**PhD Dissertation**

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**International Doctorate School in Information and Communication Technologies**

DISI - University of Trento

# Renewable Energy and the Smart Grid: Architecture Modelling, Communication Technologies and Electric Vehicles Integration

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April 2015

# Abstract

*Renewable Energy is considered as an effective solution for relieving the energy crisis and reducing the greenhouse gas emissions. It is also be recognised as an important energy resource for power supplying in the next generation power grid–smart grid system. For a long time, the unsustainable and unstable of renewable energy generation is the main challenge to the combination of the renewable energy and the smart grid. The short board on the utilities' remote control caused low-efficiency of power scheduling in the distribution power area, also increased the difficulty of the local generated renewable energy grid-connected process. Furthermore, with the rapid growth of the number of electrical vehicles and the widely established of the fast power charging stations in urban and rural area, the unpredictable power charging demand will become another challenge to the power grid in a few years.*

*In this thesis we propose the corresponding solutions for the challenges enumerated in the above. Based on the architecture of terminal power consumer's residence, we introduce the local renewable energy system into the residential environment. The local renewable energy system can typically support part of the consumer's power demand, even more. In this case, we establish the architecture of the local smart grid community based on the structure of distribution network of the smart grid, includes terminal power consumer, secondary power substation, communication links and sub data management center. Communication links are employed as the data transmission channels in our scheme. Also the local power scheduling algorithm and the optimal path selection algorithm are created for power scheduling requirements and stable expansion of the power supply area.*

*Acknowledging the fact that the information flow of the smart grid needs appropriate communication technologies to be the communication standards, we explore the available communication technologies and the communication requirements and performance metrics in the smart grid networks. Also, the power saving mechanism of smart devices in the advanced metering infrastructure is proposed based on the two-state-switch scheduling algorithm and improved 802.11ah-based data transmission model.*

*Renewable energy system can be employed in residential environment, but also can be deployment in public environment, like fast power charging station and public parking campus. Due to the current capacity of electrical vehicles (EV), the fast power charging station is required not just by the EV drivers, but also demanded by the related enterprises. We propose a upgraded fast power charging station with local deployed renewable energy system in public parking campus. Based on the queueing model, we explore and deliver a stochastic control model for the fast power charging station. A new status called "Service Jumped" is created to express the service state of the fast power charging station with and without the support from the local renewable energy in real-time.*

**Keywords**

Smart Grid, Renewable Energy, Distribution Grid, Communication, Electric Vehicles, fast power charging station

*To my parents.*

# Acknowledgments

It is very hard to find to words that are capable enough to express my gratitude to everyone that have contributed to the completion of this theis.

First of all, I would like to thank Prof. Claudio Sacchi, Prof. Lucio Marcenaro, and Prof. Igor Bisio for accepting the invitation to be part of my PhD defense committee.

I would also like to thank my advisor, Prof. Fabrizio Granelli, for his guidance during the last three years of the PhD degree and for giving me the opportunity to work and grow as a researcher at the University of Trento. You have always been very kind with me and have always tried to provide me with all the opptunities to improve and upgrade my research.I feel sincerely happy and honor to follow your advice and guidance in these years. Not just because you are an excellent scientist and researcher, but also a good man that people can trust and believe. I wish you all the best for the future and hope we can continue working together for many years.

At the same time, I would like to express my appreciation to Prof. Michael Devetsikiotis who accepted my requirement to conduct my research intern in his lab at North Carolina State University and became my co-advisor. It is a great opportunite to me to follow Dr. Devetsikiotis's guidance and collaborate with other Ph.D. candidates in NC State University. Our numerous discussions and insightful suggestions have increased the quality of my PhD tremendously.

I would also like to thank Dr. Daniele Miorandi, for his high level re-

quirement on my research and great help on my qualifying exam. Without your kind help and carefully review of my reports, I may not able to have a good start on my research in University of Trento. Hope we can continue our collaboration and deliver fruitful research results.

Likewise, I cannot forget my main research collaborators during these three years: Raúl Palacios, Islam Safak Bayram, Anteneh Atumo Gebremariam, Yong Ding and Saud Althunibat. I would like to thank you all for all your very useful comments and suggestions to improve our papers and my research in general. I look forward to continuing our fruitful collaboration in the future.

Also, my special gratitude goes to Andrea Stenico, Luca Raimondi and Francesca Belton, who have always been available to help me whenever I have had a problem in ICT school.

I would also like to thank my close friends, who are living in China or other countries, since the time they knew I was going to Trento to do research and pursue the PhD degree at the University of Trento, they have always been supporting me.

In this monment, I cannot forget that this achievement could not have been possible without the support of my parents. At each important step of my life, you always give me advices, comments and lead me to become a man who can judge right and wrong, and has correct understanding of himself. Without you, I would not be where I am now. Wish my parents, from the deepest of my heart, have a long, healthy, and happy life.

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# Chapter 1

# Introduction

What is the "Smart Grid"?

The "Grid," means electric grid, a huge network of transmission lines, substations, transformers, feed lines, meters and more, which can delivery electricity from the power plant to terminal power consumer's residences, industry and commerce. Our current electric grid was built since 1890s and improved upon as technology advanced through many decades.

The current official definition of smart power grid (or smart grid in short) is stated as, the digital technologies employed in the power grid network, which allows for two-way communication between the utilities and its consumers. These new technologies like computers, automation, and sensors and equipment will work together with the electrical grid to support our dynamic and quickly changing power demand in this next-generation electric power grid [1] [8].

## 1.1 Motivation for Smart Grid and Renewable Energy System

With the coal, natural gas, petroleum and other non-renewable energies are continually being consumed by human being for the development of society, these energy-based electrical power grid is also built up since 1890s and considered as the most important energy resource in nowadays. We all known, these non-renewable energy, during and after the consumption process by human being, can cause the environmental pollution that already became a serious challenge to the sustainable development of human society.

The electrical power is considered as a so called ”clean” energy resource if we compare it with cool, natural gas, petroleum and other non-renewable energies that are existing in our daily life. But unfortunately, when we discover the power generation process, the fossil-fuel power station is still the most popular power plant, which supports almost 67.2% electricity generation of USA in 2014 [4]. Even the nuclear energy is also recognised as an alternative energy of fossil-fuel, but the Chernobyl disaster and Fukushima Daiichi nuclear disaster are deeply impacted the ordinary people's awareness of the usage of nuclear energy and the government's determination in the development of nuclear energy.

Then, we need to explore a new way to innovate the power grid and let the upgraded power grid assistant the development of human society.

### 1.1.1 The current power grid and Impacts of Renewable Energy System Penetration

In general, the architecture of the current power grid includes power plant, dynamic power utilities, transmission grid and distribution grid [61]. The power plant is recognised as the original power resource of power grid. Based on the different usage raw materials, the power plant can be divided into the following categories: fossil-fuel power plant, nuclear power plant, geothermal power plant, biomass-fuelled power plant, hydroelectric power plant, wind farm and photovoltaics system, etc.. The fossil-fuel power plant, nuclear power plant and hydroelectric power plant are the main and popular power generation resources in the worldwide now. In recent years, the wind farm and photovoltaics system that are recognised as the renewable energy resource, have been highlighted as the ”clean energy” in the media and highly attracted attention of government and public [27].

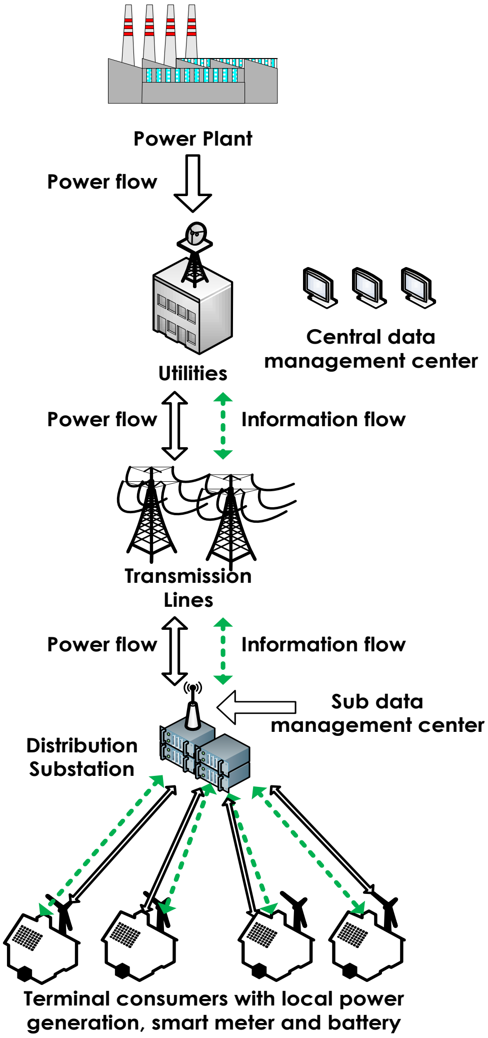

Figure 1.1: A simple diagram of the main smart grid sections

The electric utility, as the same meaning as the text, is the electric power company that embark each part of the electricity for sale in the electric power market [33]. The electric utility is considered as the main provider of energy in many countries. The main aim of the electric utility is to satisfy the increasing power demands from power consumers, via scheduling the power transmission and support in the power grid. The service territories of utility is usually settled by regulation, local population, and economics.

The types of power consumers in each territory is dynamic, includes residential consumers, industrial consumers, and commercial consumers.

The transmission grid is play the role as array transfer of electrical energy from power generation plants to the power substations near the power demand consumers in the power grid. The transmission grid, or called transmission networks are assembled by mass of transmission lines between the power plants and the distribution part of smart grid [38]. The transmitted power in transmission grid is usually transformed to high-voltage (HV) or very high-voltage (VHV) direct current in the side of the power plant, and transformed to medium-voltage or low-voltage by distribution substations near the ordinary power consumers over long distances, as the HV/VHV direct current could reduce the path loss on the transmission lines. The nearest part to the terminal power consumers in the power grid network is the distribution grid. The distribution grid as the final stage of delivering electric power, carries the power from transmission grid to the dynamic individual consumers. In Europe, there two types of power substations in distribution grid for transforming HV/VHV direct current to low-voltage power [2]. The primary substation transforms high-voltage power to medium-voltage power and transmits the medium-voltage power to secondary substations. The secondary substation transforms medium-voltage power to low-voltage power and distribute the low-voltage power to dynamic terminal power consumers via using feed lines. The electric meters are also settled in distribution for metering the power consumption data from the terminal electrical devices.

In order to upgrade the current power grid, the communication technologies and renewable energy systems are introduced into the power grid [1] [2] [31]. The upgraded version of the power grid is called "smart grid", or "intelligent grid" as the next generation power grid system shown in Figure 1.1. The obvious feature of the smart grid is it has two-way flow, power flow and information flow [30]. The information flow is implemented by the employed communication technologies in the smart grid networks [54]. Another highlight new point is the deployment of renewable energy as the power resources for power support in the smart grid networks. The renewable energy system is not just centralised as the power resource of power plant, but also be distributed in the distribution grid, or even the residential environment of terminal power consumers as the local power generation plant. The organised renewable energy system, like wind farm and photovoltaics system (or we call it as solar power system) can be selected as the stable power plant for generating "clean energy" and grid-connected to the power transmission grid via the scheduling of power utilities.

Meanwhile, the residential renewable energy system is recognised as the assistant power support of local power demand, especially in the peak time [21]. The traditional home environment can be updated and modified via deploying suitable communication blocks, local renewable energy system and other information applications. In this upgraded home environment, the generation and consumption of the renewable energy can be controlled by the residence owner and even "sell" the local generated renewable energy back to the utilities in a suitable grad-connected time interval that should be based on the information interactive between terminal power consumers and utilities, and scheduled by the decision from the power utilities.

### 1.1.2 Challenges and Barriers

We are clear that the development roadmap of the current power grid is the next generation power grid– smart grid. During this upgrading process, there are some challenges we can not ignore and have to explore and solve.

- Remote micro-operation of the power utilities are not enough for responding the power demand, power consumption metering and power support scheduling in the terminal power consumption area. Even we previously stated that the highlight feature of smart grid is the two-way flow for power transmission and information exchange in the smart grid networks. But the deployment of the communication links are just started from the terminal part of the smart grid networks [61]. We look back to the power blackout disasters happened in north Italy, U.S. in 2003 [9], it stated that the power outage appeared in the terminal power support area didn't be timely discovered and make the correct response by the power utilities, caused a series of blackouts in the power grid [51]. The utilities can not receive the real situation of the terminal power distribution area and give the correct response in real-time, is recognised as one of the challenges should be solved.

- The main resources for power generation are still non-renewable energy resources. As we have discussed previously, the almost 67.2% power generation of U.S. is based on the non-renewable energy resources in 2014 [4]. The popular generation of renewable energy is based on the wind farm and solar power system. But the changing of natural conditions makes the renewable energy production process can not achieve stable, sustainable and efficient [18] [27].

- The generated renewable energy storage is still a thorny problem. In general, we know that the generated power energy can not be stored for a long period. The utilities usually firstly estimates the whole power consumption of the power grid, based on the actual power demand in the past. Then the utilities can arrange the power production in the power plant, and the electricity transmission and distribution in the power grid. Especially in the residential environment, the local generated renewable energy should be consumed by the terminal power consumers in real-time, which is mentioned in the early proposals [8]. That is because the efficient energy storage device is still under exploring by academia and industry in recent years. The generated renewable energy wherever in the power plant or the terminal power consumer's residence, if it can not be stored for a long time interval, then will become "dropped power" that means not be consumed power but lost in the short-time storage device or on the power lines as heat radiation at the end.

- The residential generated renewable energy is only could be used in their own home environment and large-scale number of the terminal power consumers make the one-family generated renewable energy become very hard to be grid-connected to utilities. As we discussed in previous, the shortage of renewable energy storage impedes the assistant of renewable energy for residential power support. At the same time, if the terminal power consumer would like to sell the local generated renewable energy back to utilities, the information exchange and the grid-connected time should be decided on the current situation of power grid, otherwise it may cause unexpected power failures and even lead to blackouts.

- With the rapid development of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV), the fast power charging station becomes a popular project attracted mass of investment from companies and governments, for serving the power charging demand of EV and PHEV in recent years [58]. In the popular proposals, fast power charging station is mainly relying the power support from the power grid. As large-scale of EV/PHEV need to get power re-charging, the power demand in the fast power charging station would be vastly raised. In this situation, the terminal power distribution network surrounding the fast power charging station may withstand the excessive power load causing power outage even power blackout.

- The satisfactory renewable energy trade policy is still under the exploration. The renewable energy trade policy between the power utilities and the terminal power consumers need to achieve to the ”win-win” balance. Not just let the utilities get benefits from collecting the local generated renewable energy, but the terminal consumers also need to receive the profits from this business process. This business should not just be limited in the residential environment. Through the information devices or applications, consumers should be able to implement their income based on their own local generated renewable energy in dynamic ways in the daily life.

## 1.2 Architecture Modelling in the Distribution Grid

There are significant challenges and opportunities for research on power management in the distribution part of the grid. In particular, we focus on the Demand Side Management (DSM). DSM includes load monitoring, analysis and response. Many works are available in the literature, which address critical issues of DSM in terms of wireless communication technologies, integration of renewable energy, pricing schemes, micro grids and other relevant aspects.

*A.Wireless Communication Technologies* A wireless communication system is a key component of the smart grid infrastructure [42] [54]. The wireless communication system is used to transmit data from sensing/ measuring the status (i.e. energy consumption, voltage fluctuation, and damage to power equipment) from different devices (i.e. substations, smart meters, and sensors) [64]. With the integration of advanced technologies and applications to achieve a smart power grid infrastructure, a huge amount of data from different applications will be measured for further analysis, control and real-time pricing policy. Basically, three types of information infrastructure are needed for information transmission in a smart grid system. The first level is from sensor and electrical appliances to smart meters, resulting in a Home Area Networks (HANs). The second level, Neighbourhood Area Networks (NANs), involves communications between smart meters and the centers of sub data management of utilities, which are used to collect, analyze, and forward the information in the local area and from local to utilities. The last tier is a Wide Area Networks (WANs) setting between the sub data centers and the utilitys central data management center [64] [43].

In order to support demand side management in smart grid, the reliability of data communications system of smart grids becomes a crucial feature to ensure efficient, continuous, and secure operations of the grid. Laverty et. al [54] proposed a reliability analysis and design of smart grid wireless communication system to support demand side management. Availability is considered as the main performance metric from the theory of reliability analysis in [54] [85] [5]. The concept of availability is defined as the probability that the smart meter can send the power demand to the meter data-management system (MDMS), which is located in electrical utilities. In order to reduce the cost of network unavailability, the redundancy design is presented to minimize the cost of demand-estimation error and the damage cost.

*B.Integration of Renewable Energy Sources* Aiming at reducing the energy costs of consumers, Cecati et. al [21] proposed an energy management system (EMS) to optimize the operation of the smart grid. By integrating demand side management and active management schemes, EMS allows a better exploitation of renewable energy sources and a reduction of the energy consumption costs of consumers, with both economic and environmental benefits. According to the participants preferences and real-time power consumption costs, the grid resilience and flexibility are also improved in the scheme. To satisfy the dynamic power demands and adapt the intermittent renewable energy resources, European Parliament [66] introduced a distributed scheme for stochastic scheduling scheme. Being formulated via hidden Markov model, an algorithm based on value iteration is proposed to solve the problem of complex system dynamics in the scheme. Renewable energy models for renewable energy produced from wind turbine systems and solar panels are also presented. In the model, at each time slot, the number of available renewable energy generators is determined by the renewable energy generations status and the total power demand loads.

*C.Pricing Scheme* In smart grid, end-users become active participants in the grid system, being able to react to electricity prices. Demand forecasting is one of the popular research topics in the demand side management. A multi-input multi-output (MIMO) forecasting engine for joint combined price and demand prediction with a data association-mining algorithm is proposed by Motamedi et. al, [63] in a hybrid-forecasting framework. In this case, a mechanism is presented to determine and extract the patterns in consumers reaction to price forecasts. This framework includes three blocks. The initial demand and price forecasts are generated using the MIMO forecasting engine in the first block. Data association mining captures the demand-price interdependencies by following IF-THEN rules in the second block. Finally, in the third block, the initially generated forecasts are improved and updated price and demand forecasts are generated. The preference of dynamic power consumption of consumers is one of the data resources to formulate the available dynamic energy pricing models in the demand response of smart grids, which also can be modified via rational energy consumption policies from utilities [39] [50].

*D.Micro Grid* Micro grid is a popular definition of one kind of power distribution architectures in smart grid. A micro grid is a discrete energy system consisting of distributed energy sources (i.e. renewables, conventional, storage) and loads capable of operating in parallel with, or independently from, the main grid [26]. The purpose of micro grid is to ensure reliable energy security for dynamic consumers. The core role of micro grids is considered as one conventional generation assets (i.e. engines or turbines) fueled by natural gas, biomass or methane from landfill. Once the micro grid is connected to the main grid, it will lean on the mixed power generation sources. A micro grid includes generation that is realized as the core of micro grid, distribution system, storage and consumption, management system with advanced monitoring, control and automation components. In the case of demand reduction, programmable thermostats, occupancy sensors, efficient lighting, and advanced metering are deployed for cost saving of ordinary consumers [60].

## 1.3 Applicable Communication Technologies in the Smart Grid

The realization of such demand side management techniques requires appropriate communication architectures. The two-way communications will enable reliable interaction between the grid and the terminal power consumers. As our work focus on the distribution part of smart grid, we also pay close attention on the wireless communication technologies in the local power distribution domain [45] [43].

The status of power consumption/ generation pattern for each user is transmitted via the local power distribution control device [45]. Depending on the operating environment, the data could be delivered through routing on multiple wireless access links. Hence, wireless routing path selection represents a relevant challenge in the power distribution scenario, and is discussed in some existing research works.

Jung [52] proposed two novel methods for improving the routing reliability of IEEE 802.11s WLAN mesh based smart grid networks. Based on the Hybrid Wireless Mesh Protocol (HWMP) and the wireless access environment of neighbourhood area network (NAN), Jung [52] described airtime cost modification scheme and route fluctuation prevention scheme (ACM-RFP scheme), which would alleviate the route fluctuation problem in wireless routing process. In this ACM-RFP scheme, a modification is proposed to the route selection method in HWMP, which includes the extended route table. Multiple route information in the root announcement interval as well as previous root announcement interval is stored by each node. Each mesh node will calculate the airtime cost of all the root announcement messages, which is considered as the link-cost for the path selection process.

In order to solve the challenge in the distribution network of smart grid, Gharavi [35] considered a tree-based mesh routing scheme based on a flexible multi-gate mesh network architecture that expands on the hybrid tree routing of the IEEE 802.11s standards. A timer-based multi path routing diversity scheme is proposed to enhance the communication network reliability, based on the further exploration of multi-gate network structure. In the multiple data aggregator points (DAP) structure, a mesh node will check its tree-table to see if there is a tree with the same announcement, when it receives a DAP announcement from the root point of this structure. The proposed reserve-path multi gate diversity routing (RMGDR) scheme takes advantage of the multiple gateway tree-based routing scheme with the objective of managing the packets transmission via different path to possibly another gateway.

A load balancing relay selection algorithm (LB-RS) is presented by Jiang [49] for relay based cellular network, which chooses the optimal relay node for each user in a distributed way. This LB-RS algorithm focused on the "two-hop relay" among mobile station, relay node and base station. By taking the periodically broadcasts from base station and relay node, the mobile station will check the signals channels between the relay nodes and the associated base station to decide to either communicate with the base station directly or via a "two-hop relay". The received channel state information on the wireless access links between the mobile station and the candidates relay nodes will be employed as the main parameter for path selection in the "two-hop relay".

## 1.4 Electric Vehicles and Fast Power Charging Station

There has been a growing body of literature on the fast public charging station architecture based on DC charging mode. In [12] Bayram et al. proposed a fast charging station architecture along with an energy storage device, which is employed as an additional power supply to minimize the peak demand fluctuations and protect distribution grid components from failures. From power engineering perspective, Bai et al. [11] proposed an electric vehicle charging station model for the fast DC charging of multiple electric vehicles. An energy storage system connected to the DC bus is employed for solving the sizing problem via using Monte Carlo simulations. The DC bus is established as the bridge to enable energy sharing between chargers. Vasiladiotis et al. [76] focused on a power converter architecture, which includes integrated stationary Battery Energy Storage Systems (BESS) as the power buffers at each converter level for reducing negative influence of the charging station on the distribution grid during AC/DC conversion stage.

For the purpose of surveying the impacts on distribution transformer loading and system bus voltage profiles of the test distribution grid, Yunus et al. [82] provided a stochastic fast charging model in literature. As the necessary measures for handling the charging level problem at the charging station, local energy storage and Static Var Compensator (SVC) are required to be deployed at the fast power charging stations. Considering about the reduction of the EV's power charging time and the stress on the grid for avoiding peak power, Song et al. [73] proposed a power charging station architecture with an energy storage system sustains ultra capacitor as the core strain on the system, because of its durability, high power density, and likely further improvements in energy density.

Renewable energy resources are recognized as a promising resource for power supply. Deploying distributed generation on fast power charging stations will further reduce the stress on the grid, minimize power transmission blocking, and assist demand response resources, which will be realized by supporting the stochastic traffic of demand EV/PHEV in random area and save consumer's ordinary and excess charging cost via dynamic pricing policy [57].

## 1.5 Contribution of this Thesis

- We propose a novel terminal power distribution architecture that is supplied by renewable energy system and managed by a central entity in order to alleviate the problem of energy waste in the distribution part of smart grid system. Our approach is based on the idea that the interactions within a smart grid community can play a key role in the green effort to improve sustainability and effectiveness of the power distribution infrastructure.

- We develop a power-scheduling algorithm based on the proposed smart grid community, in which the un-consumed renewable energy resources stored in the smart batteries of community power consumers can be used to support other power consumers with higher power demand in such smart grid community. Furthermore, we provide profitable business and promotion of smart grid system for utilities and power consumers, thus enabling users to sell power and get profit from it as few taxes for using the power grid network.

- We define a model to focus on the communications performance in data dissemination, focused on the regional power distribution area and the local power distribution area of the smart grid system. Based on the considered scenario, we proposed an improved wireless routing path selection algorithm for more efficient operation of the regional power distribution infrastructure.

- We survey candidate communication technologies and identify the corresponding requirements. According to the available wireless communication technologies, we explore the power saving mechanism based on IEEE 802.11 standards, which can be employed in the data transmission process of advanced metering infrastructure in the smart grid system.

- We introduce a novel power saving mechanism based on two-mode switch scheduling strategy to reduce the power consumption of large-scale smart meters located in high-density residential community includes power and data aggregator and management (PDAM) center and mass of local generated renewable energy-based smart meters.

- We define and available and reasonable mechanism for the public parking campus with candidate fast power charging station, based on ordinary power grid and more effective supplement from renewable energy. By using a quantitative stochastic scheme, we establish a control model for the power charging queueing in proposed parking campus. The economics interests are introduced into the scheme and equally considered between utilities and power consumers.

# Chapter 2

# Architecture modelling in the Distribution Grid

In this chapter, we present a novel architecture for the distribution part of smart grid which will be the base for the next chapters.

## 2.1 Introduction

The development of smart grid has been widely promoted by governments and utilities in recent years, with the purpose to optimise the usage of energy resources [1] [3]. Dynamic smart devices like smart meters are being deployed in many European countries, like Italy, France, Germany and UK, which represent the first step towards the development of innovative smart grid [31] [38].

The modus of flow of electricity in todays power grid follows different dynamics. Smart grid proposes the solution for the critical need of reliable power by utilising two-way flow of electricity and information. The architecture is shown in Figure 1.1. As the technology evolves, the smart grid will allow a two-way flow of electricity and information that is capable of monitoring everything from power plants to consumer preferences and individual appliances. The smart grid will provide real-time information and near-instantaneous balance between supply and demand. At the power supply level, electricity is not just transported from utilities to consumers, but also can be delivered from end users to utilities via distribution feeder lines. The information of consumers is collected and integrated via information and communication technologies to analyze the behavior and preferences of the power consumed by end users in daily life. Depending on the analysis of data, utilities can deploy power distribution schemes to avoid rising the probability of potential power profligacy and upgrade the local power quality [31] [30]

The massive occurred blackout spurred the industry to aggressively pursue a more intelligent power grid. The climate change, burgeoning population and shortage of natural resources, require more efficient power grid systems for the society. Low local power quality, i.e., brownouts, has driven consumers to take higher responsibility for their reliable electricity supply. According to the architecture of power grids and market requirements, the distribution grid represents the closest part to the ordinary consumers in the power network and has direct impact on the power consumption of consumers in smart grid. Therefore, it has been chosen as the innovation target by industry and academia in recent years.

Power management, or power scheduling, is one of the main research topics in smart grid, which is being analysed, from the viewpoints of power measurement, allocation, topology of power network, power storage, etc. The interaction between utilities and consumers is expected to develop in a dynamic and effective way via the introduction of innovative approaches to power management. As wind, solar and other renewable energy sources get introduced into the architecture of the smart grid, power management becomes more complex, since the consumer can also produce and store energy by operating wind, solar or other renewable energy generators in local. As a consequence, the aspect of two-way flow of electricity makes the problem of power scheduling a challenging but rewarding endeavour.

## 2.2 Architecture and Model Based on the Distribution Grid

### 2.2.1 Overview

Controlling power distribution in smart grid is a well-known research topic, which implies different aspects of electrical power management. Utilities aim to improve the efficiency in power consumption among the end consumers or scheduling power demand from the end consumers, in an attempt to avoid peak power loads and excessive power line losses in power network. In this framework, communications represent a central topic both for enabling the deployment of the next generation power distribution systems and for providing suitable models to analyze such systems.

In this section, we introduce and model a new architecture for a smart grid community, where an information center is established as the core controller of the community power grid. Based on this novel approach, the potential impact of smart battery, smart metering and renewable energy sources have been studied. Then, we provid an optimal algorithm for power allocation in the new architecture, which can minimize the possibility of peak power loads even in situations of overloading, and reduce the line loss of power scheduling. Finally, we proposed a methodology to analyze the pricing scheme of the system.

### 2.2.2 Smart Home and Smart Community

In order to avoid peak power loads, reduce additional line loss and strengthen the utilities micro-operation in the terminal area of power grid network, a new local power distribution architecture of smart grid with renewable energy and power storage is needed, based on the existing local distribution area shown in Figure 1.1. The renewable energy stored/ generated in the ordinary consumers residence will be considered as an additional source to satisfy the consumers demand. Depending on the renewable energy, power re-distribution, and micro-operation of the new architecture, the power demand could be promptly and safely satisfied without additional power supply from utilities or at least significant reduced.

This new mechanism is located in the local distribution area shown in Figure 1.1. The architecture of the mechanism is displayed in Figure 2.1. The new architecture is characterized by a local power distribution controller, short named as I.T. center that includes the power distribution equipment (distribution secondary substation) and the sub data management center with a wireless communication transmission gateway, and many terminal power consumers, short named as T($n$) where $n$ is the index associated to each terminal users. As the I.T. center and power users have been combined as a community, this new mechanism will be named as a community smart grid. The power substation includes transformers to change voltage levels between high transmission voltages and lower distribution voltages. The local I. T. center is connected with the terminal user T($n$) by wired power lines. The information communication layer of the I. T. center is allocated for control of all the smart meters located in the residential environment of terminal power consumers. The wireless channels are used for communications between I.T. center and end users. In the initial analysis, we assume that wireless and wired communications are ideal (i.e. no loss of wireless signals and no other relevant effect of information dissemination). Therefore, the I.T. center becomes the central element of the power distribution management in the community smart grid architecture.

In the consumers home area, local power generations (such as wind and solar generators), smart meters, smart batteries and other basic devices are also deployed by utilities. The value of energy consumption measured by

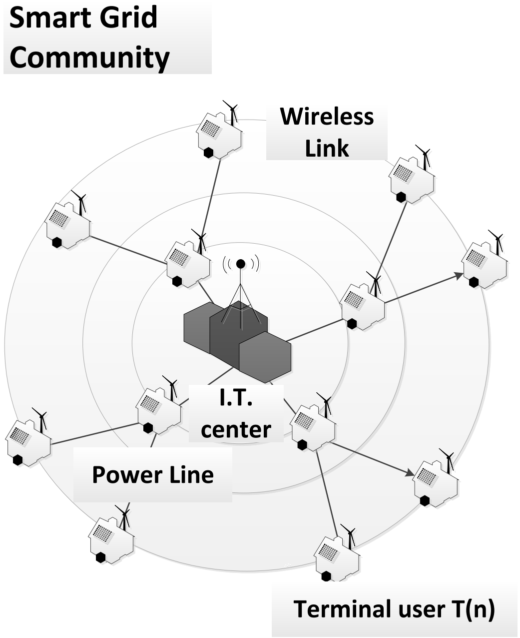

Figure 2.1: The architecture diagram of the community smart grid

the smart meter can be then conveyed to the I.T. center in real-time. We assumed that the capacity of smart batteries is large enough to store the electrical energy that is generated by solar or wind sources in each terminal consumer's house, including excessive energy (if needed and available by the power lines). Hence, the smart battery can store excessive power when the demand is lower than usual. At the same time, the terminal consumers can make profit by selling the unused power to neighbors or utilities via the management of I.T. center. The value of sold electrical energy can be measured by the smart meters in two sides and recorded by the I.T. center. Thus, the power demand of users can be supplied by using the excessive power from other consumers in the same community. As a result, the utilities and the end users could both make profitable business from selling or buying the electrical energy through the efficient power demand management scheme. The home architecture of the terminal consumer is shown in Figure 2.2

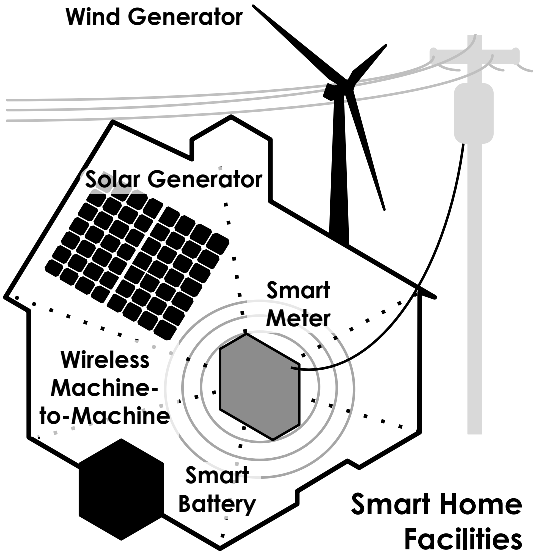

Figure 2.2: The home architecture in community smart grid

### 2.2.3 Local Power Scheduling Algorithm

The theoretical analysis of the scenario proposed above is then carried out, by defining the simple mathematical framework as shown in Table 2.2.

We utilized matrix theory to express the relationships between any T($n$) and I. T. center when the power feeder line has to be established between any T($n$) and the I. T. center.

$$R = \begin{bmatrix} 0 & \dots & x \\ \vdots & \ddots & \vdots \\ x & \dots & 0 \end{bmatrix}$$

$[R]$=$[R_{i,j}]$, $i, j$ = the code of each T($n$), $x = 0$, or 1.

The relationship of each end user and the I.T. center can be represented by $x$. The link between any terminal consumer and the I.T. center cannot

Table 2.1: Simple mathematical framework with needed elements

| *Element* | *Explanation* |
|---|---|
| $P_C(n)$ | the reference value of consumed power, or required value in normal operating conditions |
| $P_D(n)$ | required amount of extra power requested by user T($n$) to the I.T. center |
| $P_B(n)$ | the value of stored power in T($n$)'s battery |
| $C$ | the total amount of the battery's storage |
| $P_G(n)$ | the amount of produced power by the wind or solar generator located in user T($n$)s home area. |
| $P_{PL}(n)$ | Customer, distribution, transmission, bulk generation, operations, service providers |
| $P_{PL}(n_S;\, n_D)$ | the line loss during power transformation from the power supply user (T($n_S$)) to the demand user (T($n_D$)) |
| $T_D(n)$ | power demand consumer |
| $T_S(n)$ | power supply consumer |

be established when $x=0$, while the link can be established when $x=1$. Obviously, all the values located in the principle diagonal are 0.

In this community smart grid, the value of excessive power consumption of $T_D$(n) should be the margin between the required power ($P_D(n)$) and the usual consumed power ($P_C(n)$). In order to meet the required value from demand side, the $T_S(n)$ should consider the margin value, the value of stored energy $P_B(n_S)$ and line loss ($P_{PL}(n_S;\, n_D)$). Then the formula about point to point transformation from $T_S(n)$ to $T_D(n)$ can be formulated as

$$P_D(n_D) - P_C(n_D) = P_B(n_S) - P_{PL}(n_S; n_D) \tag{2.1}$$

When $T_D(n)$ and $T_S(n)$ are dynamic, the I.T. center registers the identification codes of $T_S(n)$ and $T_D(n)$ in two queues, namely, the queue of demand and the queue of supply. The order in the queue of demand ($L_D$) is determined by the amount of stored energy in $T_D(n)$ batteries whereas the order in the queue of supply ($L_S$) is given by the amount of excess energy in $T_S(n)$ batteries. Let $k$ denote the chosen code in both $L_D$ and $L_S$. Hence, $L_D$ and $L_S$ should fulfill

$$L_D(k) = \min_{[R]}\{\sum_{i=1}^{N} P_B(n)\} \tag{2.2}$$

$$L_S(k) = \max_{[R]}\{\sum_{i=1}^{N}(P_B(n) - P_{PL}(n_S; n_D))\} \tag{2.3}$$

While (2.2) provides the $T_D(n)$ with the lowest amount of stored energy in its battery, (2.2) determines the $T_S(n)$ with the highest amount of stored energy in its battery when path losses are subtracted. Notice that the line loss ($P_{PL}(n_S, n_D)$) might vary with the distance, since the signal is degraded by a loss of phase and amplitude. We assumed there are enough amplifiers through the electric network to reconstruct the signal. Besides, the distance from all to all end users is generally quite short, as the architecture is deployed within a local area. Hence, the power line losses can be assumed as constant. With the purpose to distribute the unused power resources of the system to those end users with higher power priorities, determining the terminal users with sufficient energy in their smart batteries ($P_B(n)$) to cover such power demand is an essential stage. In a given battery, ($P_B(n)$) depends on the power produced by wind or solar sources ($P_G(n)$), the usual power consumed by the end user ($P_C(n)$) and the power requested by a terminal user with insufficient power resources to satisfy its own power demand ($P_D(n)$). Therefore, we can express ($P_B(n)$) as

$$P_B(n) = \max_{[R]}\{P_G(n) + P_C(n) - P_D(n)\} \leqslant C \tag{2.4}$$

When the community smart grid contains several $T_D(n)$, the algorithm shown in Figure 2.3 runs according to the following steps:

1. All demanding users ($T_D(n)$) send power demand messages to the I. T. center via smart meter;
2. The I. T. center broadcasts message with the priority list within the

set of $T_D(n)$ from Equation (2.2);

3. The smart meters measure the available energy in the smart batteries with Equation (2.4) and response the I.T. center with the value of energy storage, the location in community, and the serving period;
4. The I. T. center establishes the demand-supply list of $T_S(n)$ with Equation (2.3). If any single $T_S(n)$ can not support the required power, more $T_S(n)$ will be scheduled for supporting the demand side;
5. The I. T. center chooses the optimal $T_S(n)$ for $T_D(n)$ via point to point or point to multi-points communication, depending on the queues of demand and support sides;
6. The I. T. center adjusts the links of power transformation line for $T_S(n)$ and $T_D(n)$;
7. The target $T_S(n)$ then routes the power to the $T_D(n)$ via the I. T. center. During this procedure, the I. T. center, the smart meters of $T_D(n)$ and the target $T_S(n)$ record the value of transmitted power;
8. Step 5-7 have to be repeated until all $T_D(n)$ are served;
9. The utilities issues the bill message to $T_D(n)$ and $T_S(n)$ via I. T. center at the end of this process.

### 2.2.4 Investment and Benefit Analysis Model

In this section, starting from the proposed model, analyses the ecosystem from the point view of pricing and utilities, both from the consumers and the providers perspectives. Indeed, for effective marketing of smart grid, utilities should persuade the terminal consumers that they could benefit form such a novel paradigm, and at the same time, they should explicitly provide effective gains on power selling by exploiting the smart

Table 2.2: Investment and benefit analysis parameters

| *Terms/Description* | *Value* |
|---|---|
| $N$: number of terminal users | 20 |
| $M_{SM}$: investment per smart meter | 600* |
| $M_S$: investment per solar generator | 2840* |
| $M_{SB}$: investment per smart battery | [420, 2100]* |
| $P_C^{max}(n)$: max. average power consumption. | 10 |
| $P_B(n)$: energy stored in smart battery | [0, 5] |
| $p_B$: probability of point to point power supply-demand | $1/N$ |
| $P_D(n)$: extra power demand after subtracting available energy stored in battery | [1, 10] |
| $p_d$: probability of the utility supplying the demand because of consumers with insufficient energy storage | $1/5$ |
| $P$: unit of power price | 0.2164 [23] |
| $e$: unit of power price over limitation | 0.2722 [23] |
| $w$: transaction fee rate of the utility | 10, 20, 30% |

*** Value was collected from related online market, and unit is €**.

facilities located in the users premises. So a suitable return on investment needs to be established as a core component of the considered architecture. In order to define such mechanism, the following terms are introduced in Table 2.2.

The return on investment mechanism was designed by considering the financial balance for utilities and consumers. The utilities will design the mechanism in such a way to recover the investment on smart meters and solar generators by the power consumers' electricity bills and percentage on the consumers' gain for selling excess power within the community, as shown in Equation (2.5). On the other hand, the consumers can get benefits from selling excess energy in order to compensate the investment on smart batteries, as shown in Equation(2.6). During this power selling excess between consumers, the utilities will gain benefits from local power scheduling cost, which has flexible rate from 10% to 30% that will be decided by utilities.

The equation of calculations of the return on investment for utilities and consumers should fulfil

$$\begin{aligned} H_{Utility}(n) = min\{M_{SM} + M_S - \sum_{i=0}^{N} p_B P_B(n) pw \\ - ep_d(P_D(n) - P_B(n) - P_C^{max}(n) - \sum_{i=0}^{N} p_B P_B(N))\} \end{aligned} \quad (2.5)$$

$$\begin{aligned} H_{User}(n) = \min\{M_{SB} - \sum_{i=0}^{N} p_B P_B(n) p(1-w) \\ + ep_d(P_D(n) - P_B(n) - P_C^{max}(n) - \sum_{i=0}^{N} p_B P_B(n))\} \end{aligned} \quad (2.6)$$

In Figure 2.4 the consumer's amortization is shown for different values of the percentage of the sold excess energy provided to the utility. For the same values, the utility's amortization is proposed in Figure 2.5. It should be noted that, in this model, we consider a fixed price for selling of excess power of consumers. However, since both the availability of excess power and the demand can fluctuate in a more realistic scenario, the price for selling of excess power should vary dynamically, too. This aspect will be studied in the future work on this topic.

### 2.2.5 Performance Evaluation

This section analyses the performance of the new algorithm for power scheduling in the novel mechanism when compared with the existing power grid. To this goal, we collected the power consumption data from dynamic target families located in the city of Trento. We randomly selected the target families as the members of this community smart grid. Then we employ a simulation environment with the simulation parameters shown

Table 2.3: Simulation parameters

| *Element* | *Value* |
|---|---|
| I.T. center | 1 |
| Consumers | 20 |
| Power consumption per family per day (kWh) | [2.5, 10] |
| Battery storage (kWh) | [0, 5] |

in Table 2.3.

Based on the statistical data of power consumption per consumer in the community smart grid, Figure 2.6 shows the effective result of the new mechanism on supporting the power demand in this community. We assumed that each consumer has its own local renewable energy generator and battery in residence. Then the new scheme provides a highest gain of nearby 45% of saving power supporting and an average saving of 40%, when compared to the legacy scheme.

Once we explore the relationship of the deployment rate of renewable energy generator and battery, and the power scheduling result, we got Figure 2.7. Obviously, only after the deployment rate of these smart devices beyond 50%, the power schedulings effect by our new mechanism could be manifest in the global level of this community smart grid.

## 2.3 Conclusion

A novel smart grid architecture is presented and modeled in this paper, where a community smart grid is supplied by renewable energy sources and managed by a central entity in order to alleviate the problem of energy waste in smart grid. Our approach is based on the idea that the interactions within a community smart grid can play a key role in the green effort to improve sustainability and effectiveness of the power distribution infrastructure. A power-scheduling algorithm is then proposed, in which the unused renewable energy resources stored in the smart batteries of community users can be used to supply other users with higher power demand in such community smart grid. Our simulation results prove the potential advantages of the new scheme to reduce power consumption, with a highest gain of up to 45% of saved power in comparison with the reference scheme. Furthermore, we provide profitable business and promotion of smart grid systems for utilities and electricity consumers, thus enabling users to sell power and get profit from it at few taxes for using the utilitys power network.

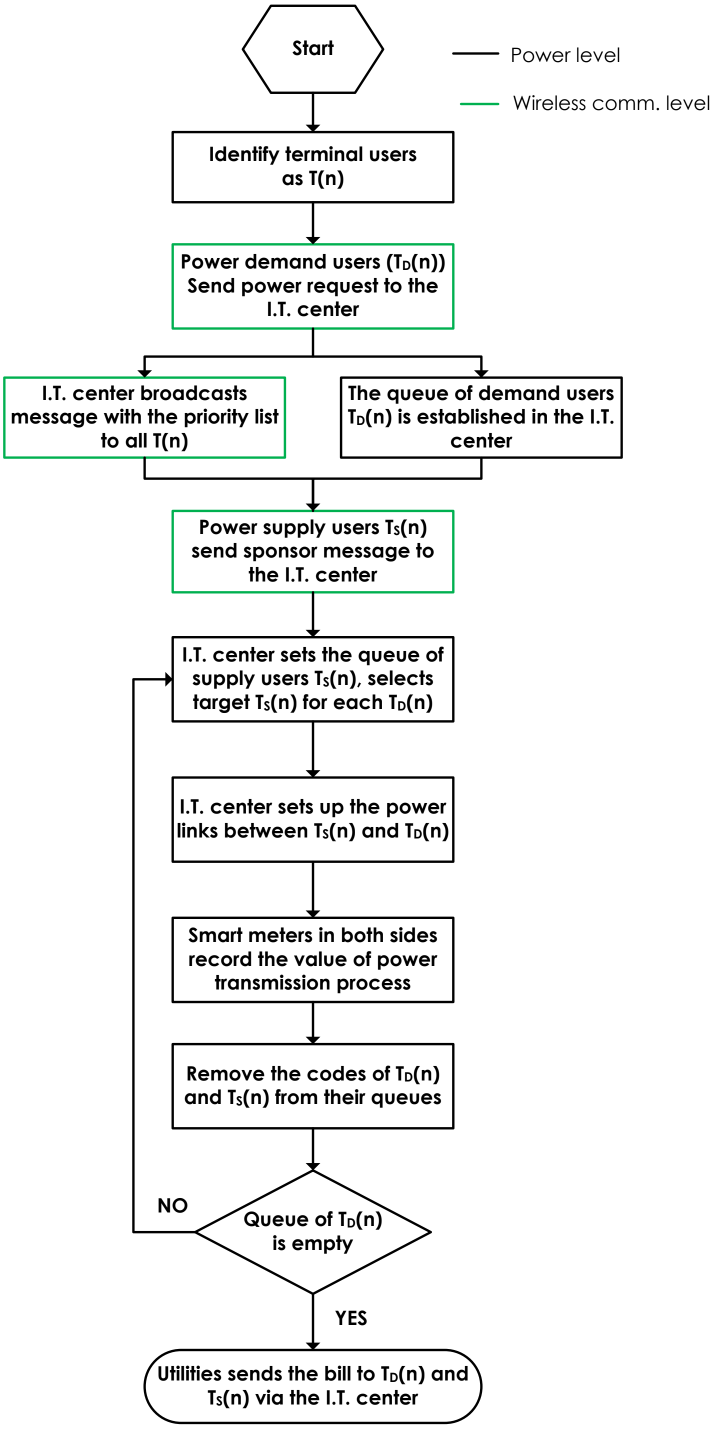

Figure 2.3: The flowchart of local power scheduling algorithm

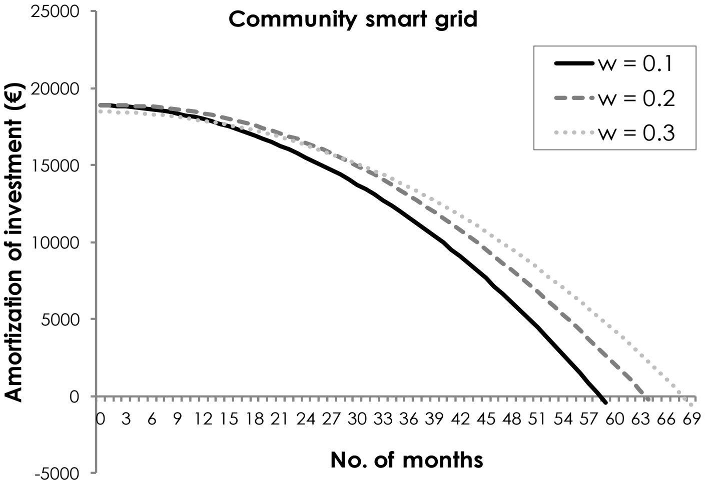

Figure 2.4: Amortization of deployment costs of smart batteries by selling power in the community smart grid

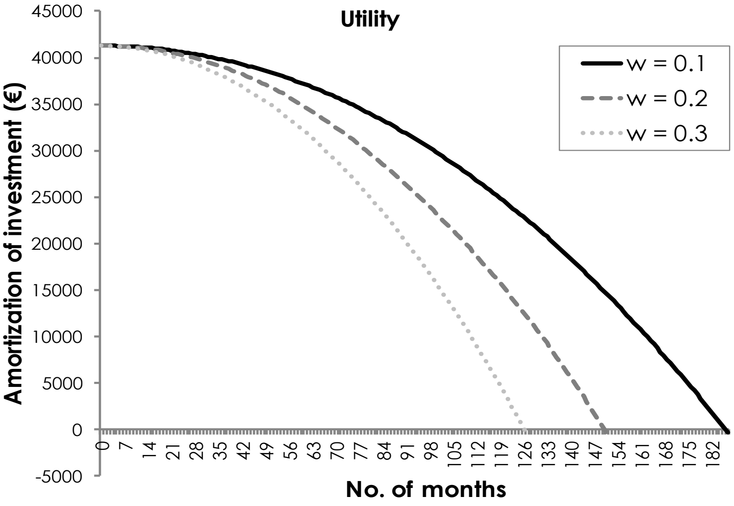

Figure 2.5: Amortisation of deployment costs of smart meters and solar generators by selling power in the community smart grid

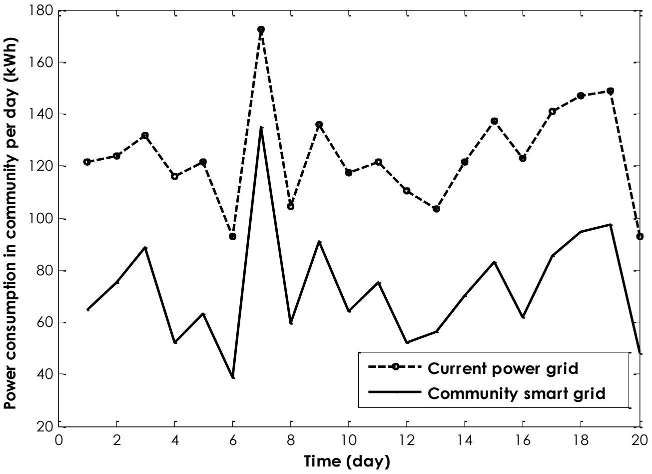

Figure 2.6: Power scheduling via the community smart grid

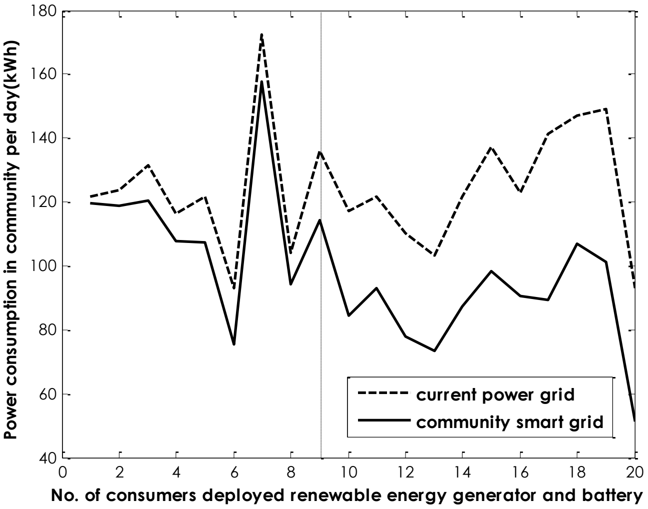

Figure 2.7: Power scheduling with the increase of deployment of renewable energy generator and battery in community smart grid

# Chapter 3

# Self-Organisation Issues of the Updated Distribution Grid

In this chapter, we present an improved routing algorithm for wireless path selection for the smart grid distribution network.

## 3.1 Introduction

Smart grid is referred to the next generation power grid, with advanced features and two-way flow of electricity and communication. Those features include demand side management, fault alarm, advanced metering. The smart grid is expected to provide real-time information and near instantaneous balance between supply side and demand side [1] [3]. Consumers' power consumption data is collected and integrated through advanced communication technologies for analyzing the power consumption behaviors and preferences by utilities. The key point for deploying these features is to develop a reliable and efficient communication infrastructure [1] [3].

From Figure 3.1 we can identify primary substations, working between 110 kV and 20/10 kV in the medium voltage level in power distribution

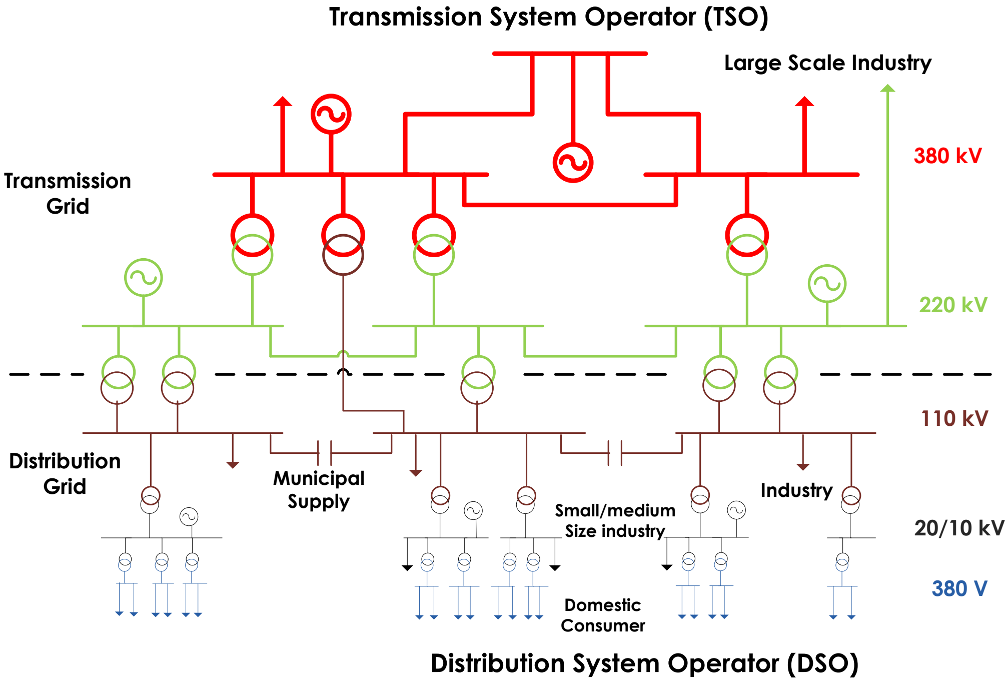

Figure 3.1: A typical power transmission and distribution grid networks with transform devices

grid. Normally, the primary substation is recognized as an important component of the distribution infrastructure, which can transform the medium voltage electrical power to the low voltage electrical power. The main goal of the secondary substation is to transform the low voltage power to domestic consumption standard power that can be transmitted in local feed lines to terminal power consumers.

As shown in Figure 3.1, the architecture of the power distribution grid is supported by a communications networks, that provides the interaction, information dissemination and interaction among the connected devices.

Indeed, the smart grid represents the combination of two infrastructures: (i) the power distribution infrastructure, and (ii) the communications infrastructure. The characteristics of reliability, security, interoperability and efficiency of the electrical grid are clearly defined by the employed techniques at the communication level, and constrained by reducing environmental impacts and promoting investment growth [45]. Besides the power consumption data transmission, communication techniques also can play core role on power scheduling, real-time interaction between utility and consumer, and other interaction scenarios [1] [45].

In the traditional smart grid scenario, the grid is expected to estimate the local power grid capacity and other relevant factors in order to optimize the energy usage across the network, making use of existing power plants and micro generation facilities (e.g. renewable sources at users' premises). For this task, it is possible to envisage the usage of wireless communication technologies in the local power distribution domain [45] [43].

The status of power consumption/ generation pattern for each user is transmitted via the local power distribution control device [45]. Depending on the operating environment, the data could be delivered through routing on multiple wireless access links. Hence, wireless routing path selection represents a relevant challenge in the power distribution scenario, and is discussed in some existing research works.

## 3.2 Proposed Framework Based on the Distribution Grid Networks

This section provides a definition of the considered scenario and a statement of the problem addressed in the paper.

As shown in Figure 3.1, we propose to define the power grid network under 110 kV as the regional power distribution area (RPDA), where the primary substation (including base station and primary data management center) plays the core role of local power management and controls many secondary substations. The power distribution network under 20/10 kV is defined as the local power distribution area (LPDA), where the secondary substation is set as the main controller (including relay station

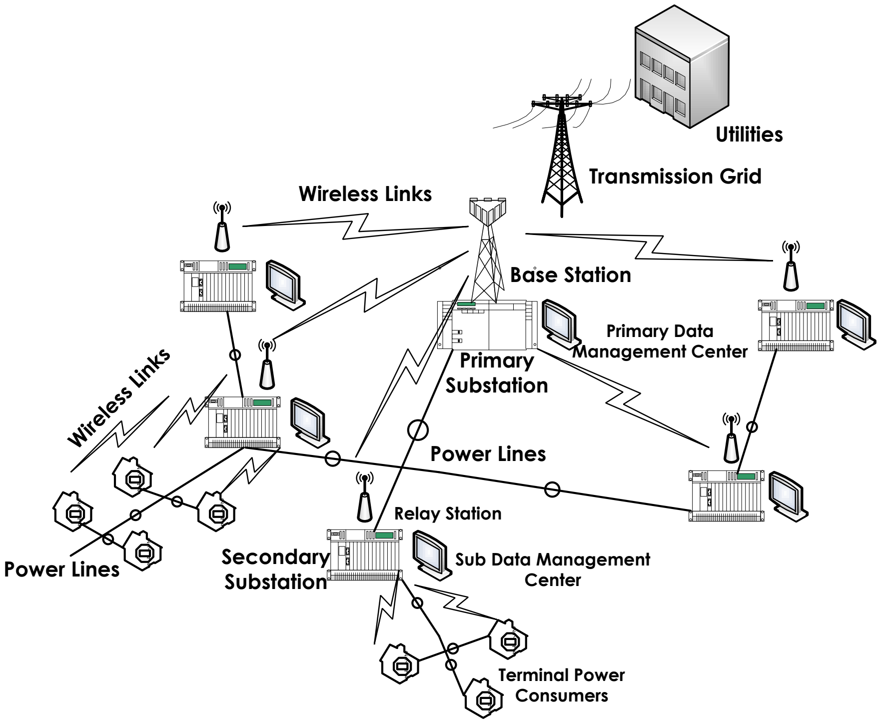

Figure 3.2: Two-way flow power distribution network

and sub-data management center), and schedules multiple terminal power consumers.

In this scenario, the performance of the wireless communication path between the secondary substation located in the new additional LPDA and the primary substation represents a challenge, influencing the possibility of achieve optimal power allocation setups or supporting timely fault detection. From Figure 3.1, the primary substation schedules power distribution in RPDA, while the secondary substations can be recognized as the terminal nodes. Based on this architecture, we propose to use the following communication system.

The approach is built up based on the RPDA shown in Figure 3.2. The primary substation, indicated as PS, is set to be the main controller of in the RPDA, collecting and transmitting the power consumption and other data between utility and the secondary substations. Meanwhile, the secondary substation can be deployed as smart terminal nodes of PS.

In the secondary substation, we deploy one relay station as the wireless communication gate and sub-data management center that can collect and transmit the related data between primary substation and terminal power consumers. The secondary substation is indicated as R($n$), where n is the index associated to each secondary substation. The RPDA's main controller PS is connected with R($n$) by wired power distribution lines. The communication interface is the IEEE 802.22 wireless standards. In our proposed R($n$)'s local architecture shown in Figure 3.3, we enhanced and expanded the existing secondary substation, which R($n$) can re-schedule the power distribution to keep the local power demand-supply balance via sub-data management center - that is connected with some smart devices located in consumer's residential environment, like smart meter and other facilities. Renewable energy is introduced into the local architecture to assistent local power re-schedule via R($n$) and sub-data management center's manipulation, which is prodcued by household wind turbines and solar generators in this scenario. With the contribution of distributed sub-data management centers, the PS can schedule and scan the global power consumption status within the RPDA and power consumption details from the terminal power consumers through R($n$).

In case a new local power distribution area (LPDA) is added into regional power distribution network, the new added secondary substation is deployed to be sub-controller of this local area. The location information and terminal consumer's initial power consumption data will be conveyed via the sub-controller to the primary data management center located in the primary substation. If the information transmission can not be achieved via one single hop, then the multi-hop wireless links between the target area and the primary substation should be timely and reliably

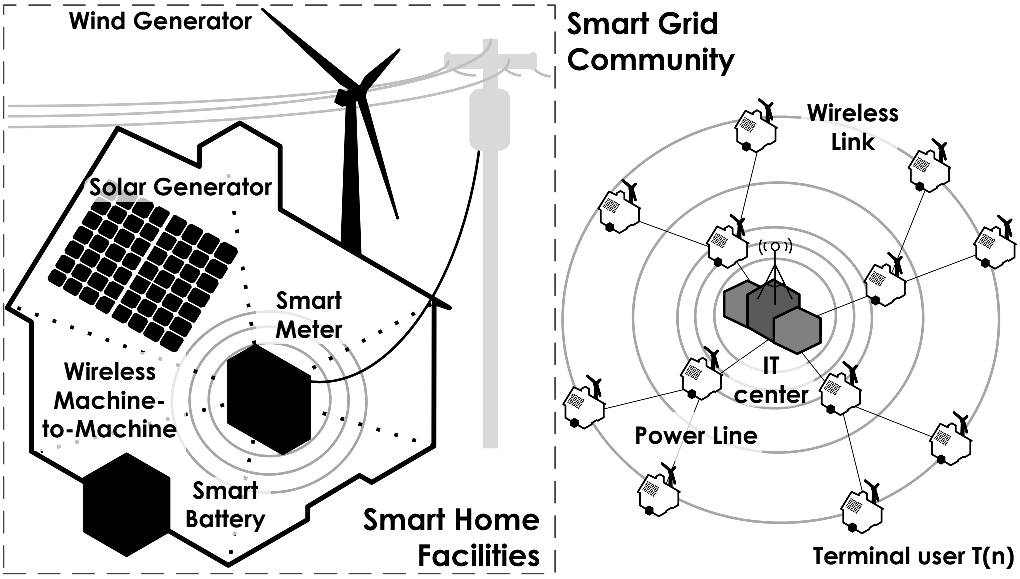

Figure 3.3: The architecture of local power distribution network controlled by secondary substation and terminal consumer's residence network

deployed. For instance, we assume when any power fault happened in the terminal consumer's residential, LPDA, or the power lines between primary and secondary substations, the alarm data packages that include accurate fault location and other required information should be reported to the primary substation and delivered to utility as well.

## 3.3 Improved Path Selection Algorithm in the Distribution Grid Network

The problem of establishing the multi-hop wireless links between the target relay station (RS) and the base station (BS) located in primary substation (PS) can be formulated as a shortest path routing problem. In the case proposed in the paper, we propose to formulate the problem as a weighted shortest path routing problem.

*Weighted Shortest Path Routing Problem*: For a given source vertex (node) in graph, algorithm finds the path with lowest cost (i.e. the shortest path) between that vertex and any other vertex. It can also be used for

Table 3.1: Correspondence of path selection and weighted shortest path routing

| Multi-hop Path Selection | Weighted Shortest Path Routing |
|---|---|
| AMDP | Weight |
| Number of RSs and BS | Vertices $V$ |
| Wireless access link ($L$) | $E$ edges |
| IEEE 802.22 network | Graph $G$ |

finding costs of shortest paths from a single vertex to a single destination vertex [24].

Based on the characteristics of the IEEE 802.22 standard (focused on dynamic spectrum allocation and cognitive radio access principles), we decided to use the average missed detection probability (AMDP) of spectrum occupancy on the link between any two RSs or BS as the most relevant parameter for the description of the wireless access link $L$ in this algorithm.

$$M_{n+1,n+1} = \begin{bmatrix} 0 & \dots & x \\ \vdots & \ddots & \vdots \\ x & \dots & 0 \end{bmatrix}$$

$[M]$=$[M_{i,j}]$, $i, j$ = the code of each R($n$) and PS, $x$ = 0, or 1.

We utilize the matrix theory to express the neighborhood relationships between any R($n$) and PS when the wireless link has to be established. The relationship of each R($n$) and PS can be represented by $x$. If any two R($n$)s, or R($n$) and PS are not neighbors, then the wireless link can not be established between them. Hence, we use $x$ to express the neighborhood relationship between that two R($n$)s, or R($n$) and PS. Once $x$=1, the wireless access link is available between that two R($n$)s, or R($n$) and PS, which means the neighborhood relationship is existing between them.

For the purpose of getting the lowest AMDP on the R($n$)'s neighborhood wireless access link $L$, we built another matrix for describing the performance of the link between the RS, which has dynamic value based on the spectrum sensing result on each routing step.

$$N_{n,k} = \begin{bmatrix} \mathrm{C}_{1,1} & \dots & \mathrm{C}_{1,k} \\ \vdots & \ddots & \vdots \\ \mathrm{C}_{n,1} & \dots & \mathrm{C}_{n,k} \end{bmatrix}$$

$$N{=}[N_{n,k}]$$

where $C$ is the missed detection probability of available spectrum located on any RS and BS [55] [53]; $n$ is the number of RSs and BS in the wireless network; $k$ is the number of the available spectrum on each RS or BS.

The missed detection probability $C_n^k$ is decided by the status of the $k$ available spectrums located on RS. Based on the analysis of whether the primary user of spectrum is in operation or not, we can get the detection probability. Then the missed detection probability can be calculated by spectrum sensing based on the detection probability [53].

Now, we can get the equation of AMDP of each available spectrum $k^{th}$ located on RS $i$ and its neighbor RS $j$ as follow,

$$arg\ C_{i,j}^k{=}(C_i^k{+}C_j^k)/2 \text{ (1)}$$

where $i, j{=}$ the code of RSs and BS.

Hence, the target wireless access link between RS $i$ and RS $j$ will be decided via the equation as follow,

$$C_{i,j}^{target}{=} \min \{argC_{i,j}^k\} \text{ (2)}$$

It means that subsequent target RS $j$ can serve a novel available spectrum with lowest AMDP, located on the wireless link between RS $i$ and RS $j$ for the current path selection step among RS $i$'s neighbors.

Dijkstra's algorithm provides the optimal solution for the single-source shortest-paths problem on a weighted, directed graph $G$=($V$, $E$) for the case in which all edge weights are nonnegative. Dijkstra's algorithm preserves a set S of vertices whose final shorts-path weights from the source s have already been determined [24].

As we have previously discussed, the AMDP of available spectrum on the wireless links between any RS and BS is a dynamic metric that could be diversification based on the real-time respective status of the spectrum located on each RS or BS in each routing step. So we define an improved Dijkstra's algorithm–dynamic neighborhood routing path selection (DNRPS) algorithm as follows.

The proposed algorithm shown in Figure 3.4 runs according to the following steps:

1. The neighborhood relationship matrix M is established in primary data management center and sent to each existing sub data management center located in the secondary substations.
2. Make all RSs and BS located in the IEEE 802.22 network as unselected and set the new RS located in the new local power distribution area as current RS.
3. For the current RS, consider its entire unselected neighboring RSs, and calculate the AMDP of available spectrums located on each existing wireless link.
4. Select the target RS from the current regional power distribution network neighborhood matrix M, which can serve the most available spectrum with the lowest AMDP to the current RS.

5. Set the target RS as current RS, then check its neighborhood matrix, get the neighbor list.

6. Calculate the AMDP of available spectrums located on the wireless links among the target RS and its neighbor RSs.

7. Record and store the id of the target RS in each step into an adjacency list structure, required to form the route.

8. If the target RS is the BS located in the primary substation, then breaks and ends the algorithm. Otherwise, set the target RS as the current RS in next step and continue from step 3.

For spare graphs, that is, graphs with far fewer than O($|N+1|N$) edges, the improved Dijkstra's algorithm can be implemented very efficiently by modeling wireless network in the form of adjacency lists and using a binary heap, or Fibonacci heap as a priority queue to implement extracting minimum efficiently. Thus, with a binary heap, the improved algorithm requires O($(|L|+|N+1|)\log|N+1|$) time, which is dominated by O($|L|\log|N+1|$), assuming the graph is connected. The Fibonacci heap further improves this to O($|L|+|N+1|\log|N+1|$).

## 3.4 Performance Evaluation

This section analyses the performance of our proposed DNRPS algorithm for the wireless routing path selection between new addition local power distribution area and the primary substation in the novel mechanism when compared with the existing schemes [52] [35] [49]. The major difference among the other methods is the employment of dynamic spectrum access on each wireless link. We considered the existing power distribution situation and local natural environment, and also explored the open resources about the capacity of primary substation and secondary substations from industry. Then we employed the simulation environment with the parameters shown in Table 3.2.

Table 3.2: Simulation Parameters

| Element | Value |
|---|---|
| Number of primary substation | 1 |
| Number of secondary substation | 39 |
| Number of new addition LPDA | [1,5] |
| Time for spectrum sensing | 1ms/station |
| Delay requirement of immediate message | 3 ms, 10 ms, 20 ms |

Based on HWMP method and the working principle of 802.11s wireless mesh networks, schemes [52] [35] were proposed by those authors. As we quoted and listed in the introduction part, those schemes can be considered as improved wireless routing path selection mechanism for the local power distribution area, where the main wireless communication links are located between the secondary substation and the smart meters deployed in power consumer's residences. In other words, these two schemes can be considered as good choices for the wireless communication in local power distribution area (LPDA). But in the advanced communication level in neighbourhood area network where the wireless communication demanded by primary substation and secondary substations that we defined as regional power distribution area (RPDA) in our considered scenario, these schemes didn't present more effective and expected activation.

Figure 3.5 shows the effective result of our mechanism by employing the novel wireless routing path selection algorithm for each wireless access session. Analyzing the cumulative delay, the result show that the proposed scheme provides a highest gain of near 19% of reduction in the wireless communication delay, when compared to the schemes in the literature ( Figure 3.6).

## 3.5 Conclusion

Communications represents a relevant component in the architecture of the future smart grid. In this chapter, we analyzed the distribution section of the power grid, and defined a model to focus on the communications performance in data dissemination. We didn't reconstruct the distribution networks, but established efficient wireless links based on the existing power infrastructures to let the real-time wireless communication get indemnification. Then, we introduced an improved path selection algorithm to enable reduction of the delay and support a scale-up of the system. Simulation results demonstrate a relevant improvement in the performance of the system.

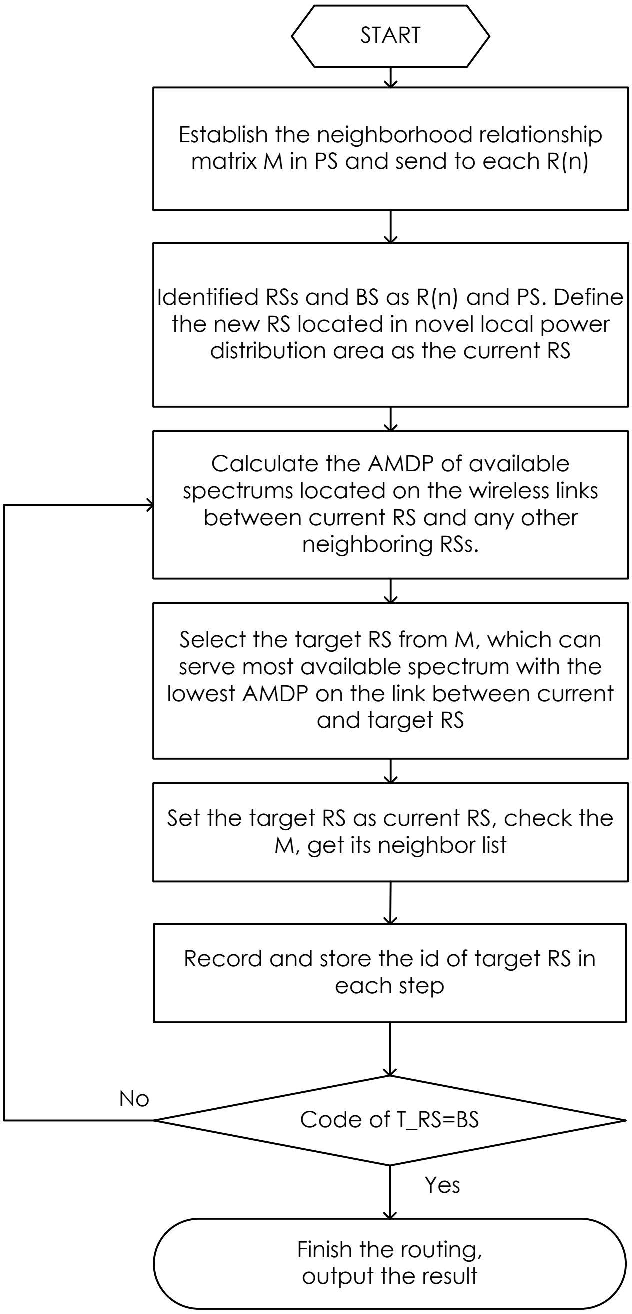

Figure 3.4: The flowchart of improved wireless routing path selection algorithm

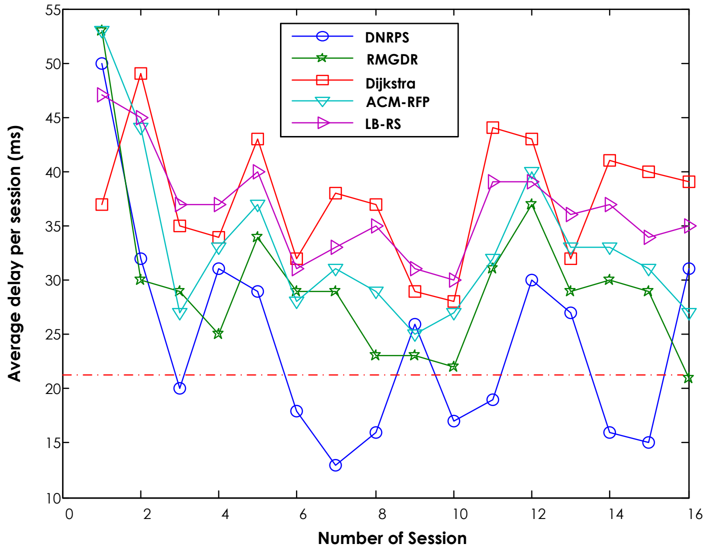

Figure 3.5: Compare the average delay on each session

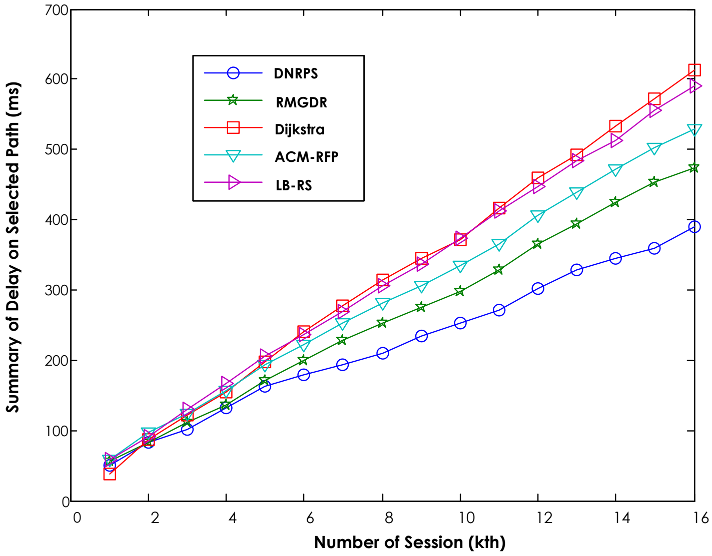

Figure 3.6: The summary of delay on selected path after $k^{th}$ session

# Chapter 4

# Enabling Communication Technologies

Enabling communication technologies can active the communication links connects different part of the smart grid networks and make the information flow smooth and effective.

## 4.1 Introduction

The existing electric power grid is required to be more intelligent for the purpose of providing reliable, sustainable and economical supply of electricity. In order to provide these aims, the current power grid is being upgraded to the next-generation power grid system, call smart grid, via the research and experiences being carried in academia and industry in recent years. One of the most important features of smart grid is the integration of two-way flows that include power flow and information flow. The information flow can be employed to provide effective and controlled power generation and consumption [43] [45]. This new feature of smart grid also can stimulate power consumers participation to control and manage their own electricity consumption by providing near real-time information on their electric usage and associated payment. Indeed, latest communication and information technology can play a very important role for controlling, manage, and optimising different infrastructure and smart devices and systems in smart grid [29]. The communication interfaces and electrical interfaces corresponding to different smart grid domains have been stated in Table 4.1 [45].

The distribution grid is the nearest part to the ordinary power consumers in the smart grid system. More flexibility, higher uncertainty, and more possibility of risk are highlighted as the unignored characteristics in the distribution grid. Advanced communication and information technology serve the opportunities to let utilities deploy remote operation in terminal power supply area. On the other hand, terminal power consumers can deliver power demand information, gain their own residential power consumption, and even more residential power system scheduling via employing those latest communication and information technology.

Table 4.1: Smart grid domains and the associated communication and electrical interfaces with typical applications [45]

| Domain | Communication interface | Electrical interface |
|---|---|---|
| Customer | Distribution, markets, operation, service provider | Distribution |
| Distribution | Customer, transmission, market, operations | Customer and transmission |
| Transmission | Distribution, bulk generation, markets, operators | Bulk generation and distribution |
| Bulk generation | Transmission, markets, operations | Transmission |
| Markets | Customer, distribution, transmission, bulk generation, operations, service providers | None |
| Operations | Customer, distribution, transmission, markets, service providers | None |
| Service providers | Customer markets, operations | None |

In this chapter, we furnish a overall study on the importance of communication infrastructure and networking in the smart grid. Section 4.2 reviews the available communication standards and technologies. The power line communication (PLC) is presented in the first part, which is recognised as wired communication model for the "last mile" communication in distribution grid. Several kinds of wireless communication protocols are introduced in the second part of Section 4.2. Section 4.3 describes the communication requirements and performance metrics in different level of networks, which include home area networks (HANs), neighbourhood area networks (NANs) and wide area networks (WANs). These three networks are organised as the distribution communication networks. Section 4.4 outlines the concludes this whole chapter.

## 4.2 Available Communication Standards and Technologies

### 4.2.1 Power Line Communication

The "last mile" is a phrase that is always be used by telecommunications and internet business to refer to the final part of the telecommunications networks transmitting communications connectivity to terminal consumers, which actually reaches the customer [32]. In case of smart grid, it typically means connecting the substation and power consumers to the high-speed communication backbone network. Many communication technologies, like power line communication (PLC) can be used to provide this last-mile connection [45] [34].

Based on the omnipresent power distribution lines, especially the feed lines from the substation to the terminal power consumers, and associated advantage of low installation expense, power line communication can be widely employed in smart grid [20]. PLC refers to deliver data by modulating the standard 50 or 60 Hz alternating current on the existing power lines [32]. The highlight advantages of PLC, like extensive coverage and low cost, would eliminate the extra requirement of communication infrastructure for the last-mile connection in distribution grid. PLC can also be used for short-haul communications of power network management in terminal power supply area in the smart grid [15].

PLC is becoming quite popular technology in home area networks for home energy management system (HEMS) [34]. There are intriguing possibilities of tying smart grid applications with HEMS in home environment. There is also a strong confidence that these applications will cause to a change in how the terminal power consumers distribute energy consumption. There are two types of PLC technologies, broadband PLC (BB-PLCs) and narrowband PLC (NB-PLCs) stated in [34] by Galli, et al. BB-PLCs technologies operating in the high frequency bands (1.8-250 MHz) and also having a physical layer rate ranging from several Mbps to hundred Mbps. Meanwhile, LB-PLCs technologies operating in the any of the low frequency bands (3kHz-500kHz). Galli, et al. also presented that NB-PLCs have several advantages when compare to BB-PLCs, especially the highlighted ”easy of upgrade to future version”. NB-PLCs solutions can be easily implemented as ”soft” modems using a digital signal processing (DSP) whereas this is not possible with scaled down version of BB-PLCs devices.

There have been several works in the literature targeting power line communications in smart grid based on related communication mode. Son, et al. [72] proposed a home energy management system (HEMS) based on power line communication. This HEMS can serve called ”easy-to-access” interactive interface between HEMS and consumer in real time. The information of energy consumption and controlling of intelligent devices in residential environment can be provided by residential deployed smart metering and power line communication. The residential intelligent devices are connected with other parts of the system via employing power line communication technology in HEMS. Auto-configuration is highlighted as the most important function of HEMS in paper [72]. It means when any new device plug-in, automatic device discovery is carried on by using PLC in HEMS. HEMS can detect the new device by its load current in the residential power line system. With the information the HEMS received from the new device, HEMS can recognise the device's application and location in the residence. Also, residential automatic peak load management is implemented via employing HEMS for reducing energy consumption.

The future smart homes with more and more information application and smart devices will obviously improve our daily life with more comfortable residential environment. Based on the advantage of the power sockets and the distribution of the power line networks in the home environment, Lin, et al. [56] recommended power line communication as the communication infrastructure of wired local area networks. PLC based information applications (IA) located in the home environment and the internet bridging for data exchange among mobile devices were also explored and stated in paper [56].

The most threatening challenge to power line communication is the delivered signals via power line communications can not successfully pass through the meter and the transformer, even people spent mass of time on this research for decades. In recent years, it has finally made some progress.

In present, the commercial network bridge products based on power line communication, only can support LAN environment [16]. For the Internet part, DSL, cable or optical fiber are still employed to complete the access process, with high costs and prices in the market. Meanwhile, the power line communication is using mass of power lines as the information transmission carrier. But in some power line aging areas, the power line circuit already became wear and tear, which may affect the quality of transmitted signal in the power lines, and reduce the actual transmission rate in the same time. Residential power appliances, like microwave, hair dryer, etc. can also interfere the transmission quality in the power lines.

### 4.2.2 Wireless Communication Protocols

Not just power line communication, but many other wireless communication protocols also have been explored for being deployed in the smart grid. We select several popular wireless communication protocols to present in this section. Considered the coverage of these wireless communication protocols, we separate those protocols to two kinds, short-range solutions includes ZigBee and Wi-Fi, and long-range solutions includes WiMAX, LTE and IEEE 802.22 [45].

$ZigBee$

ZigBee is stated as IEEE 802.15.4 standard, which is developed by ZigBee Alliance [6] for low power, low transmission rate of data and short-range, usually less than 100m, wireless networks applications. IEEE 802.15.4 standard is carried on the physical (PHY) layer and Media Access Control (MAC) layer. Usually, the operating licence-free industrial, scientific and medical (ISM) radio bands include 868 MHz (Europe), 915 MHz (USA and Australia), and 2.4 GHz (worldwide) with corresponding date rate 20 kbps, 40 kbps and 250 kbps [45].

ZigBee technology is expected to be large deployed in wireless sensor network (WSN) [42] and in smart grid, especially in smart metering applications [29]. In the released specifications of ZigBee, the ZigBee Smart Energy V2.0 specifications is highlighted as an IP-based protocol, which could monitor, control, inform and automate the delivery of energy [7].

$Wi-Fi$

Wi-Fi is a local area wireless technology that is also recognised as the trademark of the Wi-Fi alliance, based on the IEEE 802.11 standards that are widely employed in WLANs [45] [47] [85]. In worldwide, there mass of Wi-Fi certified devices and the number of industry alliance already beyond 300. The operating licence-free ISM radio bands include 2.4 GHz and 5 GHz. Wi-Fi standard is widely used in residential environment for wireless communication and access by the mobile devices and other devices. For example, in the home area networks, Wi-Fi technology supports machine to machine (M2M) communication that is one of very important applications in the smart grid [65].

According to the IEEE 802.11 standards, the energy-efficient is always highlighted in the details of sub-standards, like 802.11c, 802.11d and 802.11ah that is under manufacturing and will be published in 2016. Currently available embedded Wi-Fi products engrafting the power saving methods that mentioned in the sub-stands, can be employed in the information applications in the smart grid. The embedded Wi-Fi is expected to be a highlight technology for the short distance wireless communication links in smart grid communication networks, especially in home area networks [29].

$WiMAX$

WiMAX is the short name of worldwide interoperability for microwave access, which is recognised as a wireless communication standard that can address many requirements of smart grid applications [84]. WiMAX refers to IEEE 802.16 wireless communication standards defined by the WiMAX Forum. IEEE 802.16m is the latest version in IEEE 802.16 family standards. Internet access, middle-mile backhaul to finer networks, and the multi-hop relay, are the main usages of WiMAX based soon its bandwidth and range [37].

Even WiMAX is not particularly created for the communication in the smart grid, but as an available communication protocol, it still provides the necessary functions to support the smart grid, like wide coverage, low latency and high throughput [45]. As one kind of cellular networks, WiMAX can be employed in the communication links in the smart grid architecture. Especially the WiMAX-based smart meter working in the home area networks, can achieve the communication requires, like lower cost, better coverage and fast installation etc. [43]. At the same time, the service of cellular networks are shared by dynamic consumers that may cause decrease in network performance in urgent situations. So the private communication network maybe needed by the power utilities to solve this kind of problem.

*LTE*

LTE is another kind of cellular protocol, besides WiMAX mentioned in the above. It is considered as one of 4G standard protocols can serve high-speed data communication on the wireless links [71]. Till 2014, LTE standard already has been accepted as the commercial service in most countries in the worldwide. Many different bands have been covered by the LTE standard. Hence, we can employ the LTE standard to establish a low-latency and high-reliable network for the data transmission and other communication applications in the smart grid.

Considered the architecture of distribution grid and transmission grid in the smart grid network, the LTE standard can be settled on the upper link between terminal power consumers and utilities, and also the wireless communication links between the primary substation and secondary substation, to lead the utilities achieve more accurate scheduling in the local power supply area. Also, any power fault happened in transmission grid can be delivered back and alarm the utilities based on the features of the LTE standard. Phasor measurement unit (PMU) is a quite popular communication application in the transmission grid based on the capacity of the LTE standard, which can alarm the power error and transmit back the needed situation data to the utilities that has remote controlling requirement on the high voltage power transmission lines.

### 802.22

IEEE 802.22 standard is based on the white spaces in the television (TV) frequency spectrum for wireless regional area networks (WRAN) [10]. After the white space frequency spectrum was opened to public wireless communication bands, IEEE 802.22 standard was developed for norming the frequency usage on these bands. In MAC layer, the popular technology is cognitive radio that needs to catch the capacity to adapt in the dynamic environment by sensing the spectrum.

Table 4.2: IEEE 802.22 characteristics [69]

| *Parameter* | *Specification* |
|---|---|
| Typical cell radius (km) | 30-100km |
| Methodology | Spectrum sensing to identify free channels |
| Channel bandwidth (MHz) | 6, 7, 8 |
| Modulation | OFDM |
| Channel capacity | 18 Mbps |
| User capacity | Downlink: 1.5 Mbps; Uplink: 384 kbps |

The application of cognitive radio in the smart grid is realised as the assistant radio in urban area and a backup in disaster management, also the broadband access based on the wide area coverage due to the good propagation characteristics of TV bands [36].

These feature of cognitive radio can serve the wireless communication requirements in the transmission part of the smart grid. that the high voltage power lines always need to through the rural area where has weak cellular system or other wireless communication standards coverage. As machine-to-machine (M2M) communication technology is widely used to support advanced metering infrastructure in the smart grid, cognitive radio and M2M communication can be integrated as cognitive radio M2M (CM2M) for the related applications in the smart grid [31] [28] [83].

In the transmission part of the smart grid system, the CM2M technology can add the flexibility of operation procedures, the post-fault controlling, and operation of power electronic converters. This feature can help to solve the fails that happened in the high-voltage system and restore normal operations as soon [83].

## 4.3 Communication Requirements and Performance Metrics

### 4.3.1 Communication requirements

Two-way" flow is the most important feature of the smart grid, which is also recognised as the main difference between traditional power grid and the smart grid. Meanwhile, from the power generation to transmission network, distribution system and consumption area, "two-way" communication with low-latency and sufficient bandwidth is also required to upgrade the capacity of the power grid and improve the service of the developing smart grid [70]. Usually, there are several kinds of smart grid communication requirements as follows,

1. Security: Security is the most important requirement to power grid communication from power utilities. In order to avoid any attack from outside, the secure infrastructure located in the power grid network should be developed and standardised to protect the operation procedures of power grid.

2. Reliability and availability: Ageing power infrastructures, especially the devices and feed lines in the distribution part of the power grid, may cause unexpected power fault even blackout, like the disasters happened in 2003 in U.S. and Europe. With the development of power infrastructures, the reliability and availability of communication in the smart grid are not just the challenges, but also the issues can not be

ignored and should be solved. Latest modern and secure communication technologies can be employed in the smart grid network to guarantee the reliability of the communication part of smart grid [43]. The availability of the communication architecture is established on the framework composed by the recognised fine communication technologies.

3. Quality of service (QoS): The QoS of communication requirements in the smart grid can be separated into two points, detailed mechanism of power price and routing methodologies for the powerful data communication infrastructures. More effective communication between utilities and power consumers can lead the power consumer follow the price scheduling managed by the utilities, for avoiding power consumption in the peak load period or high price duration in daily life. A good routing methodology can help smart monitoring system collect and feedback the data to utilities as soon as possible. Also the communication channel between utilities and power consumers can avoid unnecessary disturbance during the data interactive process [19].

### 4.3.2 Performance metrics

From the discussion that we presented in the above, we can find there are three main communication networks in the smart grid system. Home area network (HAN), neighbourhood area network (NAN), and wide area network (WAN) are covering the transmission and distribution architecture in the smart grid system [45]. The selected communication technologies can be deployed into these three networks to perform the corresponding communication tasks that is shown in Table 4.3.

In the distribution grid, power substation is divided into two kinds, primary substation and secondary substation. Primary substation is charging

Table 4.3: Hierarchical overview of smart grid communication infrastructure [45]

| $Classification$ | $Domain$ | $ExampleMembers$ | $ExampleTechnologies$ |
|---|---|---|---|
| WAN | Transmission | Routers, Towers, Stations | Satellite, Microwave, Cognitive Radio, IEC 61850 |
| NAN | Distribution | Relays, Access Points, Bridges | WiMAX, Cellular (LTE), PLC, Wireless Mesh |
| HAN | Comsumer | Thermostats, PCs, Automation | ZigBee, WiFi, HomePlug |

Table 4.4: IEEE 61850 communication networks and systems in substations: communication requirements for functions and device models [78]

| $MessageTypes$ | $Definitions$ | $Delayrequirements$ |
|---|---|---|
| Type1 | Message requiring immediate actions at receiving IEDs | 1A: 3 ms ore 10 ms; 1B: 20 ms or 100 ms |
| Type2 | Message requiring medium transmission speed | 100 ms |
| Type3 | Message for slow speed auto-control functions | 500 ms |
| Type4 | Continuous data streams from IEDs | 3 ms or 10 ms |
| Type5 | Large file transfers | 1000 ms (not strict) |
| Type6 | Time synchronisation messages | No requirement |
| Type7 | Command messages with access control | Equivalent to Type1 or Type3 |

the voltage transform from high voltage to medium voltage. The secondary substation is defined as the infrastructure that transforms medium voltage power to low voltage power in the distribution grid network. In our proposed scheme, the substations is updated as the regional power and data controller Hence it is also worth to exploring the performance metrics of substations on managing the message exchange events in the distribution grid, which are shown in Table 4.4 .

## 4.4 Conclusion

In this chapter, we explored the candidate communication protocols that can be deployed in the smart grid system to establish the information channel. Power line communication technology is employed to solve the "last mile" communication issues. The wireless communication protocols are running the communication flow in transmission grid, distribution grid and terminal power consumer's residences. Wired and wireless communication technologies both have advantages and disadvantages. We should select the optimal communication standard to meet the specific requirements of the particular communication environment. We also studied the performance metrics in different network area and the particular communication requirement to substation in the smart grid system. These metrics can help us understand the dynamic standards working in different area in the smart grid.

# Chapter 5

# Upgraded Power saving Models in Advanced Metering Infrastructure System

## 5.1 Introduction

With the evolution of existing power grid, smart grid is popularly referred to the next generation power grid, in which communication flow is a key features of the smart grid system [3] [1] [45]. Consumers power consumption data is collected and integrated through advanced communication technologies for analyzing the end-user power consumption behaviors and preferences by utilities. The smart meter is a device widely deployed in the user premises and responsible for collecting end-user power consumption data and reporting them to the utilities. The smart meter is the terminal power consumption data collection and transmission device in power consumer's residential environment, which is currently being widely arranged by utilities. Also the deployment of smart meter is encouraged and supported by governments through public policies and investment projects in the world [3] [1] [2].

From Figure 5.1 we can identify the distribution part of smart grid referred to as distribution grid, including primary substation, working between 110 kV and 20/10 kV in the medium voltage level, and secondary substation, working below 20/10 kV, which is settled for transforming the low voltage power to domestic consumption standard power that can be transmitted in local feed lines to terminal power consumers. As published roadmap mentioned, the architecture of the power grid is supported by the communication network, which provides the interaction, information dissemination and interaction among the connected devices.

The smart grid includes power flow and information flow. The transmission of power consumption data is one of most important tasks for the information flow in the smart grid. At the same time, two-way communication between utilities and terminal power consumers is realised as one of important features of the information flow in the smart grid [1]. In the terminal power consumers residences, the measurement of power consumption data is carried by the smart meters. Advanced metering infrastructure (AMI) is an integrated system of smart meters, communications networks, and data management systems that enables two-way communication between utilities and customers [45]. As the main block for metering and transmitting the power consumption data in terminal consumers residences, the power saving of smart meter become a problem that can not be overlooked when the number of deployed smart meter is really huge in the high-density residential community.

Power saving in the communication field has become a popular research topic in recent years. With the development of smart grid, many smart devices are created and employed in the next-generation architecture of smart grid, especially in the distribution grid network. A smart meter is settled to collect power consumption data of terminal consumers and transmit the data to utilities, in residential environment. The smart meters are continuously operating day and night to monitor the end-user power consumption in real-time and report the collected data back to the utilities

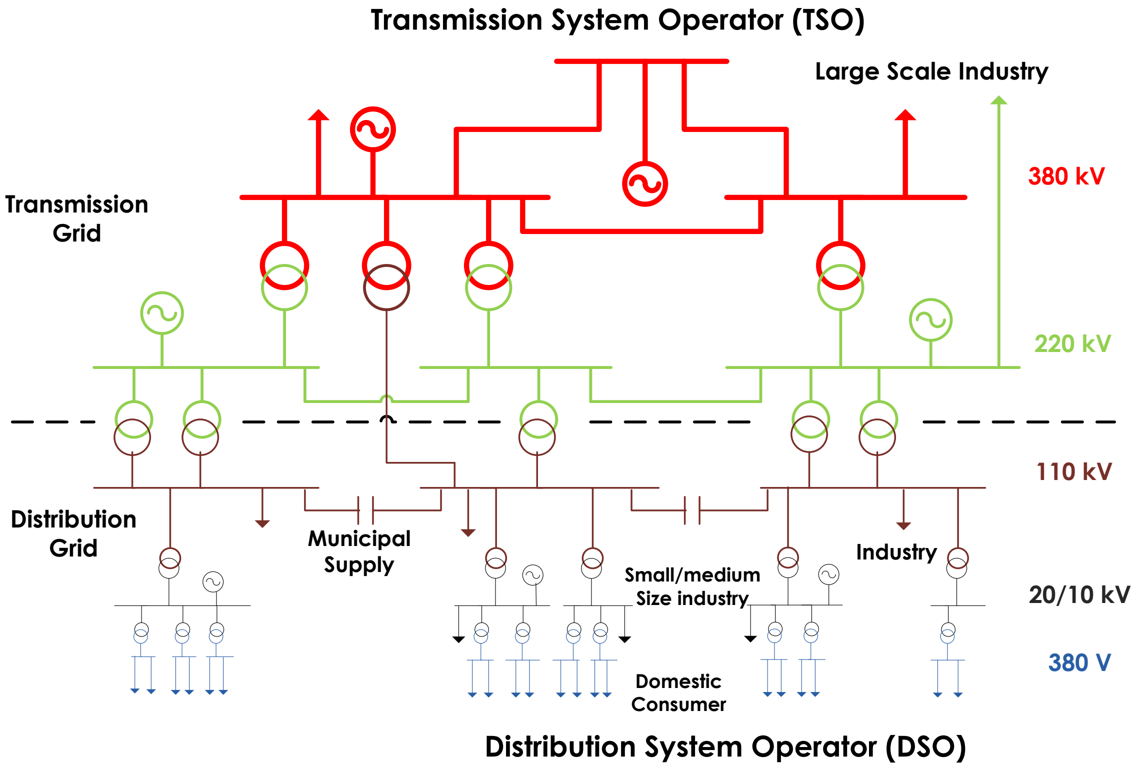

Figure 5.1: A typical power transmission and distribution network in Europe

management centers. As a result, they consume significant amounts of energy. The deployment rate of smart meters is already over 90% even 95% in many European countries, especially in the West European countries [40]. Along with the deployment of green energy in the terminal part of smart grid, the dynamic power demand from power consumers, and remote micro-operating requirement from utilities that will challenge the capacity of smart meters on data collection, transmission and local management etc. [3] [40]. This will cause longer working time and more power consumption of smart meters. Particularly, after locally generated renewable energy is selected as the power resource of smart meters, the deployment of large-scale smart meters in terminal power consumption area prompt us cannot ignore how to solve this problem.

## 5.2 Advanced Metering Infrastructure System

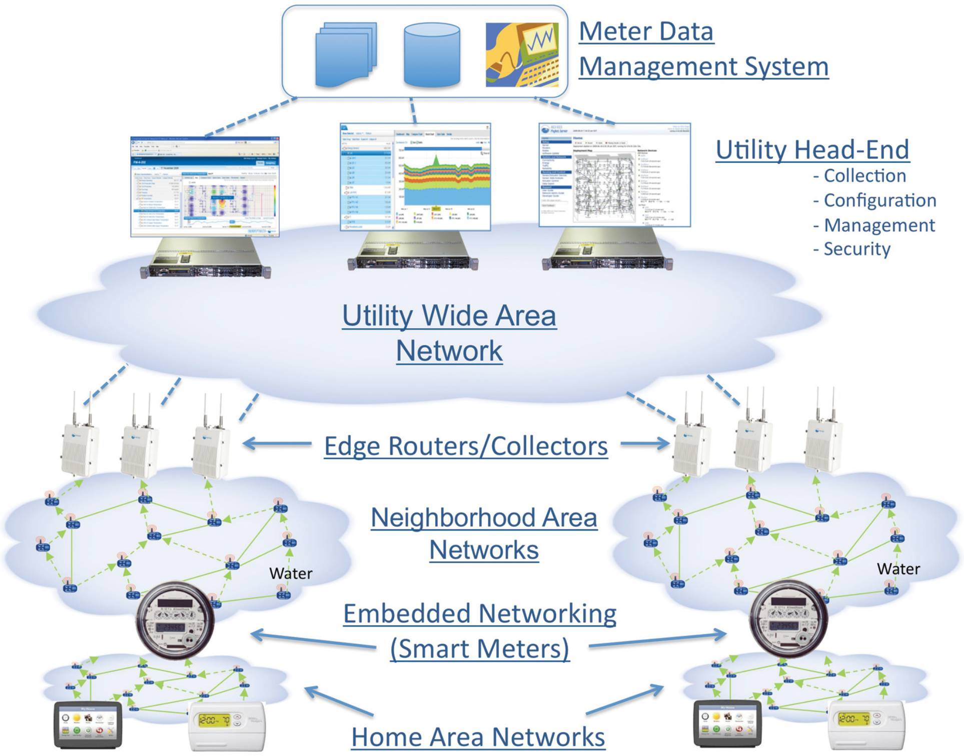

Figure 5.2: A simple architecture of advanced metering infrastructure system [75]

From the definition of advanced metering infrastructure (AMI) given by the electric power research institute (EPRI) of U.S., we can know that, "Advanced metering systems are comprised of state-of-the-art electronic/digital hardware and software, which combine interval data measurement with continuously available remote communications [77]. " There are two highlight points in this definition, data measurement and continuously remote communications. It means the main task of AMI system is to measure the data from terminal area of the smart grid and transmit back to the meter data management system in utilities as shown in Figure 5.2. As other full-duplex communication systems, AMI also executes the continuously remote communications that ordered by the utilities to deliver the remote information from the meter data management system back to the terminal home area networks.

From Figure 5.2, we also can find three communication layers: Home Area Networks (HANs), Neighbourhood Area Networks (NANs) and Wide Area Networks (WANs). The devices perform respective communication tasks, are allocated on the corresponding communication layers. Between HANs and NANs, there is a sub communication layer–Embedded Networking composed by a large number of smart meters.

Figure 5.2 illustrates the components of an AMI system. HANs (Home Area Networks), typically named as Customer Premise Equipment (CPE) and not included in the AMI system. Collection networks for meter data, referred to in Figure 5.2 as Neighborhood Area Networks (NANs), may be any one of wireless, cellular, power-line, etc. The utility Wide Area Networks (WANs) may similarly be private or public Wi-Fi, T1, WiMAX, fiber or cellular networks.

## 5.3 Local Stochastic Power Region Division Scheduling Model

This section provides a definition of the considered scenario and the problem statement addressed in the paper.

As shown in Figure 5.1, we propose to define the power grid network under 20/10 kV as the local smart grid community, where the secondary substation (including wireless communication controller and sub-data management center) plays the core role of local power management and controls a dense network of smart meters allocated in this local smart grid community. This upgraded local core architecture is named as community Power and Data Aggregator and Management (PDAM) center in our scheme that is shown in Figure 5.3. The architecture of the local smart grid community is shown in Figure 5.4. In this local smart grid community, we propose the

PDAM center as the local core manager of power and information flow. Besides the PDAM center, we also propose large-scale smart meters located in this high-density residential community, which can execute the task of data transmission hub between a terminal power consumer and the PDAM center.

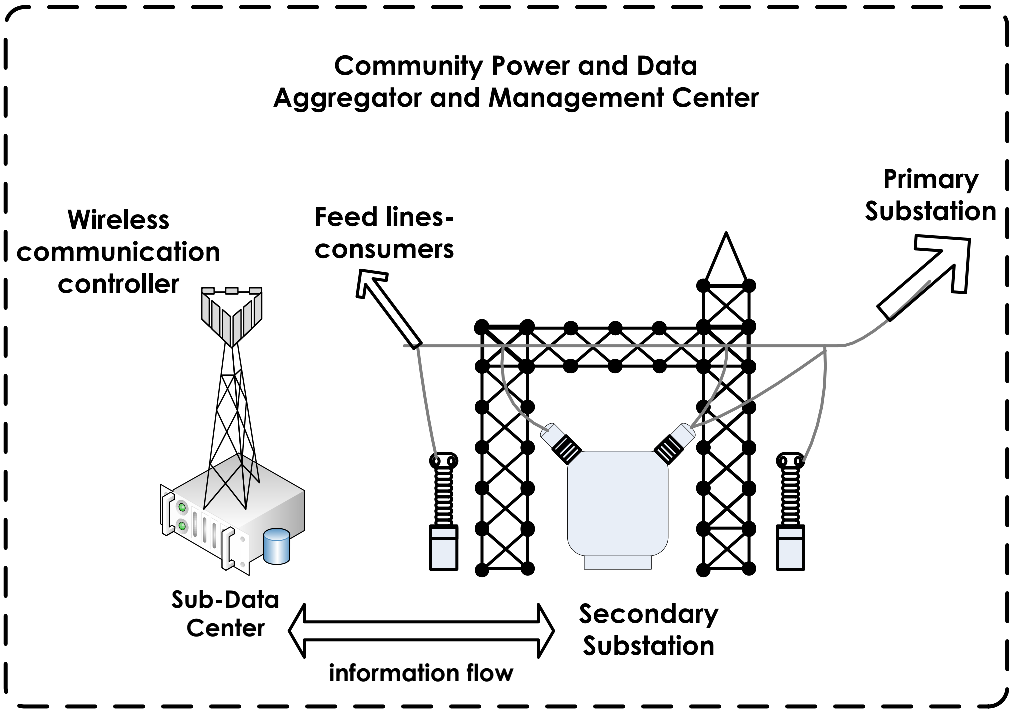

Figure 5.3: Community Power and Data aggregator and management center

Renewable energy is employed in the local smart grid community to assist local power demand and sub-data management center's power scheduling manipulation, which is produced by household wind turbines and solar generators in this scenario. The power resource for supporting smart meters located in residential environment is also locally produced renewable energy in our proposed local smart grid community. During the smart meter's measurement and transmission process, the considered huge number of smart meters and their continual working state, their power consump-

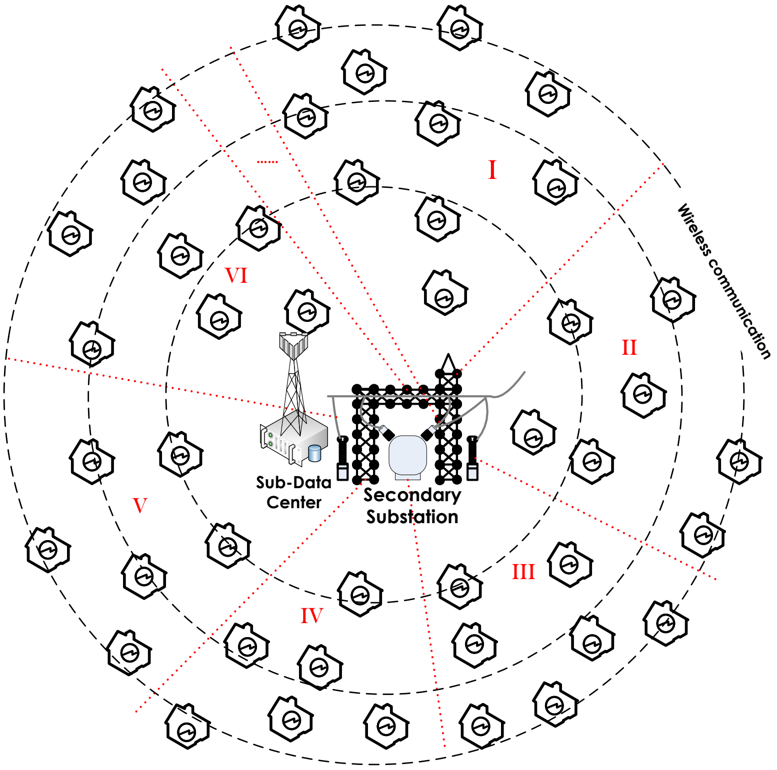

Figure 5.4: The architecture of the local smart grid community with several divided regions

tion would become power demand risk in this local high-density residential community.

The proposed approach is to build the local smart grid community architecture shown in Figure 5.4 . The PDAM center is settled to be the core controller in the local smart grid community, transmitting the local power consumption data and other related data back to utilities. The information interaction between utilities and the terminal power consumers is also controlled via the PDAM center. The smart meter placed in the power consumers residence with, is employed as the smart terminal node of the PDAM center. In this local smart grid community, the main type of power demand is basic residential electricity. Furthermore, the load balancing on different feed lines is similar, in order to maintain the stability of power grid network in this community. Based on the industry's recent exploration in the Netherlands, the idea of load balancing is invited into upper level power supply in distribution grid, like the power supply capacity of primary substation and secondary substation. Considering these two preset conditions and the industry experience, we propose that the power supply range could be divided into N regions per day with region code I, II, III, IV, V, VI, etc.. The load balancing in each region should be similar. But the number of smart meters employed in each region could be the dynamic. This mechanism is executed during 24 hours in the local smart grid community. In this period, each region can be in two different operational states, awake state or doze state. Once a target region is selected to be in doze state by the PDAM center in the current two-mode switch scheduling process, all the smart meters allocated in this target region will be in doze state in scheduled doze state time interval. This means that during the doze state duration, smart meters still can collect the ordinary power consumption data of residential environment, but the transmission process between these smart meters and PDAM center is stopped. At the end of the current doze state period, the smart meters of a doze state region automatically turn to awake state and convey the accumulated residential power consumption data to the PDAM center from smart meters during non-peak and non-busy communication periods in this local smart grid community.

In this scenario, the proposed local smart grid community includes large-scale active smart meters, collecting power consumption data of residential devices and transmitting the data to PDAM center in real-time. Based on the existence of numerous active smart meters in this community, the amount of the buffered traffic is too heavy to be accommodated within the transmission time interval. Also the excessive periodically transmitted beacon frames, which contain ordinary power consumption data of consumers, could become extremely long and reduce the effective utilisation of the communication channel in this community. Furthermore, the transmitted information about urgent power demand from terminal power consumers would be delayed in this communication network where channel congestion may appear. As we discussed previously, the long latency of data transmission and too long awake state hours may let smart meters consume more locally produced renewable energy, especially when we inspect the overall amount of power consumed by the smart meters of the local smart grid community. The consequence of this is that there is less energy stored in the smart batteries of residential users, leading to unexpected poor information interactive between smart meters and PDAM center, even cause power consumption malfunction in the proposed local smart grid community.

### 5.3.1 Local Stochastic Power Region Division

The excess power consumption of smart meters caused by heavy buffered traffic and traffic congestion in the wireless communication level of local smart grid community, can be improved via employing the novel power saving scheduling mechanism based on two-mode switch power saving scheduling strategy in the local smart grid community.

Based on the architecture presented in Figure 5.4, we consider a simple architecture of the local smart grid community shown in Figure 5.5. As we discussed previously, this local smart grid community can be divided into several regions that has awake and doze state. The state of these regions can be scheduled by employing our proposed two-mode switch scheduling strategy. By following the scheduling instruction of the PDAM center, the whole range of this community can be divided into a finite number of state mode-switch regions. We use $Z(\mathrm{n})$ to represent these divided regions, in which n is the unique code for each region in this division.

For example, in Figure 5.5, $Z(1)$ with shadows represents the target

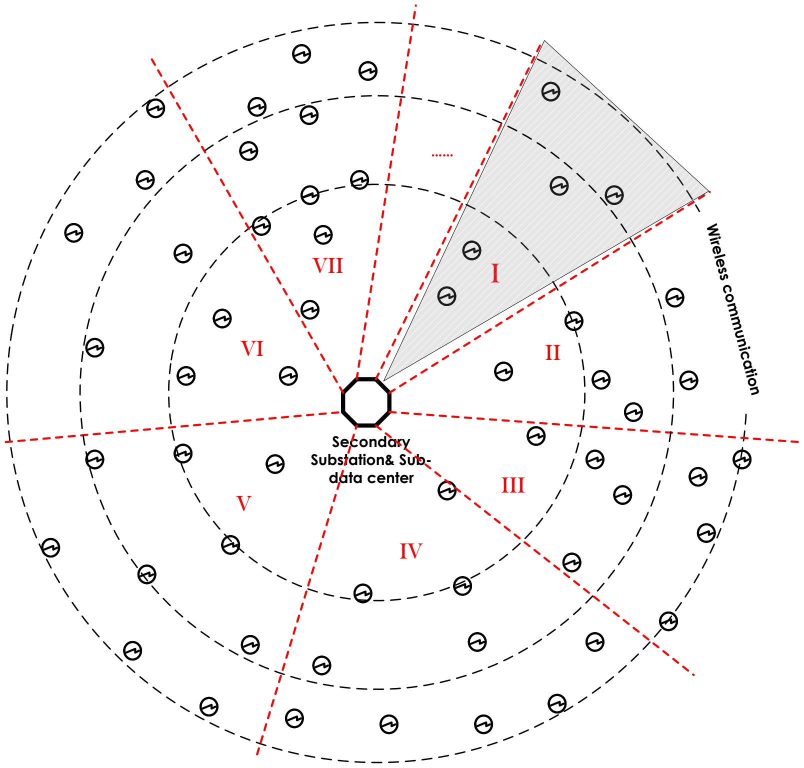

Figure 5.5: The simplified architecture of the local smart grid community with divided regions

region in doze state in current scheduling cycle. All the smart meters allocated in target region $Z(1)$ are also forced to maintain in doze state. As we proposed previously, the data transmission process from smart meters to PDAM center is paused during the doze state duration in the whole target region $Z(1)$.

A unique state-represent chain is established in PDAM center for recording the state of each region in each scheduling cycle. In this state-represent chain, code 0 means awake state. It means all the smart meters in this target region is forced to keep in awake state. The transmission between the smart meters and the PDAM center is guaranteed. On the other hand, code 1 means doze state in this current scheduling cycle. It means all the smart meters in this target region is required to be in doze state. The transmission between the smart meters and the PDAM center is stopped during this scheduling cycle. Hence, data chain [1, 0, 0,..., 0] can repre-

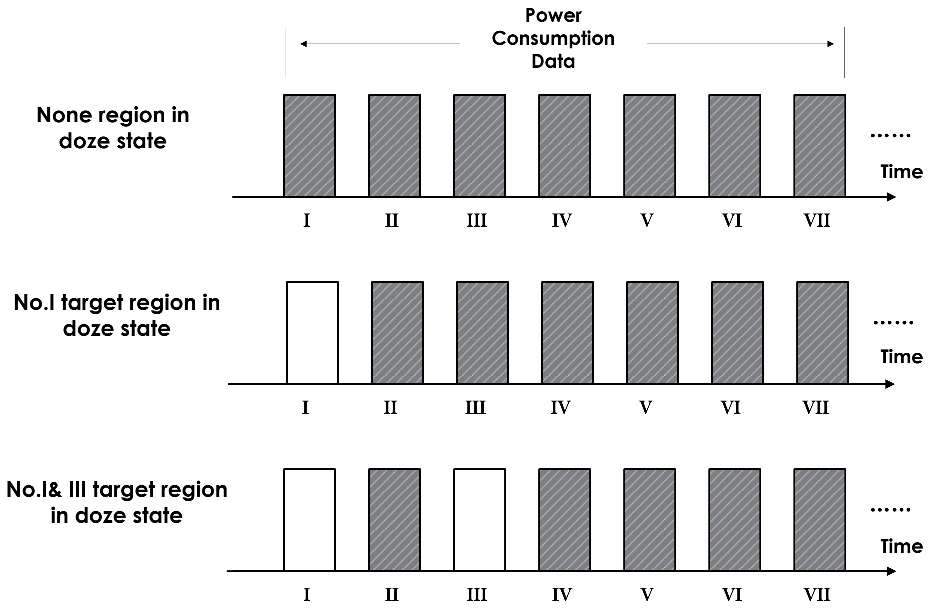

Figure 5.6: Dynamic communication status in the local grid community

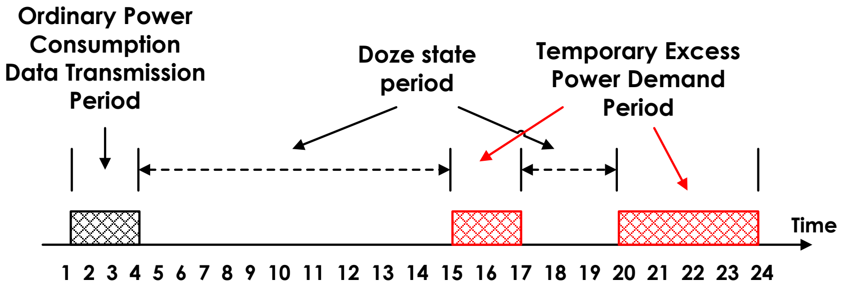

Figure 5.7: Mode-switch of residential smart meter in a whole state scheduling cycle

sents the state of all the regions that are divided by the PDAM center in the local smart grid community, as there is only one target region $Z(1)$ in doze state. Furthermore, when we assume $Z(3)$ is also selected as the target region in doze state, the unique state-represent chain is recorded as [1, 0, 1, 0,..., 0]. In this case, the data transmission status mentioned in the example in communication level of the local smart grid community is shown in Figure 5.6.

We also explore the influence of employing the state mode-switch scheme on a micro unit in the local smart grid community, i.e., a smart meter.

Obviously, the state of smart meter should follow the state of the target region that it belongs to. The smart meter should be in doze state obeying the scheduling order from the PDAM center. During any excess power demand that appears in terminal consumer's residence, the target smart meter can automatically start up communication priority for sending power demand data to the PDAM center. The PDAM center responses this power demand data, and allows the smart meter in doze state to record and transmit power consumption data in real-time. At the same time, the PDAM center would allow the target smart meter sending ordinary daily power consumption data till the end of the urgent awake state period. This is shown in Figure 5.7.

### 5.3.2 Target Power Zone Two-state-switch Scheduling

As we discussed previously, all the smart meters allocated in the stochastic target regions in doze state also need to keep in doze state during the target region?s doze duration. Unless any excess power demand appears in those target regions. When the urgent power demand appears in the local smart grid community, the related smart meter will get the priority to wake up and send power demand data to the PDAM center. Till the response information is transmitted back from PDAM center, the related smart meter will start transmitting the urgent power demand data to the PDAM center in real-time. In order to realise the purpose of power saving, we define a two-mode-switch scheduling strategy as follows.

The two-mode-switch scheduling strategy shown in Figure 3.4 runs according to the following steps:

1. The smart meters in the local smart gird community are identified with a unique code that is recorded in the PDAM center.

2. The local smart grid community range is divided into several regions

N. The PDAM center identify i zones as target regions in doze state in a 24 hours scheduling cycle.

3. For other regions in awake state, the PDAM center lets the smart meters allocated in these regions, choose available communication channel to transmit ordinary power consumption data in real-time.

4. When the 24-hours scheduling cycle ends, the whole process will be repeated again from step 2. Otherwise all the smart meters allocated in the target region in awake state will continue transmitting power consumption data in real-time.

5. For the target region in doze state, all the smart meters employed in these regions can still collect ordinary power consumption data in residential area, but data transmission from smart meter to the PDAM center is paused.

6. If any temporary excess power demand appears in a target region in doze state, the target smart meter will automatically be awaken and send the power demand information to the PDAM center in real-time. After the urgent power demand transmission requirement is responded by PDAM center, the smart meter will transmit the urgent excess power consumption data to PDAM center in real-time.

7. Then, the daily power consumption data of this local smart grid community can be smoothly collected and transmitted from smart meters to PDAM center. Also the urgent power demand can be supported by the data inter activities between the related smart meters and PDAM center.

## 5.4 Upgraded Transmission Model

### 5.4.1 Power Saving Theory Based on IEEE 802.11 Standards

Based on the IEEE 802.11standards, the Wi-Fi technology is defined as a local area wireless technology for low cost data exchange in Machine-to-Machine (M2M) communications [65] [78] [47], which is also called Wireless LAN (WLAN). When the Wireless Stations (STAs) and Access Point (AP) compete for access to the shared wireless channel, a distributed contention based access method is mandatorily used. This method is call Distributed Coordination Function (DCF). There are two modes of power management for STAs under operation of DCF mode in wireless communication. In active mode, STAs are keeping awake state so that the radio transceivers are usually switched on. During this period, the energy for supplying their transceivers is consumed even in idle interval. In Power Save Mode (PSM), STAs retain a low-power doze state so that their radio transceivers are turned off. In this doze state, the energy consumption is limited.

### 5.4.2 Updated Power Saving Model for Data Transmission in AMI system

IEEE 802.11ah is an up-and-coming Wireless Local Access Network (WLAN) standard that denotes a WLAN system operating at sub 1 GHz license-exempt bands. 802.11ah is utilized for various deployment including large-scale sensor networks, outdoor Wi-Fi for cellular traffic offloading, where the available bandwidth is relatively narrow. Furthermore, IEEE 802.11ah Medium Access Control (MAC) layer has adopted some enhancements to fulfil the requirement from system, which includes the improvement of power saving features, and etc. [74].

In the legacy IEEE 802.11 Standards, in order to transmit the whole data that contains extremely long beacon frame, the devices inevitably keep in active status to complete the receptions of their buffered packets. Even in the mentioned power saving mode, when the device maintains in doze state, the radio components are forced to turn off. Then it cannot sense incoming signals at all. In our case, once the smart meters allocated in the deep sleep zone within doze state, because of the settled power saving mechanism, they can not measure and collect the power consumption data of residential environment in real-time. As the radio components are turned off, the local urgent power demand can not able to timely sense and send urgent power demand data to PDAM center.

As introduced in the IEEE 802.11ah Standards, we employ a new mechanism called "page segmentation" [74] into our wireless communication scheme, but modify it to adapt the requirement of our system. In IEEE 802.11ah Standards, the whole partial virtual bitmap about power consumption can be spliced into multiple page segments, and each beacon is responsible for carrying the buffering status of only a certain page segment. Then the smart meter should be waked up again and again at the transmission time of the beacon that carries the buffering data of the segments it belongs to.

During the data transmission period, if the mode of smart meter is immoderately switched between awake state and doze state, it would drive pyrrhic excess power consumption. For the purpose of power saving and high efficiency of smart meters in the local smart grid community, we settle the status of smart meters allocated in deep sleep zone in doze state, be active during the page segmentation and multiple page transmission period, without mode-switch repeatedly between awake and doze state on the wireless communication level. For any urgent power demand appears in the target deep sleep zone in doze state, the related smart meter can employ our improved "page segmentation" mechanism for balancing power saving and high efficiency.

## 5.5 Performance and Evaluation

This section analyses the performance of our proposed power saving scheduling strategy. The theoretical analysis of the scenario proposed above is then carried out, by defining the simple mathematical framework as shown in Table 5.1.

From Table 5.1, we can obtain several equations about the total number of divided region in the local smart grid community and power consumption of smart meters as follows,

$$i + j = N, 0 \leqslant i \leqslant N, 0 \leqslant j \leqslant N. \tag{5.1}$$

$$P_S = P_a \cdot \sum_{j=1}^{j} S_a^j + P_d \cdot \sum_{i=1}^{i} S_d^i + P_a \cdot w \cdot \sum_{i=1}^{i} S_d^i \tag{5.2}$$

We considered the existing power distribution architecture and local natural environment, and also explored the open resources about the capacity of primary substation and secondary substations from academia and industry. Then we employed these parameters shown in Table 5.1, Table 5.2 and Table 5.3.

Figure 5.8 shows, the relationship between the power saving gain and number of divided regions in the local smart grid community, we can see that the value of slope of curve becoming higher when the number of divided regions is increased. At the same time, the power saving rate also follow the same trend. These five curves represent the same trend that when the number of target regions in doze state is increased, the power saving gain is higher and higher. As the power consumption value of the smart meters has obvious difference between awake state and doze state, the increase of the number of smart meters in doze state can lead to higher power saving gain. Meanwhile, the curve represents the number of the di-

Table 5.1: The defined parameters in proposed scheme

| Definition | Parameters |
|---|---|
| Total power consumption of smart meters in community | $P_S$ |
| Power consumption of smart meter in awake state | $P_a$ |
| Power consumption of smart meter in doze state | $P_d$ |
| Number of target region in doze state | $i$ |
| Number of target region in awake state | $j$ |
| Number of smart meter per target region in doze state | $S_d^i$ |
| Number of smart meter per target region in awake state | $S_a^j$ |
| Percentage of power demand related smart meter per target region in doze state | $w$ |

Table 5.2: Simulation parameters for calculating the relationship of power saving rate and number of divided region in local smart grid community

| Parameters | Value |
|---|---|
| Number of smart meter | 1,000 |
| Percentage of target region in doze state | 10%, 20%, 30%, 40%, 50%, 60%, 70% |
| Number of divided regions | 10, 20, 30, 40, 50 |
| Power consumption of smart meter in awake state | [8 15] w/h |
| Power consumption of smart meter in doze state | [1.35 3] w/h |

vided regions equals to 50, has greater slope than the curve describes the number of the divided regions equals to 10. It means if the number of divided regions in the local smart grid community is increased, the two-mode switch strategy is more effective.

Figure 5.9 shows that we observe that the power saving gain of smart meters under employing the improved power saving mode page segmentation can be higher with the increasing of the number of divided regions in local smart grid community. The improved page segmentation can reduce the power consumption of the smart meters when they transmit urgent power demand data to PDAM center compare with normal none-power

Table 5.3: Parameters for calculating power consumption of urgent power demand smart meters with different wireless communication scheme

| Parameters | Value |
|---|---|
| Number of smart meter | 1,000 |
| Number of divided region | 50 |
| Number of target region in doze state | 5, 10, 15, 20, 25, 30, 35, 40 |
| Power consumption of smart meter under normal transmission scheme | [8 15] w/h |
| Power consumption of smart meter under improved transmission scheme | [3 5] w/h |
| Urgent power demand rate | [2.5%, 5%, 7.5%, 10%,...20%] |

saving mode transmission. Specifically, when the urgent power demand appears more and more in the local smart grid community, the power saving gain could become higher as shown in Figure 5.9.

## 5.6 Conclusion

Power saving represents a relevant research topic in the architecture of the future smart grid. In this chapter, we have analyzed the distribution section of the power grid, and have defined a high-density local smart grid community including PDAM center, including a secondary substation and sub-data management center, and a massive deployment of residential smart meters supplied by local renewable energy. Then, we introduced a novel power saving mechanism based on two-mode switch scheduling strategy to reduce the power consumption of smart meters in this local smart grid community. Performance evaluation results demonstrate a relevant improvement in the performance of the system. When the number of the smart meters is being raised in the local smart grid community, the power saving rate is also increased to maxim 45%. The increase of the number of divided region in the local smart grid community can obvious reduces the global power consumption of the smart meters to maxim 50%, when the

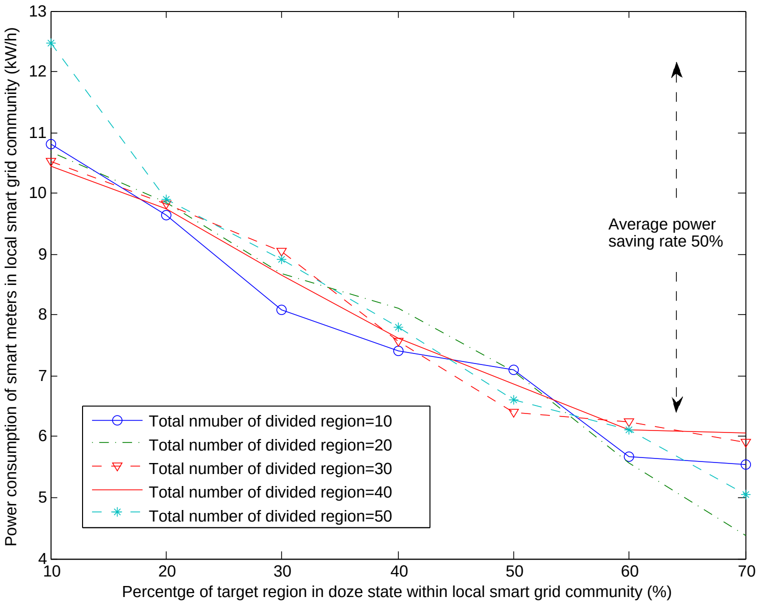

Figure 5.8: Power consumption of the local smart grid community using the proposed scheme with dynamic number of target regions in doze state

number of doze state zone is also grown. When the urgent power demand appears in doze state zones, the power consumption of the smart meters is significantly cut, by employing the improved transmission mechanism.

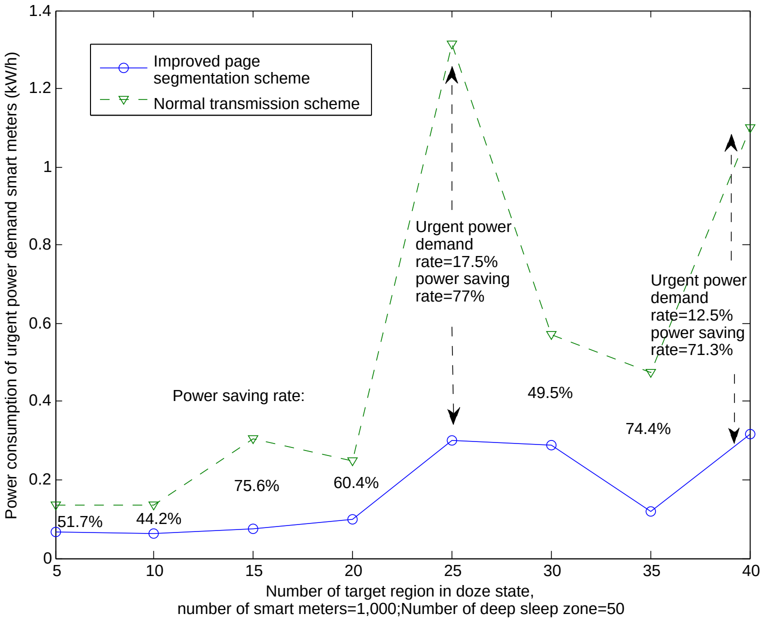

Figure 5.9: Power saving margin between conventional scheme and improved scheme in urgent power demand data transmission process

# Chapter 6

# Fast Power Charging Station Design

## 6.1 Introduction

In order to reduce the usage of nonrenewable energy resources, foreign oil dependence, and the Green House Gas (GHG) emissions, Electric Vehicles (EV) and Plug-in Hybrid Electric Vehicles (PHEV) have gained popularity in the western world [46] [68] [25] [59] [48]. This trend is also supported by the improvements in the battery storage technology [46] and incentives offered by the governments to reduce the cost of ownership. For instance, according to [46], more than $250,000$ EV/PHEVs were sold in the first three years of their introduction. It is further projected that 50% of the new car sales will be composed of EVs and PHEVs by year 2050. On the other hand, to achieve the projected market portion charging stations have to be deployed to extent the all-electric driving range.

As the main power supply bases of EV/PHEVs, the design and the operation of the EV/PHEV charging stations are considered as one of the most important research topics in smart grid. Not just as public power charging stations for ground transportation, but such smart grid infrastructures can also be deployed in parking lots, university campuses, and at any other related public places to accommodate the EV demand during daytime. These stations will ubiquitously solve the charge depleting issues of users living in densely populated areas and provide complimentary charging service to customers with garage charging options.

Academia and industry have already established a conductive charging system architecture for electric vehicles as the standards for charging system and details can be found in its updated version [44] [67]. In order to compete against gas-powered counterparts, fast charging technology is highly desired by the EV owners. Fast charging technology also enables utilities to make extra profit by serving customers. On the other hand, the power grid is not designed to serve ”energy-hungry” vehicles, and concurrent charging of large amount of EVs will strain the power grid beyond its operation capacity [12] [14]. To that end, several fast charging station technologies have already been introduced via the exploration in academia and industry [11] [76] [82] [73].

## 6.2 Fast Power Charging Station Design and Parking Campus with Renewable Energy System

In this section, we present an optimal updated architecture of the fast power charging station and upgraded fast power charging station-based electric vehicles public parking campus with employment of local renewable energy system.

### 6.2.1 Proposed Parking Campus

Public fast power charging station is recognized as an effective solution for promoting the durability of EV/PHEV during the consumer’s daily traffic activities. However, as profiled in the introduction, the additional power demand introduced by the broad-scale penetration of EV/PHEVs will be hardly supported by the current power grid. In this section, we provide a definition of the considered charging station scenario which accommodates large-scale EV/PHEVs demand with updated fast power charging station, which is assumed to be subject to extensive development efforts in the near future.

We propose this parking campus located in industrial park or university campus where the customer demand is highly stochastic and thus unpredictable. The goal of the station is to supply wide-range of consumers with particular level of quality of service, by establishing a local power charging system based on local renewable energy system (strong power dynamos (wind and solar)) which also includes local energy storage infrastructures as depicted in Fig. 6.1. During parking time, each EV/PHEV can choose fast power charging service or not, which depends on the consumer's private willing, the current power status of its automotive battery, and parking duration.

### 6.2.2 Updated Fast Power Charging Station

In this proposed parking campus, the global power demand from grid is dynamic. For the purpose of reducing the probability of overload in local distribution power network and neutralize transmission blocking, [12] settled local energy storage item on fast power charging station. The local device can be charged by power grid when the charging station is inactive. Compared with the fast power charging station scheme proposed in [12], the updated charging station combines local renewable energy as the additional power support resources. The core insight is the parking EV/PHEVs power demand can be satisfied either by power grid supported by utilities or with the local energy storage devices charged by local renewable energy resources, even directly get charging service from the local renewable energy resources. The architecture of upgraded fast power charging station is shown in Figure 6.2. Depending on the above characterisation, we proposed a strategy due to the following points:

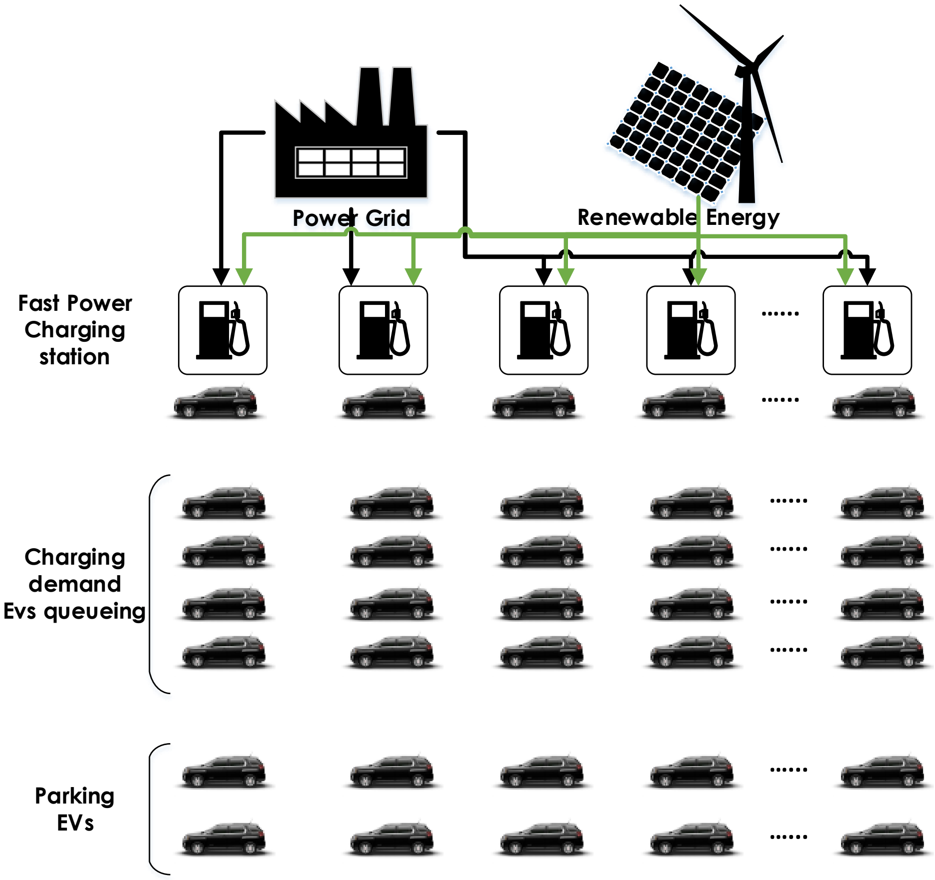

Figure 6.1: EV/PHEV Parking Campus with Upgraded Fast Power Charging Station

1. Charging station attracts a constant power from the grid and the local renewable energy resources.

2. To suffice stochastic and interim power charging demand, we employ a local renewable energy system includes local energy storage item and local renewable energy dynamos (wind and solar).

3. When the fast power charging station is inactive, all available energy produced by the local renewable energy dynamos can be employed to fill the local energy storage item. Also, the power consumption in energy storage infrastructures during power charging service stage,

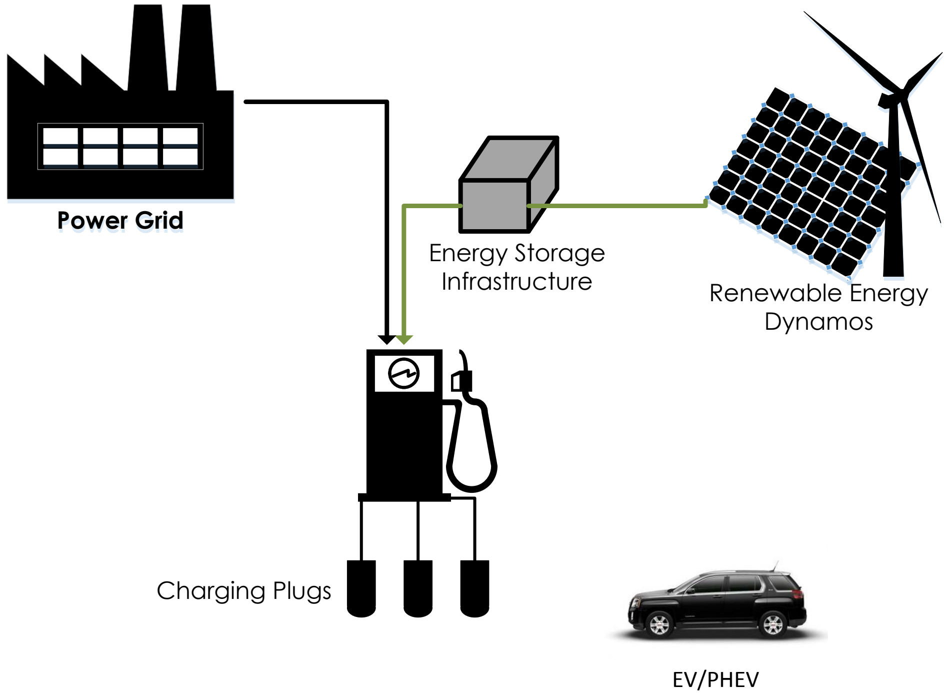

Figure 6.2: Architecture of Upgraded Fast Power Charging Station

can be supplied by the local generated renewable energy in real-time.

4. Depending on the produce efficiency of local renewable energy dynamos, the charging capacity of fast power charging stations in parking campus can be elevated via sustainable local renewable energy supplying.

## 6.3 Conclusion

In this chapter, we introduced an upgraded architecture of fast power charging station with the employment of local renewable energy system. Considered the general driving situation and status of the ordinary electric vehicles, we leaded a public parking campus into our mechanism as the framework for the updated fast power charging station and serve the power charging for the parked electric vehicles. Then the parking duration for the electric vehicles can be consumed for charging demand supported by the power grid or local generated renewable energy.

# Chapter 7

# Controlling System of Electric Vehicles in the Upgraded Parking Campus

In this chapter, we deliver a control model for power charging queueing in the fast power charging station.

## 7.1 Introduction

Electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) are being considered as aspirant competitors of traditional fuel engine vehicles and more attractive goods to consumers in recent years. In Chapter 6, we proposed the updated fast power charging station located in the public EV/PHEV parking campus, with local renewable energy system. The current power grid is being challenged by the increasing power demand from ordinary power supply and extract demand of developing power charging station for EV and PHEV. As the proposed relevant component, the local renewable energy can become the positive power supplement for reducing the integral demand of charging stations to power grid and slowing down the consumption of non-renewable natural energy. In this chapter, we present a quantitative stochastic scheme for analyzing the performance of the outlined system via employing arguments from queueing theory and economics, after clean energy is deployed.

## 7.2 Stochastic Controlling Model for the Fast Power Charging Stations

In this section, we present the available queueing model for the controlling of fast power charging station.

### 7.2.1 Queueing Model for the Fast Power Charging Station

Our explored stochastic model for the fast power charging station has some resemblance with an Erlang-B blocking system [41]. But there are still some significant differences. As we employed local renewable energy dynamos in proposed parking campus, the power support based on renewable energy resources can be recognized as long-term sustainable supply. So the efficiency of the additional power supply on charging station will depend on service level of the local renewable energy dynamos. Once the generation level of local renewable energy dynamos can be maintained on high status with delightful Quality-of-Service, more parking EV/PHEVs can be charged via additional power supply based on the local generated renewable energy. Then the global service level of fast charging station can be upgraded or fall down to the basic service when the efficiency of local renewable energy dynamos is influenced by irresistible negative factors. This status is proposed as "Service Jumped" in our model. We assume that arrivals of EV/PHEVs can be patterned as a Poisson process. We select the term block customers for those ones who require power charging service but can not be served immediately. In this case, we premeditate two types of blocking and the status of "Service Jumped":

1. Type 1: Classical Erlang-B blocking appears when all charging plugs are in active, the consumers do not have the willing to wait and leave. This type of blocking due to number of servers (charging plugs) in the system [17].
2. Type 2: This blocking appears when the consumer charging demand can not be satisfied because of power or energy shortage in the system. So the consumers will wait in the parking campus.
3. Status of "Service Jumped": The service level of fast power charging station in proposed parking campus can be improved to higher level to serve large-scale charging demand consumers, and also be pulled back to lower level cause longer blocking queueing. It occurs when the efficiency of local renewable energy dynamos is changed by less predictable natural conditions.

We majorly analyze type-2 blocking situations and the status of "Service Jumped" in subsequent chapters.

### 7.2.2 Stochastic Controlling Model

Electrical vehicles arrive to the proposed parking campus in the light of a Poisson process of rate $\lambda$. We assume that the number of EV/PHEVs can be accommodated by the power grid in this parking campus is $N$. If additional vehicles require charging service, those can be charged by the local energy storage infrastructures at any time. We assume quantifiable charging levels of the local energy storage devices in number of EV/PHEVs that can be supported. The capacity of local storage device is defined as $K$. Then we can provide that if fully charged it can present service to $K$ EV/PHEVs simultaneously, under the quantization assumption. We also assume $\mu$ as the exponentially distributed rate of the service times of the EV/PHEVs. We select $\nu$ as the service rate for describing the charging time of the local energy storage device. As referred previously, a vehicle can be charged from the grid so long as the number of EV/PHEVs does not outride $N$. Additional vehicles can be supported by the local energy storage infrastructures, proved that the storage power level can satisfy the additional requirement, otherwise they will be blocked. Also, as we analyzed above, “Service Jumped” can appear and sustain the fast charging station serve more EV/PHEVs in the parking campus when the local renewable energy dynamos are keeping high production efficiency. The“jumped” level is defined as $\beta$. The capacity of the“Service Jumped” is $Q$.

The dynamics of proposed stochastic suppositions and mechanism of the charging station, are seized by a continuous-time birth-death Markov chain with finite three-dimensional state space presented in Fig. 7.1. First dimension of the state space conforms to the number of EV/PHEVs can be supplied by the fast power charging station, as well as the second one to the charge level of the local energy storage device. The third dimension provides the renewable energy supply level for current charging status on fast charging station, which depends on the status of ”Service Jumped”. Especially, we assume $(i, j, \beta)$ denote a generic state, with $0 \leqslant i \leqslant N{+}j$ and $0 \leqslant j \leqslant K$. For instance, the (0, 0, 0) status corresponds to a condition where there are no EV/PHEVs being serviced, the local energy storage item is empty, and no additional power supply from local renewable energy dynamos; similarly, all the status $(i, 0, 0)$, $0 \leqslant i \leqslant K$ to a composition where $i$ EV/PHEVs are being charged, but the local energy storage device is still empty and no additional power supply from local dynamos as well. In order to avoid painting the figure too complex, we just select the row maintains (0, 0) to $(N, 0)$, and another row maintains $(0, K)$ to $(N{+}K, K)$ from two-dimensional state space to represent the “Service Jumped” status. In the updated level $\beta$, the fast power charging time of the local energy storage device is still $\nu$. At the same time, the service times of the EV/PHEVs are still exponentially distributed by $\mu$, like in the two-dimensional state space. The Markov chain states $(N{+}j,\ j,\ \beta)$, $0 \leqslant j \leqslant K$ indicates the blocking ones, where the current power charging queueing on fast power charging station objects new arrivals.

The birth and death rates are all profiled in Fig. 7.1. The death rates are proportional to the number of EV/PHEVs being served and also same as the birth rates, as we should consider about the arrivals of new EV/PHEVs and charging the local energy storage infrastructure. Also the "Service Jumped" level is being considered as one of important parameters in our mechanism. The total number of status in the Markov chain is :

$$\Theta = \sum_{1}^{Q} \beta \cdot [(N+1) \cdot (K+1) + \sum_{1}^{K} i] \tag{7.1}$$

## 7.3 Controlling System Performance Evaluation

### 7.3.1 Evaluating with Deployment of Local Renewable Energy Resources

The model is based on the following principles: the parking campus operator obtains revenue from each charged EV/PHEV. At the same time, all the parking EV/PHEV should pay for duration in the parking campus. Let $C_g$ and $C_r$ be the revenue obtained per EV/PHEV when charged from the grid and the local energy storage device. We assume that $i_s$ represents the service status, and $s$ is the number of EV/PHEV under this state. Further, let $C_P$ denotes the parking cost per EV/PHEV. Finally, we assume that the local renewable energy dynamos and storage device have a fixed installation cost $C_0$. In order to denote the stationary probability for generic status, we select $\delta_s$ as the parameter in the following equation. Then the profit equation per each EV/PHEV in the proposed parking campus can be composed as follow:

$$P = \sum C_g \cdot i_s \cdot \delta_s + \sum C_r \cdot i_s \cdot \delta_s + C_P - C_0 \tag{7.2}$$

### 7.3.2 Parking Campus Profit Model

By using some simple financial principles, relates pricing parameters and existing parameters in parking campus system, we present a profit model for parking campus and also acceptable results for consumers. In global level of the power support for the proposed parking campus, the following principle should be considered, which power demand from grid in parking campus plus the additional local renewable energy supply should less than current power grid supply in parking campus. So we define several parameters as follow:

1. the value of power demand per EV/PHEV in parking campus $P_n^D$;
2. power charging duration in parking campus $t$;
3. power resource price $p$ includes two kinds of prices, $p_r$ is the price of renewable energy; $p_g$ is the price from power grid.

So the consumer's payment can be calculated by using the following equation:

$$Sum = \int_0^{t'} (p_g \cdot P_n^D)\mathrm{d}t + \int_0^{t''} (p_r \cdot P_n^D)\mathrm{d}t \tag{7.3}$$

$$t' + t'' \leqslant t \tag{7.4}$$

$$p_r \leqslant p_g. \tag{7.5}$$

From Table 7.1 we explore the popular dynamic EV/PHEV power charging times that are decided by the charging power on fast charging station.

Table 7.1: Charging Speed in DC Fast Charge Station [13]

| Charging Power | Compact EV | SUV/Sedan | Heavy Truck |
|---|---|---|---|
| 50 kW | 15 min | 22 min | 46 min |
| 75 kW | 11 min | 15 min | 32 min |
| 100 kW | 8 min | 12 min | 22 min |
| 125 kW | 6.5 min | 9 min | 19 min |
| 150 kW | 5 min | 8 min | 16 min |

Through employing the parameters we discussed previously and the ones from Table 7.1, we get Fig. 7.2 to depict the compared result. As we can recognize from Fig. 7.2, if the power grid become only power supply resource, the global level power demand would be raised via the rising of charging queueing on station in the proposed parking campus. Even the middle curve shows that the power consumption can be partly satisfied with local energy storage infrastructure, but the improvement is not so gratifying. Furthermore, the local energy storage infrastructure also need to be charged via using the power from grid, when the system is idle. Obviously, the mechanism based on local storage item and renewable energy dynamo sustain the optimal solution among other two representative schemes.

## 7.4 Conclusion

In this chapter, we proposed an EV/PHEVs parking campus with upgraded fast power charging stations supplied by local renewable energy resources. A quantitative stochastic model for analyzing the introduced mechanism is explored by using queueing theory and financial considerations. The focus in our paper is the addition of local renewable energy system includes renewable energy dynamos and local energy storage infrastructure on fast charging station in the proposed parking campus. The renewable energy resources are employed as additional power supply to reduce the probability of peak load in local distribution grid network and satisfy immediate charging demand, especially when the capacity of power grid is not idle and unavailable. The insights included in our mechanism are provided via analysis and evaluation results, which would become crucial in early designing the smart grid and parking campus with fast power charging station of the future.

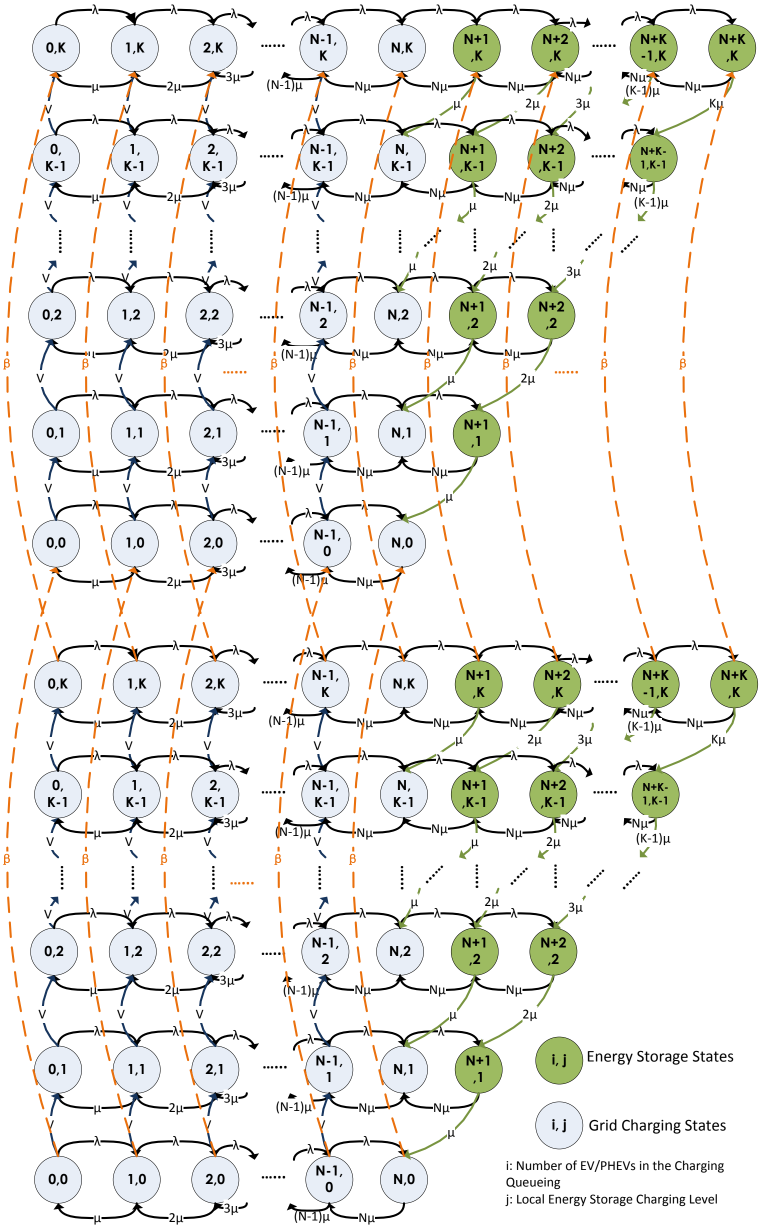

Figure 7.1: Continuous Time Markov Chain

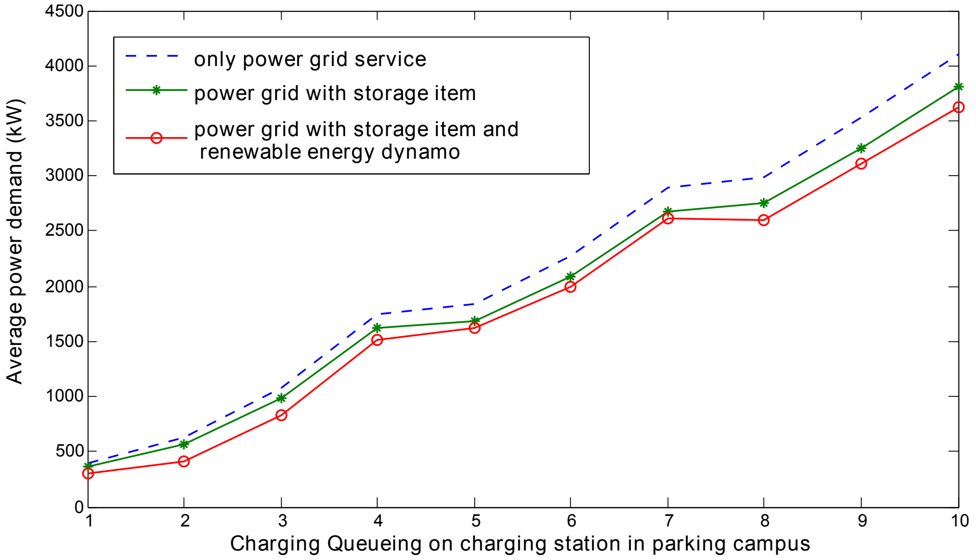

Figure 7.2: Global level power supply under different mechanism in parking campus

# Chapter 8

# Conclusion and Future Work

## 8.1 Summary and Conclusion

The main contribution of this thesis is to propose the solution of current dynamic challenges appear in power grid and related issues via deploying of renewable energy system in the distribution network of smart grid. These challenges and issues can be played into three, architecture modelling, communication, and electrical vehicle and fast power charging station.

The contribution of the first topic which is explained in Chapter 2 and 3 can be listed as:

- We proposed a type of smart home architecture with local deployed renewable energy system as the assistant of power supply resources for the terminal power consumer in its residence environment. The selected renewable energy systems are solar power system (photovoltaics) and wind turbines that are popular infrastructure in residential environment.

- Based on the proposed smart home architecture, we introduced the smart grid community, includes power and information, two-way flow located in the terminal distribution power support area. The smart grid community is established on the power infrastructure, as substation, communication block and sub data center.

- The proposed architecture ensures the power grid reliability, especially in the distribution grid recognised as the terminal part of power supply with intricate power consumption status.
- The local power scheduling scheme can help power demand consumer and other power consumers who can serve the demand with locally generated renewable energy, get connection and establish demand-supply channel for local power scheduling between both sides.
- A path selection algorithm was created for the new addition power supply area get connection with the controller of the local smart grid community without too long time delay and keeping the stability of transmission.
- The proposed economic model motivates the government and utilities should increase the investment to the distribution area to deploy more and more local renewable energy systems for encouraging the terminal power consumers to get familiar and use renewable energy.

The realisation of above control mechanism requires connectivity between terminal power consumer and regional power and information controller based on the secondary substation and the primary substation in the distribution grid network. As the second main issue in this thesis, we firstly introduced many kinds of available combination technologies can be employed in the smart grid network, especially in the distribution grid. Hence, in Chapter 4,

- We addressed the available communication standards and technologies, includes power line communication and wireless communication protocols. The disadvantages were also stated in the section.
- We also surveyed on the communication requirements, standards and selected communication technologies that can satisfy the communi-

cation requirements and performance metrics in home area network, neighbourhood area network and wide area network.

As one of the most important communication application in smart grid, advanced metering infrastructure system is carrying the information flow between the terminal power consumer and utilities in the smart grid network. The power saving issue of advanced metering infrastructure is not just related to the power consumption of smart devices in the smart grid, but also can affect the construction of residential information center, the transmission mode of upper communication layer in future. Hence, in Chapter 5,

- We introduced the identification of advanced metering infrastructure (AMI) system and the power saving theory based on IEEE 802.11 Standards.
- Regarding the data transmission mode in AMI system, we presented an updated power saving mode by employing the "page segmentation" mechanism from IEEE 802.11ah standards.
- We also delivered a local stochastic power region division scheduling model, based on two-state-switch scheduling strategy extended the concept of "awake and doze state of communication devices" to the divided power supply regions based on "load balancing" principle.

The fast power charging for electrical vehicles (EV) based on power grid is a quite popular research topic in academia and industry in recent years. In Chapter 6 and Chapter 7,

- We established a new fast power charging station architecture based on employing local renewable energy system. The local generated renewable energy also can serve the power charing demand of EV.

- Considered the ordinary EV daily driving status, we proposed a updated EV public parking campus with the new fast power charging station.
- We also selected the suitable queueing model for the controlling of fast power charging station, and furthermore, we created a new state named "service jumped" to describe the situation that the efficiency of local renewable energy is changed by less predictable natural conditions.
- We further shown a parking campus with fast power charging station profit model to let the utilities and the power consumers can both get benefits from this model.

## 8.2 Future Work

This thesis focused on upgrading the architecture of distribution grid, improving the wireless communication models, and modelling fast power charging stations based on the employment of renewable energy system in smart grid. Also, by giving the basic introduction to many open questions that have not been covered in this thesis, those topics have been identified through the thesis.

### 8.2.1 Automation of Power Substation

The traditional definition of power system automation is the automatic controlling activities realised via instrumentation and control devices in power system. Considered the recent research on microgrid and other proposed architecture models in distribution grid, The automation of power substations became an attracting research topic. The secondary substation is recognised as the power transmission hub in terminal distribution area.

As we discussed in the above, via deploying renewable energy system in terminal distribution area, the secondary substation can be upgraded as local power and information management center. Once the power outage happened on the power lines between primary substation and secondary substation, a short time automatic controlling in the terminal area where the secondary substation is authorized as the management center, would become a challenge to utilities. This comprehensive automatic controlling process includes continuous power supply, alarm to the utilities, and communication in terminal area etc..

### 8.2.2 More Effective Wireless Communication Model

In Chapter 4, we discussed the enabling communication technologies in the smart grid. These preliminary work can help us to continue the establishment of communication links between secondary substation and primary substation, and also the research on transmission grid that has minor concern on wireless communication part.

### 8.2.3 Mobile Stochastic Fast Power Charging Model Based on Consumer's Participation

Renewable energy system is introduced into fast power charging station and parking campus that we presented previously in this thesis. Not just in the public fast power charging stations, but also the residential deployed renewable energy system is accepted as the widely recognised program in many cities. In general, the produced power can not be stored in a long time interval as we expected. So the residential generated renewable energy may become "drop energy" that can not be consumed by power consumer when there is no access power demand in residence. Unscheduled decentralised grid-connected requirement from terminal power consumers may cause disturbance in the power grid. So we propose that the local generated renewable energy can be scheduled grid-connected after the target terminal power consumers submit the requirement and get response from the local power and data management center. The utilities can issue virtualised electronic credits to the terminal power consumers who ”sold” their local generated renewable energy to the utilities. The virtualised electronic credits can be stored in the smart phone application (Apps) as two-dimensional code or barcode. When the consumers has power charging demand for their electric vehicles, the utilities can authorize the drivers to use the virtualised electronic credits in the fast power charging station by scanning the two-dimensional code or barcode stored in the smart phone. Then the EVs can be re-charged without paying by cash or credit card in the fast power charging station. One principle should be highlighted in this process to the terminal power consumers. When the virtualised electronic credits are received and be used in fast power charging station, the utilities will charge service fee from the credits. So it means the virtualised electronic credits can not cover the value of the local generated renewable energy in consumer’s residence. We will explore the consumer’s participation in this process. Also the influence to the controlling system of fast power charging station, especially to the power charging queue, will also be studied.

### 8.2.4 Application of Beidou Navigation Satellite System in Fast Power Charging Station Networks

The Beidou Navigation Satellite System (BDS) is China’s independently developed navigation satellite system in recent years, which can be capable of providing location, navigation, and timing services to users on a continuous global basis [62] [81]. This navigation satellite system is also known as COMPRESS or Beidu-2, which had the previous version called Beidou

Navigation Satellite Experimental System only served the customers in China and neighbouring regions since 2000 [22]. The fully deployed BDS consists of five geostationary earth orbit satellites, twenty-seven medium earth orbit satellites and three inclined geosynchronous satellite orbit satellites [79] [80]. The International Committee on Global Navigation Satellite Systems (ICG) of United Nations has identified Beidou satellite navigation system, the US Global Positioning System (GPS), the Russian GLONASS system (GLONASS) and the European Galileo (Galileo) as the four core global suppliers. The BDS supports both global services and regional services [22]. The global services can be further divided into open service that is similar as GPS and Galileo, and authorized service that requires high reliable usage. Meanwhile, the regional services include wide area differential services that serve high accuracy positioning reaches one meter, and short message service/ positioning report service ensures the BDS user and the BDS station to exchange short messages (currently 240 English characters per message).

Then we would like to try to explore the open questions like finding the nearest fast power charging station for positioning of driving EVs required power re-charging demand. As we all known, the driving EV that has urgent power charging demand should get the accurate location of the nearest fast power charging station to seize the power charging service as soon as possible, especially in the unfamiliar urban or rural environment. The BDS could serve positioning report service to the BDS consumers via employing short message exchange may solve the power shortage challenge that we mentioned. In this positioning and information interactive process, the geographic coordinates of EV itself and several nearby fast power charging stations should be detected, aggregated, and feedback to the EV driver by BDS. Meanwhile, the optimal allocation for establishing new fast power charging station in the existing fast power charging station networks via employing the BDS positioning report service in real-time, is also another popular topic we can seize and study in this research field. Before construct a new fast power charging station in inner city or urban area, besides to consider the estimated traffic and surrounding environment, the optimal location of new fast power charging station in the charging station networks also need to be predicted. Furthermore, the electric vehicle with re-charging demand, should have the chance to move from the long waiting charging queue in one fast power charging station to another fast power charging station that can serve better, via information exchange between this EV and BDS.

# Bibliography

[1] The smart grid: An introduction. Technical report, Department of Energy, Washington D.C., 2011.

[2] Smart grid mandate- standardization mandate to european standardisation organisations (esos) to support european smart grid developement. Technical report, European Commission, 2011.

[3] Consultation on future network technologies research and innovation in horizon 2020. Technical report, European Commission, Brussels, Belgium, June 2012.

[4] U.S. Energy Information Administration. Electric power monthly with data for december 2014. Technical report, U.S. Energy Information Administration, http://www.eia.gov/electricity/monthly/pdf/epm.pdf, February 2015.

[5] Osameh M Al-Kofahi and Ahmed E Kamal. Survivability strategies in multihop wireless networks [accepted from open call]. *Wireless Communications, IEEE*, 17(5):71–80, 2010.

[6] ZigBee Alliance. Ieee 802.15. 4, zigbee standard. *On http://www. zigbee. org*, 2009.

[7] Zigbee Alliance. Zibgee smart energy overview, 2011.

[8] S Massoud Amin and Bruce F Wollenberg. Toward a smart grid: power delivery for the 21st century. *Power and Energy Magazine, IEEE*, 3(5):34–41, 2005.

[9] G Andersson, P Donalek, R Farmer, N Hatziargyriou, I Kamwa, P Kundur, N Martins, J Paserba, P Pourbeik, J Sanchez-Gasca, et al. Causes of the 2003 major grid blackouts in north america and europe, and recommended means to improve system dynamic performance. *Power Systems, IEEE Transactions on*, 20(4):1922–1928, 2005.

[10] IEEE Standard Association et al. Ieee 802.22-2011 standard for wireless regional area networks in tv white spaces completed, 2011.

[11] Sanzhong Bai, Du Yu, and Srdjan Lukic. Optimum design of an ev/phev charging station with dc bus and storage system. In *IEEE 2010 Energy Conversion Congress and Exposition*, pages 1178–1184, 2010.

[12] I Safak Bayram, George Michailidis, Michael Devetsikiotis, Subhashish Bhattacharya, Aranya Chakrabortty, and Fabrizio Granelli. Local energy storage sizing in plug-in hybrid electric vehicle charging stations under blocking probability constraints. In *Smart Grid Communications (SmartGridComm), 2011 IEEE International Conference on*, pages 78–83. IEEE, 2011.

[13] I Safak Bayram, George Michailidis, Michael Devetsikiotis, Fabrizio Granelli, and Subhashish Bhattacharya. Smart vehicles in the smart grid: Challenges, trends, and application to the design of charging stations. In *Control and Optimization Methods for Electric Smart Grids*, pages 133–145. Springer, 2012.

[14] Islam Safak Bayram. *A three-layered system level modeling approach to electric transportation.* North Carolina State University, 2013.

[15] Roberto Benato and Roberto Caldon. Application of plc for the control and the protection of future distribution networks. In *Power Line Communications and Its Applications, 2007. ISPLC'07. IEEE International Symposium on*, pages 499–504. IEEE, 2007.

[16] Lars Torsten Berger, Andreas Schwager, and J Joaquín Escudero-Garzás. Power line communications for smart grid applications. *Journal of Electrical and Computer Engineering*, 2013:3, 2013.

[17] Gunter Bolch, Stefan Greiner, Hermann de Meer, and Kishor S Trivedi. *Queueing networks and Markov chains: modeling and performance evaluation with computer science applications.* John Wiley &amp; Sons, 2006.

[18] Godfrey Boyle. *Renewable energy.* OXFORD university press, 2004.

[19] Nicola Bressan, Leonardo Bazzaco, Nicola Bui, Paolo Casari, Lorenzo Vangelista, and Michele Zorzi. The deployment of a smart monitoring system using wireless sensor and actuator networks. In *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, pages 49–54. IEEE, 2010.

[20] Gerd Bumiller, Lutz Lampe, and Halid Hrasnica. Power line communication networks for large-scale control and automation systems. *Communications Magazine, IEEE*, 48(4):106–113, 2010.

[21] Carlo Cecati, Costantino Citro, and Pierluigi Siano. Combined operations of renewable energy systems and responsive demand in a smart grid. *Sustainable Energy, IEEE Transactions on*, 2(4):468–476, 2011.

[22] Li Chengzhi. The chinese gnss—system development and policy analysis. *Space Policy*, 29(1):9–19, 2013.

[23] European Commssion. Energy price statistics. Technical report, European Commssion, 2012.

[24] Thomas H Cormen, Charles E Leiserson, Ronald L Rivest, and Clifford Stein. *Introduction to algorithms*. MIT press, 2009.

[25] US DOE. Ev everywhere grand challenge blueprint. *US Department of Energy. January*, 31, 2013.

[26] LR Dohn. *The business case for microgrids White paper: The new face of energy modernization, sl: Siemens AG*, 2011.

[27] Omar Ellabban, Haitham Abu-Rub, and Frede Blaabjerg. Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*, 39:748–764, 2014.

[28] Zhong Fan, Georgios Kalogridis, Costas Efthymiou, Mahesh Sooriyabandara, Mutsumu Serizawa, and Joe McGeehan. The new frontier of communications research: Smart grid and smart metering. In *Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking*, pages 115–118. ACM, 2010.

[29] Zhong Fan, Parag Kulkarni, Sedat Gormus, Costas Efthymiou, Georgios Kalogridis, Mahesh Sooriyabandara, Ziming Zhu, Sangarapillai Lambotharan, and Woon Hau Chin. Smart grid communications: Overview of research challenges, solutions, and standardization activities. *Communications Surveys &amp; Tutorials, IEEE*, 15(1):21–38, 2013.

[30] Xi Fang, Satyajayant Misra, Guoliang Xue, and Dejun Yang. Smart grid—the new and improved power grid: A survey. *Communications Surveys &amp; Tutorials, IEEE*, 14(4):944–980, 2012.

[31] Hassan Farhangi. The path of the smart grid. *Power and Energy Magazine, IEEE*, 8(1):18–28, 2010.

[32] Hendrik C Ferreira, Henricus M Grové, Olaf Hooijen, and AJ Han Vinck. *Power line communication.* Wiley Online Library, 1999.

[33] Peter Fox-Penner. *Smart Power Anniversary Edition: Climate Change, the Smart Grid, and the Future of Electric Utilities.* Island Press, 2014.

[34] Stefano Galli, Anna Scaglione, and Zhifang Wang. Power line communications and the smart grid. In *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, pages 303–308. IEEE, 2010.

[35] Hamid Gharavi and Bin Hu. Multigate mesh routing for smart grid last mile communications. In *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*, pages 275–280. IEEE, 2011.

[36] A Ghassemi, S Bavarian, and L Lampe. Cognitive radio for smart grid communications. In *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, pages 297–302. IEEE, 2010.

[37] Arunabha Ghosh, David R Wolter, Jeffrey G Andrews, and Runhua Chen. Broadband wireless access with wimax/802.16: current performance benchmarks and future potential. *Communications Magazine, IEEE*, 43(2):129–136, 2005.

[38] Vincenzo Giordano, Flavia Gangale, Gianluca Fulli, M Sánchez Jiménez, I Onyeji, A Colta, I Papaioannou, A Mengolini, C Alecu,

T Ojala, et al. *Smart Grid projects in Europe: lessons learned and current developments.* Citeseer, 2011.

[39] Hadi Goudarzi, Safar Hatami, and Massoud Pedram. Demand-side load scheduling incentivized by dynamic energy prices. In *Smart Grid Communications (SmartGridComm), 2011 IEEE International Conference on*, pages 351–356. IEEE, 2011.

[40] European Technology Platform Smart Grids. Smartgrids sra 2035 strategic research agenda. Technical report, European Technology Platform Smart Grids, 2012.

[41] Donald Gross. *Fundamentals of queueing theory.* John Wiley &amp; Sons, 2008.

[42] Vehbi C Gungor, Bin Lu, and Gerhard P Hancke. Opportunities and challenges of wireless sensor networks in smart grid. *Industrial Electronics, IEEE Transactions on*, 57(10):3557–3564, 2010.

[43] Vehbi C Gungor, Dilan Sahin, Taskin Kocak, Salih Ergut, Concettina Buccella, Carlo Cecati, and Gerhard P Hancke. Smart grid technologies: communication technologies and standards. *Industrial informatics, IEEE transactions on*, 7(4):529–539, 2011.

[44] David A Hein. System and method for evaluating vehicle charging circuits, April 30 2013. US Patent 8,432,175.

[45] Ekram Hossain, Zhu Han, and H Vincent Poor. *Smart grid communications and networking.* Cambridge University Press, 2012.

[46] David Howell. Current fiscal year (2012–2013) status of the hybrid and electric systems r&amp;d at the us–doe.

[47] IEEE. Ieee, part 11: Wireless lan medium access control (mac) and physical layer (phy) specification. *IEEE Std.*, 2012.

[48] Justine Järvinen, Fiona Orton, and Tim Nelson. Electric vehicles in australia's national electricity market: energy market and policy implications. *The Electricity Journal*, 25(2):63–87, 2012.

[49] Fan Jiang and Benchao Wang. A load balancing relay selection algorithm for relay based cellular networks. In *Wireless Communications, Networking and Mobile Computing (WiCOM), 2011 7th International Conference on*, pages 1–5. IEEE, 2011.

[50] Carlee Joe-Wong, Soumya Sen, Sangtae Ha, and Mung Chiang. Optimized day-ahead pricing for smart grids with device-specific scheduling flexibility. *Selected Areas in Communications, IEEE Journal on*, 30(6):1075–1085, 2012.

[51] Sung-Kwan Joo, Jang-Chul Kim, and Chen-Ching Liu. Empirical analysis of the impact of 2003 blackout on security values of us utilities and electrical equipment manufacturing firms. *Power Systems, IEEE Transactions on*, 22(3):1012–1018, 2007.

[52] Ji-Sun Jung, Keun-Woo Lim, Jae-Beom Kim, Young-Bae Ko, Younghyun Kim, and Sang-Yeom Lee. Improving ieee 802.11 s wireless mesh networks for reliable routing in the smart grid infrastructure. In *Communications Workshops (ICC), 2011 IEEE International Conference on*, pages 1–5. IEEE, 2011.

[53] Navid Tafaghodi Khajavi and SM-S Sadough. Improved spectrum sensing and achieved throughputs in cognitive radio networks. In *Wireless Advanced (WiAD), 2010 6th Conference on*, pages 1–6. IEEE, 2010.

[54] David M Laverty, D John Morrow, Robert Best, and Peter A Crossley. Telecommunications for smart grid: Backhaul solutions for the

distribution network. In *Power and Energy Society General Meeting, 2010 IEEE*, pages 1–6. IEEE, 2010.

[55] Khaled Letaief and Wei Zhang. Cooperative communications for cognitive radio networks. *Proceedings of the IEEE*, 97(5):878–893, 2009.

[56] Yu-Ju Lin, Haniph A Latchman, Minkyu Lee, and Srinivas Katar. A power line communication network infrastructure for the smart home. *Wireless Communications, IEEE*, 9(6):104–111, 2002.

[57] Marco Liserre, Thilo Sauter, and John Y Hung. Future energy systems: Integrating renewable energy sources into the smart power grid through industrial electronics. *IEEE Industrial Electronics Magazine*, pages 18–37, 2010.

[58] João A Peças Lopes, Filipe Joel Soares, and Pedro Miguel Rocha Almeida. Integration of electric vehicles in the electric power system. *Proceedings of the IEEE*, 99(1):168–183, 2011.

[59] James F Miller and David Howell. The ev everywhere grand challenge.

[60] Parimita Mohanty, G Bhuvaneswari, and R Balasubramanian. Optimal planning and design of distributed generation based micro-grids. In *Industrial and Information Systems (ICIIS), 2012 7th IEEE International Conference on*, pages 1–6. IEEE, 2012.

[61] James Momoh. *Smart grid: fundamentals of design and analysis*, volume 63. John Wiley &amp; Sons, 2012.

[62] Oliver Montenbruck, André Hauschild, Peter Steigenberger, Urs Hugentobler, Peter Teunissen, and Shinichi Nakamura. Initial assessment of the compass/beidou-2 regional navigation satellite system. *GPS solutions*, 17(2):211–222, 2013.

[63] Amir Motamedi, Hamidreza Zareipour, and William D Rosehart. Electricity price and demand forecasting in smart grids. *Smart Grid, IEEE Transactions on*, 3(2):664–674, 2012.

[64] Dusit Niyato, Ping Wang, and Ekram Hossain. Reliability analysis and redundancy design of smart grid wireless communications system for demand side management. *Wireless Communications, IEEE*, 19(3):38–46, 2012.

[65] Dusit Niyato, Lu Xiao, and Ping Wang. Machine-to-machine communications for home energy management system in smart grid. *Communications Magazine, IEEE*, 49(4):53–59, 2011.

[66] European Parliament. Directive 2006/32/ec of the european parliament and of the council on energy end-use efficiency and energy services and repealing council directive 93/76/eec. Technical report, European Parliament, 2012.

[67] P Ponticel. Sae standard on ev charging connector approved. *Automotive engineering online, Accessed*, 15, 2010.

[68] Heike Proff and Dminik Kilian. *Competitiveness of the EU automotive industry in electric vehicles*. University of Duisburg-Essen, 2012.

[69] Raghuram Ranganathan, Robert Qiu, Zhen Hu, Shujie Hou, Marbin Pazos-Revilla, Gang Zheng, Zhe Chen, and Nan Guo. Cognitive radio for smart grid: Theory, algorithms, and security. *International Journal of Digital Multimedia Broadcasting*, 2011, 2011.

[70] Thilo Sauter and Maksim Lobashov. End-to-end communication architecture for smart grids. *Industrial Electronics, IEEE Transactions on*, 58(4):1218–1228, 2011.

[71] Stefania Sesia, Issam Toufik, and Matthew Baker. *LTE: the UMTS long term evolution*. Wiley Online Library, 2009.

[72] Young-Sung Son, Topi Pulkkinen, Kyeong Deok Moon, and Chaekyu Kim. Home energy management system based on power line communication. *Consumer Electronics, IEEE Transactions on*, 56(3):1380–1386, 2010.

[73] Junseok Song, Amir Toliyat, D Turtle, and Alexis Kwasinski. A rapid charging station with an ultracapacitor energy storage system for plug-in electrical vehicles. In *Electrical Machines and Systems (ICEMS), 2010 International Conference on*, pages 2003–2007, 2010.

[74] Weiping Sun, Munhwan Choi, and Sunghyun Choi. Ieee 802.11 ah: A long range 802.11 wlan at sub 1 ghz. *Journal of ICT Standardization*, 1(1):83–108, 2013.

[75] M Thaker and A Roland. Internet standards come to the advanced metering infrastructure, 2011.

[76] Michail Vasiladiotis, Alfred Rufer, and Antoine Béguin. Modular converter architecture for medium voltage ultra fast ev charging stations: Global system considerations. In *Electric Vehicle Conference (IEVC), 2012 IEEE International*, pages 1–7. IEEE, 2012.

[77] Don Von Dollen. Report to nist on the smart grid interoperability standards roadmap. *Prepared by the Electric Power Research Institute for NIST (June 2009)*, 2009.

[78] Wenye Wang, Yi Xu, and Mohit Khanna. A survey on the communication architectures in smart grid. *Computer Networks*, 55(15):3604–3629, 2011.

[79] Zhen Dao Wang, Qi Jia Zhou, and Zhong Zhou Ruan. Design of vehicle location and communication system based on beidou navigation satellite system (bds). In *Applied Mechanics and Materials*, volume 610, pages 814–821. Trans Tech Publ, 2014.

[80] Aigong Xu, Zongqiu Xu, Maorong Ge, Xinchao Xu, Huizhong Zhu, and Xin Sui. Estimating zenith tropospheric delays from beidou navigation satellite system observations. *Sensors*, 13(4):4514–4526, 2013.

[81] YuanXi Yang, JinLong Li, AiBing Wang, JunYi Xu, HaiBo He, HaiRong Guo, JunFei Shen, and Xian Dai. Preliminary assessment of the navigation and positioning performance of beidou regional navigation satellite system. *Science China Earth Sciences*, 57(1):144–152, 2014.

[82] Kalid Yunus, H Zelaya De La Parra, and Muhamad Reza. Distribution grid impact of plug-in electric vehicles charging at fast charging stations using stochastic charging model. In *Power Electronics and Applications (EPE 2011), Proceedings of the 2011-14th European Conference on*, pages 1–11. IEEE, 2011.

[83] Yan Zhang, Rong Yu, Maziar Nekovee, Yi Liu, Shengli Xie, and Stein Gjessing. Cognitive machine-to-machine communications: visions and potentials for the smart grid. *Network, IEEE*, 26(3):6–13, 2012.

[84] Xu Zhichao and Li Xiaoming. The construction of interconnected communication system among smart grid and a variety of networks. In *Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific*, pages 1–5. IEEE, 2010.

[85] Ziming Zhu, Sangarapillai Lambotharan, Woon Hau Chin, and Zhong Fan. Overview of demand management in smart grid and en-

abling wireless communication technologies. *Wireless Communications, IEEE*, 19(3):48–56, 2012.