation.

Meanwhile, the load shedding is activated and the voltage is drawn back to normal after several seconds. The curves illustrate that the proposed algorithm possesses comparable performance as the relay load shedding. Due to its faster response and bulk shedding nature, the relay load shedding has a smaller rise time. But in contrast to the simulation in section 4.2, the power electronics interfaced distributed generation system in the micro-grid usually has a much smaller inertia than the rotational machines in the power grid; so they can respond to the small load changes very swift, generating a smaller overshoot than the relay load shedding.

In the second scenario, we simulate the performances of the load shedding when a three-phase short-circuit occurs at 1.9 s on the distribution feeder before the MGCC detects it and island the micro-grid. Because the transient of the three-phase fault is dramatical, the MGCC can detect it in a very short time period, which we assume is 100 ms. Therefore at 2s, islanding happens and the micro-grid is disconnected from the main system. The voltage responses are shown in Fig. 4.13. In contrast to Fig. 4.12, before islanding, a sharp voltage drop occurs out of the fault, then 100 ms later, islanding takes place and draws the voltage back into the normal
range. However, if no load shedding is taken after islanding, the state of the micro-grid is quite unstable, which is reflected by a long-time dip in the voltage curve. With the relay load shedding, the system voltage is quickly recovered, but suffers from an overshoot of more than 0.2 pu. The proposed load shedding reduced this overshoot to about 0.1 pu and possesses a very similar performance afterwards.

![Figure 4.12](image.png)

**Figure 4.12** The voltage responses in micro-grid during fault islanding
Chapter 5

Hardware and Software Implementation

5.1 Introduction to the Experiments

This experiment is established to test the validity of the application of WSNs in the smart grid. Due to the limitations of the power level the available equipment in our labs, the experiment is only constructed to show the information collection and two-way communication ability of the WSNs in the smart grid, not to fully validate them in the smart grid environment. But the results of this experiment demonstrate that WSNs would make it much easier for local area communication, thus their application in the smart grid is promising.

5.2 Communication standards

Using which communication technology to support smart metering is always a heated discussion topic. In our hardware implementation, the communication network aims at the last miles, so low-cost, easy setup and flexible topology are desired features. We therefore choose ZigBee enabled wireless sensor networks as our communication technology. Below, we will introduce the advantages of WSNs in the smart grid and its underlay protocol, IEEE 802.15.4 and ZigBee.

5.2.1 WSNs

In the past, because of their limitations: long delay, loose data rate and uncertainties in quality of service, WSNs did not draw much attention to the applications in the smart grid. Nowadays, as the WSN technologies evolve, researchers find that WSNs have many advantages over other wired and wireless communication schemes in the smart grid, for instance, its robustness, cost efficiency, self-restoration and rapid deployment. Further in the future, the need of pervasive communication infrastructure covering large geographical areas and various application fields,
from wide area monitoring to in-home smart metering, makes WSN more attractive than other technologies. Under power system environment, WSN has some specific features that make it outstanding among all the communication techniques:

1. Self-healing capability: Power systems demand a high level of communication reliability. Failures of communication channels or unavailability of critical data may result in serious instability problems. Although nodes in WSNs are vulnerable spots that may suffer from energy depletion, environmental effects, internal malfunctions or even malicious human behaviors, WSNs are born with the ability of fault-tolerance and self-healing. When any node fails in the network, there is mechanisms to find a new route to guarantee continuous data transmission [11].

2. Localization: Nodes in WSNs are able to automatically estimate their own positions and the positions where some certain events happen [56]. The error range of this location estimation can be controlled within several meters, which is usually enough for power system fault diagnosis. Therefore it is very appealing in power system monitoring when there is a need for tracking fault spots. It can avert the trouble and cost of integrating GPS into sensors, which will greatly reduce the fault localization cost and help to speed up the emergency response time.

3. Collaboration: Unlike other wired and wireless technologies, WSN nodes always scatter over a large geographical area with mutual connections, which makes it easier for collaboration among nodes to achieve some kind of global optimization. Collaborative WSNs and cognitive WSNs grasp this feature to improve WSNs’ performance in smart monitoring, security, localization, energy awareness and fault detection [57]. Through collaboration, the overall capability of WSNs will be improved.
5.2.2 IEEE 802.15.4 and ZigBee

WSN is based on technologies employing IEEE 802.15.4 which defines the physical layer and data link layer; it is a short-range, low-power consumption and low-cost wireless technology using Direct Sequence Spread Spectrum (DSSS), making it more robust against noise [58]. There are several wireless technologies on top of it — ZigBee, 6LoWPAN, ISA100 and wireless HART. Because of its ad-hoc nature, ZigBee is now widely adopted as the WSN technology all over the world. It has a low data rate, long battery life and secure networking which utilizes the 868 MHz, 915 MHz and 2.4 GHz of ISM radio bands. ZigBee also has a flexible network topology which supports star, tree and peer-to-peer networks. It is widely used in home automation, smart metering, health care and remote control and monitoring.

The IEEE 802.15.4 standard specifies two basic types of devices in a network: (i) the full-function device (FFD), which runs all the functions and often plays the role of network router and coordinator; (ii) the reduced-function device (RFD), which is a limited function device that communicates exclusively with a FFD, and can work in an energy-saving mode to extend the battery life.
5.3 Hardware Implementation

![Experiment platform infrastructure](image)

**Figure 5.1. Experiment platform infrastructure**

The infrastructure of this experiment is shown in Fig. 5.1. It contains a PC functioning as the control center to gather all the measurements from the sensors and send commands back to them through the sink node. A sink node serves as the coordinator of the WSN which bridges the two-way communication between the PC and all the sensor nodes. Several sensor nodes distributed across the area to play the role of wireless communication modules that transmit real-time state information of the electric machines from the smart meters to the sink node.

5.3.1 Devices Used in the Experiment

The PC we use is Dell Optiplex 755 with Windows XP system on it. The wireless sensor and coordinator nodes are CC2530 ZigBee chips from Taxes Instrument (see appendix B for the datasheet) as shown in Fig. 5.2. We also use the Smart RF05 evaluation board from Taxes
Instrument and the CC2530 coordinator node to test and power the sensor modules, shown in Fig. 5.3. The Accuenergy L-series power meter (Fig. 5.4), which has a flexible communication interface and ability to measure various types of parameters (see appendix B for the data sheet), serves as the smart meter.

Figure 5.2. CC2530 module (from Texas Instrument)

Figure 5.3. Smart RF05 evaluation boards along with CC2530 modules (from Texas Instrument)
To test the validity of the WSNs in smart metering, we construct a small experiment platform for data acquisition and processing in the power lab. The measurements from the output ports of an AC load and a solar converter are transmitted through their own CC2530 end nodes to the WSN and finally to the PC. The Chroma 63803 programmable AC&DC load with a power rating of 1.8 kW is adopted. The solar simulator is Agilent E4360A with a maximum power rating of 600W.

![Image of Accuenergy L-series power meter](image)

**Figure 5.4. Accuenergy L-series power meter (from Accuenergy)**

### 5.3.2 Interfacing Smart Meters with Sensor Nodes

The Accuenergy L-series meter has an RS485 serial communication port to facilitate external information and control access; while on the Smart RF05 evaluation board, it has an RS232 female port allowing the sensor node mounted on it to communicate with other devices. RS485 is a serial communication physical layer standard using differential signaling with a voltage level in between -7 V to +12 V; while RS232 is a serial communication standard with unbalanced signaling from ±5 V to ±15 V. An RS232 to RS485 converter is used to translate these two types of signals, as shown in Fig. 5.5.
Fig. 5.5. Interfacing the smart meter with the censor node

The Accuenergy L-series smart meter adopts Modbus series communication protocol which, out of its easy deployment and maintenance, is a widely used industrial communication standard in industry automation [59]. According to the Modbus protocol and the command table on the L-series meter’s manual, we implement the interfacing software on CC2530 sensor modules to give the sensors direct access to the meters’ stored measurements.

5.4 Software Implementation

The CC2530 wireless module is a system-on-chip ZigBee solution. It runs z-stack, a complete ZigBee 2007 protocol software stack, on it, whose structure is shown in Fig. 5.6. From the figure, we can see the protocol stack of Zigbee share something in common with OSI 7-layer model, both of which includes the PHY, MAC, and NWK layers. The highest layers in OSI are wrapped
up in the APS and ZDO layers in the stack. The two lowest layers, PHY and MAC, are specified by IEEE 802.15.4. The PHY layer simply translates the package to and from over-the-air message. The MAC layer provides the basic per-hop setup for the network, including network discovery and joining. The NWK is responsible for routing the packages. On top of it, the APS layer functions as an interface to communicate between NWL and the application layers. It filters and forwards packages from and to different endpoints. The local binding table is also managed at this layer. Furthermore, the ZDO layer is responsible for node discovering and management in the network. The smart metering object is an application object running in an end point in the application framework to provide corresponding smart metering service. The security service manages the key and other security-related issues in the network [60], [61]. In contrast to the general ZigBee stack, there is an extra layer called Operation System Abstract Layer (OSAL) running through all the layers as in Fig. 5.6, which is used by the CC2530 node to coordinate the tasks and layers in the whole software stack, similar to operation systems on PCs.

In the OSAL, there is a task array used to register different tasks. The system continues polling the array from the highest priority task to the lowest one. We add the serial port polling task into this task array to allow the CC2530 module communicate with the smart meter through its RS232 serial port. The flow chart of the software implemented on CC2530 sensor node is shown in Fig. 5.7.
Figure 5.6. CC2530 zigbee software stack
Figure 5.7. Flow chart of the software program on the CC2530: (a) End device, (b) Sink node

Firstly, the OSAL on the sink node initializes the system, and then it polls the task array and waits for any message from the PC or from the end devices. If a data acquisition command is received from the PC through the serial port, it will decode the command and send the corresponding data request to the end device. Upon receiving this request, the end device will analyze it and access the smarter meter to get measurements on request, and then the end device will send the measurements back to the sink node. The sink node will then further forwards the messages to the PC. Finally, the PC will process and display the measurement on the GUI to the customers.

5.5 Network Setup and Graphical User Interface (GUI)

In this section, the WSN setup and the GUI on the central PC will be shown.
5.5.1 Network Setup

To ensure a reliable network structure, we use binding to bind the end devices with the sink nodes. In this way, any data sent by the end devices will be captured by the sink nodes, and vice versa. Binding is very reliable in the sense that it establishes a virtual interconnection among nodes but does not specify the routes the messages travel through when forwarding, so when there is a failure occurs in the current route, the routers can find another healthy route to send the data to the target node. The network topology in the lab field is shown in Fig. 5.8. The two end devices connected with the smart meters are bond with the sink nodes. In between them, there are two routers routing the messages around.

Figure 5.8 The smart metering network and central control PC

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5.5.2 Graphical User Interface (GUI)

In order to better display all the collected measurements on the PC, we develop a GUI with Microsoft Foundation Class Library (MFC) on Microsoft Visual Studio 2008. It allows users to easily send data request through the serial port to the sink nodes and process the replied data. Our smart meter monitoring GUI is responsible for sending commands as well as processing and displaying measurements. When users press the update button on the GUI, it will send corresponding data acquisition commands to the smart meters through the WSN. Then it stays in a busy loop waiting for the responses from the smart meters. Upon receiving these responses, the program will further analyze the data and transform them into a user friendly format. The snapshot of the GUI is shown in Fig. 5.9.

![Figure 5.9. Data acquisition GUI for smart metering](image)

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5.6 Experiment Results

In this experiment, two smart meters are installed at the output ports of the AC load and solar simulator converter respectively. The output electric measurements, such as voltage, current, real power, reactive power, and frequency, are obtained through the smart meters. The solar power converter is an in-home low-voltage converter used for a single solar panel with a real power range from 0 W to 215 W and a reactive power of nearly 0 V Var. It converts the 22 V DC voltage of the solar panel into 240 V two-phase AC voltage.

The output voltage of the Agilent E4360A solar simulator is set as 22 V; and the voltage of the Chroma 63803 programmable AC load is set as 120 V to emulate the real scenario in a house. We then adjust their output power to check the validity of the data acquisition process. The time/real power variation curve is shown in Fig. 5.10. The curves of the solar generation and AC load approach the shapes of the real curves in a house.

![Figure 5.10 The time/real power input curve for the AC load](Image)

Figure 5.10 The time/real power input curve for the AC load
We capture measurements at the 12 consecutive time points in a day, and the data collected at these points are displayed in Tab. III. The voltage, current, real power, reactive power, power factor measurements and frequency are measured and collected. Furthermore, the delays of the feedback data are shown in the last column, which include the wireless communication delay, the serial port communication delay, the sensor module and smart meter module control delay, as well as the data processing delay at the PC. These together make up the round-trip delay of around 0.9 s as shown in the table. This delay is tolerable for our load shedding application, because according to our algorithm, in the emergency, only single-way communication is needed from the RLC to the HEME, and then from the HEME further to the home appliances.

The experiment above shows the WSN is a good fit for the home monitoring and automation in the smart grid. The low-cost feature makes it cheap to monitor and control all the home appliances. Besides the home area network, WSNs can also be used in small micro-grids used for real-time data acquisition and control commands transmission. Although common ZigBee module has a very short transmission range, by increasing the transmission power and the number of nodes, the coverage of the WSN can be greatly extended.
Table III. Measurements from the AC Variable Load

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<th>Time</th>
<th>Voltage/ V</th>
<th>Current / A</th>
<th>Power /W</th>
<th>PF</th>
<th>f/H</th>
<th>Q/ Var</th>
<th>Voltage/ V</th>
<th>Current / A</th>
<th>Power /W</th>
<th>PF</th>
<th>f/H</th>
<th>Q/ Var</th>
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Chapter 6

Summary, Conclusion and Future Work

6.1 Summary and Conclusions

The thesis proposed a new customer-side and system-side combined load shedding algorithm in the smart grid. It combines the features of in-home energy management and system level load control.

On the system side, the control entities take responsibilities to monitor the system state as well as to manage the residential loads. When a load-generation imbalance is detected, it would notice the houses to reduce their loads. On the customer side, the power consumers can freely choose their preferred power consumption management strategy, and the HEME would manage all the home appliances and report the real-time reducible power consumption to the system-level RLC. If a load shedding command is received at the HEME, it would reduce the in-home power consumption by the predetermined quantity.

The greatest advantage of this new algorithm is that it involves end users in the power system emergency restoration process without jeopardizing their comfort. In contrast to the conventional under-frequency relay load shedding that sheds the loads in whole areas, this algorithm lets the system-level controller negotiate with the in-home HEMEs and, as a result, makes the load shedding process almost transparent for the end users. The proposed algorithm is also more intelligent in communication and cooperation, and can give electric customers high flexibility in managing their home appliances. In addition, as the decentralization of the power
system, the proposed load shedding algorithm can also better serve the needs of the micro-grid islanding control.

To demonstrate the validity of the proposed algorithm, two simulations were brought out: one in the power distribution system, the other one in the micro-grid. The residential load models were established based on the statistics of Canadian home power consumptions. The simulation performances of the proposed load shedding were compared with those of the relay load shedding. The results showed comparable performances of those two strategies. It proved that the proposed load shedding can meet the requirements of the emergency restoration in the power distribution system and in the micro-grid. Besides, it possesses a smaller overshoot than the conventional load shedding in micro-grid islanding restoration. Further in the experiment, we set up the hardware platform for testing WSNs in smart metering. It verified the applications of the WSN technique in the smart grid.

In conclusion, the proposed load shedding proves to be an efficient strategy that can better serve the power consumers in the future smart grid. However, before applying it into the real system, more research should be done. In the next section, some advised future works will be proposed.

6.2 Recommended Future Work
Involving end users in power system emergency restoration is a relatively new topic, so there are a series of barriers need to be broken down. Although this thesis has already dealt with the main technical problems in algorithm design and system control, some other problems still exist.

In order to motivate end users to participate in the load shedding, some award and punishment mechanism is indispensable. For example, in the demand response, dynamic pricing is usually used to stimulate power consumers to adjust their electricity consumption according to
the electricity price change so that through controlling the price, the desired daily power consumption curve can be achieved. Undoubtedly, price is a good stimulus in power systems; however, dynamic pricing itself is not suitable for our load shedding application, because dynamic electricity price is generated by auction in the free electricity market, and this takes a fairly long time compared to the time scale of the load shedding process. It would be too late for emergent system restoration if we postpone the load shedding till we get the results of the auctions. An alternative way may be to sign contracts between utilities and end users, and reward the participants of the load shedding afterwards. This can avert negative time effect of the award and punishment process in the load shedding phase; however, determining the amount of the reward is not a trivial task. In a word, no matter what kind of mechanism is used to motivate end users, we should always give the emergency restoration process the highest priority, so that this mechanism would not affect the performance of the system operation.

What is more, to make the proposed algorithm practical, technical supports from the home automation is another critical part. All the houses should be equipped with HEMEs to manage and control the home appliances. The HEME is not necessarily a high-performance controller. Depending on the extent of the home automation, it could be a very small embedded system installed in a communication sink node. As the prevalence of this type of products, their price can be greatly decreased in the future smart grid.
References


Appendix A

IEEE 14 Bus System Data

Table A.1 Generator Data

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<tr>
<th>Generator Bus No.</th>
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<th>4</th>
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Appendix 2

Datasheet

Datasheet for TI’s CC2530 Module

FEATURES
- RF/Layout
  - 2.4-GHz IEEE 802.15.4 Compliant RF Transceiver
  - Excellent Receiver Sensitivity and Robustness to Interference
  - Programmable Output Power Up to 4.5 dBm
  - Very Few External Components
  - Only a Single Crystal Needed for Asynchronous Networks
  - 6-mm x 6-mm QFN40 Package
  - Suitable for Systems Targeting Compliance With Worldwide Radio-Frequency Regulations: ETSI EN 300 328 and EN 300 440 (Europe), FCC CFR47 Part 15 (US) and ARIB STD-T-66 (Japan)
- Low Power
  - Active-Mode RX (CPU Idle): 24 mA
  - Active Mode TX at 1 dBm (CPU Idle): 29 mA
  - Power Mode 1 (4 μs Wake-Up): 0.2 mA
  - Power Mode 2 (Sleep Timer Running): 1 μA
  - Power Mode 3 (External Interrupts): 0.4 μA
  - Wide Supply-Voltage Range (2 V–3.6 V)
- Microcontroller
  - High-Performance and Low-Power 8051 Microcontroller Core With Code Prefetch
  - 32-, 64-, 128-, or 256-KB In-System-Programmable Flash
  - 8-KB RAM With Retention in All Power Modes
  - Hardware Debug Support
- Peripherals
  - Powerful Five-Channel DMA
  - Integrated High-Performance Op-Amp and Ultralow-Power Comparator
- IEEE 802.15.4 MAC Timer, General-Purpose Timers (One 16-Bit, Two 8-Bit)
- IR Generation Circuitry
- 32-kHz Sleep Timer With Capture
- CSMA/CA Hardware Support
- Accurate Digital RSSI/LQI Support
- Battery Monitor and Temperature Sensor
- 12-Bit ADC With Eight Channels and Configurable Resolution
- AES Security Coprocessor
- Two Powerful USARTs With Support for Several Serial Protocols
- 21 General-Purpose I/O Pins (19 x 4 mA, 2 x 20 mA)
- Watchdog Timer
- Development Tools
  - CC2530 Development Kit
  - CC2530 ZigBee™ Development Kit
  - CC2530 RemoTI™ Development Kit for RF4CE
  - SmartRF™ Software
  - Packet Sniffer
  - IAR Embedded Workbench™ Available

APPLICATIONS
- 2.4-GHz IEEE 802.15.4 Systems
- RF4CE Remote Control Systems (64-KB Flash and Higher)
- ZigBee Systems (256-KB Flash)
- Home/Building Automation
- Lighting Systems
- Industrial Control and Monitoring
- Low-Power Wireless Sensor Networks
- Consumer Electronics
- Health Care

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Datasheet for Accuenergy L-Series Power Meters

SPECIFICATIONS

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COMMUNICATION

- RS-485 (Option)
- Modbus®-RTU Protocol
- 2-wire connection, Half-duplex, Isolated
- 1200 to 38400 baud rate

INPUT

Current Inputs (Each Channel)
- Nominal Current: 5 A ac
- Metering Range: 0−6 A ac
- Withstand: 20A rms continuous
- Input Impedance: 20ohm per phase
- Metering Frequency: 45Hz−65Hz
- Pickup Voltage: 10V
- Accuracy: 0.5%

Voltage Inputs (Each Channel)
- Nominal Full Scale: 600Vac L-N, 600Vac L-L (+20%)
- Withstand: 1500Vac continuous
- Input Impedance: 20ohm per phase
- Metering Frequency: 45Hz−65Hz
- Pickup Voltage: 10V
- Accuracy: 0.5%

Energy Accuracy (Accuvim-EL)
- Active (according to IEC 62053-22): Class 0.5s
- Apparent (according to ANSI C12.20): Class 2

Harmonic Resolution
- Metered Value: 2nd to 50th harmonics
- Accuvim-EL is 2nd to 25th

CONTROL POWER

Universal
- AC or DC

AC/DC Control Power
- Operating Range: 100−415Vac, 50/60Hz, 100−300Vdc
- Load Current: 2W
- Withstand: 3250Vac, 50/60Hz for 1 minute

Low Voltage DC Control Power (Optional)
- Operating Range: 20−60Vdc
- Burden: 3W

DIGITAL OUTPUT OPTION

- Digital Output (DO) (Photo-MOS): 3V
- Voltage Range: 0−5V
- Output Frequency: 25Hz, 50% Duty Ratio (20ms ON, 20ms OFF)
- Isolation Voltage: 2500V

DIGITAL INPUT OPTION

- Digital Input (DI)
  - Input Voltage Range: 20−160Vac/dc
  - Current (Max): 2mA
  - Start Voltage: 15V
  - Stop Voltage: 5V
  - Pulse Frequency (Max): 200Hz, 50% Duty Ratio (5ms ON and 5ms OFF)
  - SOE Resolution: 2ms

OPERATING ENVIRONMENT

- Operation Temperature: -25°C to 70°C
- Storage Temperature: -40°C to 85°C
- Relative Humidity: 5% to 95% non-condensing
- Pollution Degree: 2

STANDARD COMPLIANCE

- Product
  - USA: UL 61010-1
  - Canada: CUL 61010-1
  - Europe: IEC 61010-1
- Emission
  - Radiated/Conducted: FCC Part 15 Subpart B, Class A
  - Radiated/Conducted: EN 55011
- Harmonic
  - IEC 61000-3-2
  - Voltage Fluctuation: IEC 61000-3-3
- Surge
  - IEC 61000-4-5
- Conducted disturbances
  - IEC 61000-4-6
- Power frequency magnetic field
  - IEC 61000-4-8
- Voltage dips and interruptions
  - IEC 61000-4-11
- Generic Immunity Standard for Industrial Environment
  - EN 50082-2

ORDERING INFORMATION

- Accuvim-EL
  - Diffused Frequency Current Power Supply / I/O Module
  - XT: 40Hz(2000Hz)
  - P1: 100−415Vac, 50−60Hz
  - P2: 20−60Vdc

- A: Accuvim-EL (no COMM)
- B: Accuvim-EL (DI)
- C: Accuvim-EL (COMM + DO)
- D: Accuvim-EL (COMM + I/O)
- E: Accuvim-EL (DI+COMM+DO)

* Note: I/O Module only support by Accuvim-EL and Accuvim-DL

Remote Display Option

- D1: Compatible with Accuvim L-Series "M" (DIN Mount)

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