Design and Development of Energy Management System for Smart Homes & Buildings

by

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To my wife and parents

Abstract

The smart grid, as the next generation of power grid, has redefined the positions of the homes and buildings in the contexts of a whole energy system. With the increasing installation of Distributed Energy Resources (DERs) and retention of Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs), the energy system of homes and buildings in power distribution network is becoming more and more complex. Nonetheless, benefiting from the upgrades on the IT-based devices such as smart meters, smart appliances and Phase Measurement Units (PMUs) in home, building, electricity distribution network and transmission network, the smart homes and buildings obtain the opportunities in taking more responsibilities in the whole power grid, and are facing the transition from the passive clients to the active participants. In addition, the further promotion of the modern electricity tariffs such as Time-of-Use (TOU), Critical-Peak Pricing (CPP) and Real-Time Pricing (RTP), also enlarges the demands of customers in managing the loads and DERs within the smart homes and buildings from both financial and environmental points of view. Thus, the Energy Management System (EMS), acting as the 'manager' in the smart homes and buildings, will afford the challenging responsibilities in helping customers optimise the operation of devices and creating new value streams to the smart grid.

In order to find the efficient and effective way for managing the appliances and DERs in smart homes and buildings through the EMS, the pathway of the thesis is to investigate the optimisation and control approaches of EMS from controlling the

specific loads in homes, to fully optimising the operation of both loads and DERs in smart homes, and at last coordinating the EMSs in the buildings through the aggregator.

The control method of the space heating system with EMS is proposed in chapter 3, utilising the Genetic Algorithm (GA) to reduce the energy costs and improve the living comforts. Afterwards, a real-time control approach of EMS, considering the emerging Demand Side Management (DSM) service – RTP and Demand Response (DR), is presented in chapter 4. The proposed control approach combines the rolling optimisation (RO), Real-Time Control Strategy (RTCS) and Fuzzy Logic control, which can automatically control the devices in home and efficiently join the DR program. The physical EMS platforms for testing the two control approaches presented in chapter 3 and 4 are established in the lab respectively. The tests results based on the physical platforms prove the feasibilities of the two proposed EMSs. At last, a novel aggregator service for residential apartment building is introduced in chapter 5. Through centrally managing the EVs, battery energy storage system (BESS) and renewable generators in the building, the aggregator effectively reduces the total electricity import from the grid, so as to maximize the usage of the renewable generations and battery system. Tested with the main stream electricity tariffs, the aggregator can provide financial benefits to both energy users and stakeholders of the DERs.

Acknowledgement

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List of Abbreviations

ACHE	Adaptive Control of Home Environment
BEMS	Building Energy Management System
BESS	Battery Energy Storage System
CAN	Controller Area Network
CAGR	Compound Annual Growth Rate
CPP	Critical Peak Pricing
DER	Distributed Energy Resources
DLC	Direct Load Control
DSM	Demand Side Management
DR	Demand Response
EMS	Energy Management System
EPC	Energy Performance Certificates
ESS	Energy Storage System
EV	Electric Vehicle
FIT	Feed-in Tariff
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
HEMS	Home Energy Management System
HVAC	Heating, Ventilating, and Air Conditioning
ICT	Information and Communications Technology
IP	Internet Protocol

LPG	Lowest Price Guarantee
MIP	Mixed Integer Programming
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
OFGEM	Office of Gas and Electricity Markets
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Power Line Communication
PMU	Phase Measurement Unit
PV	Photovoltaic
RO	Rolling Optimization
RTCS	Real-time Control Strategy
RTP	Real – time Pricing
TCP	Transmission Control Protocol
TOU	Time of Using
V2G	Vehicle to Grid
VPP	Virtual Power Plant

Chapter 1 Introduction

1.1 Background and Motivations

It is evident that EMS can effectively assist grid operators to optimise the performance of the electric utilities, power plants and the power grid transmission & distribution networks. However, with the widespread installation of large renewable energy systems, such as wind farms and solar farms, the power grid is facing new challenges in balancing the demand and supply due to the intermittent nature of renewable energy. At the same time, the wide adoption of DERs (e.g. Roof PV system, Energy Storage Systems and Electric Vehicles) also increases the difficulties for the Distributed Network Operators (DNOs) in managing the power flow through the aging electricity assets.

Much progress has been made in ICT technology and control technology to help deliver on the promise of 21st century power grid - the 'smart grid', which has been defined as the standard for the modern power grid by Europe, US and many other countries. Compared with the traditional power grid, the topology of the smart grid is decentralized rather than centralized. The decentralized topology of the power network enhances the effects of distribution network and correspondingly reduces the dependence of the distribution network customers on the power supply from the large power plants and transmission network. Furthermore, the smart grid, relying more on the modern ICT and control techniques, is expected to promote the implementation of smart homes and buildings through the ICT devices, so as to encourage the customers interact with the grid operator and play a more active role in maintaining the power network.

Therefore, in order to link the end users to the system operators, the EMS is no longer the exclusive tool for the grid operators, but starting to be implemented in the smart homes and buildings. Due to the complex environments in the house and buildings, the execution of the EMS for smart homes and buildings became a hot topic in both academic and industry with yet many challenges to tackle. The general structure and operation mechanism of EMS in homes and buildings was illustrated in [1, 2]. The sensor and control network within the smart homes and building is considered as the foundation of EMS, which provides the possibilities for executing EMS. With the rise of personal area network technologies, the sensor and control network is easy to be built in homes and buildings, and thereby promotes the installation of EMS.

Furthermore, it should be mentioned that the modern electricity tariffs, DR program and other programs promoted by Demand Side Management (DSM) draw a larger blueprint for EMS. Various value streams are created by DSM, which offer EMS different approaches to serve the customers. It helps EMS act not only as the 'major-domo' in scheduling the local loads but also as a 'diplomat' between end users and energy suppliers or operators. For instance, the traditional optimisation way of the local loads with renewable resources such as roof PV by EMS is to use the PV generation as much as possible through scheduling the loads operation. Nevertheless, after the DR program is introduced, the EMS can negotiate with the DNOs to sell the spare PV generation with a considerable price rather than use it out locally. Furthermore, the RTP and other float tariffs, which require the real-time communication and control capability of EMS, endue a better flexibility to the households. The end users can enjoy even cheaper energy during off-peak time compared with the general tariffs. But meanwhile, all these new features bring new challenges to the EMS for smart home and buildings. The real-time control, data prediction and responding mechanism of EMS are becoming the emerging but critical areas in the EMS research. Last but not least, according to the communication infrastructure of EMSs employed in smart home and buildings, the coordination of large amount of EMSs is achievable [3]. The constellation effect can be formed by coordinating the different EMSs, and correspondingly enhance the efficiency of smart home and buildings in joining the emerging energy service. The aggregator, also named as coordinator, acts as the representative of the EMSs to communicate with the energy suppliers or DNOs. With the assistance of aggregator, the EMSs of smart home and buildings can trade with each other through separate billing system and entry the electricity market, creating new revenue streams. Considering the mass coordinating, control and management work, the research in management, trading and profiting mechanism of the aggregator with the EMSs is becoming increasingly important.

According to the discussion presented above, the motivations of the thesis can be concluded as follows.

(1) The risk of grid demand and supply unbalance caused by the wide adoption of renewable energy systems;

(2) The increasing demands of smart home and building owners in automatically managing the loads and DERs;

(3) The needs in exploring the solutions to respond to the emerging DSM service;

1.2 Research Focus, Objectives & Contributions

The research presented in the thesis aims to explore the efficient energy management and control approach to the loads and DERs in smart homes and buildings through EMS, so as to balance the demand and supply, reduce the energy costs and improve the efficiency of DERs.

The objectives of the research work can be summarised as follows.

- Electric Heater (EH) is a common household appliance in homes and buildings, but consumes large amount energy. Although a lot of algorithms and control approaches have been proposed on the energy management of EHs, few of the methods focus on the control of the pre-heating periods. However, benefiting from the development of ICT and wireless control techniques, the pre-heating period of EHs is becoming controllable. Especially with the promotion of the float electricity tariff, the control on pre-heating periods of EHs can help customers save the electricity bills by efficient scheduling of EHs during pre-heating periods. Therefore, an effective and feasible methodology for managing the pre-heating periods of EHs is expected to be established in the study.

- The Demand Response (DR) service, an important part of Demand Side Management (DSM), is becoming increasingly popular in smart homes recently. Nonetheless, it is difficult to ask customers to interrupt the operation of household appliances and DERs in homes manually to response the DR Service. A number of methods have been proposed to help customers respond the DR Service automatically, but most of these proposed methods are lack of the real-time adjustment capability in processing the change of working sates of household appliances. Thus, a real-time HEMS which can effectively process the DR events is expected to be implemented in the study.

- An increasing number of roof PV, small wind systems and other DERs have been installed in residential houses; however, the promotion of DERs in residential apartment buildings is restricted serious barriers such as poor economic advantages, complex ownerships and outdated billing systems. Therefore, a profit mechanism for residential apartment building is expected to be established in the study.

The contributions of the research work can be summarised as follows.

- A GA based control method is presented to optimise the operation of space heating system in smart home, and improve the living comforts of residents with consideration of the dynamic electricity tariff. A hardware based EMS solution for the space heaters is presented as well, aiming to support the execution of the proposed control method.

- A real-time control approach is proposed for managing the loads and DERs in house, utilising the RO, RTCS and fuzzy logic control to minimise the electricity bills, and help the households respond to the DR program automatically. The physical platform including EMS, communication network, control unit and physical loads and DERs is built up in the lab, which is utilized to validate the feasibility of proposed control approach.

- An aggregator service is put forward for residential apartment building, which creates a novel control and billing mechanism to solve the DER promotion problems in residential apartment buildings. Three electricity tariffs (Flat Rate tariff, TOU and RTP) are tested with the aggregator service; the results indicated that the proposed aggregator service effectively enhances the profitability of installed DERs and reduces the energy bills for residents.

1.3 Thesis Outline

Chapter 1

Research background is introduced at first, and then the motivation of the thesis is given. Later on, the research focus and contributions are summarised.

Chapter 2

The development of smart homes & buildings, communication and control network within smart homes and buildings, working mechanism and features of EMS and current situation of DERs are reviewed in this chapter.

Chapter 3

The GA based control method for the space heating system of smart home is proposed in this chapter. The working mechanism of general space heaters and the indoor thermal model are presented too, which support the development of the proposed control method. In addition, a ZigBee based physical EMS platform is introduced to execute the proposed control method.

Chapter 4

In this chapter, a real-time control approach for smart home EMS based on RO and RTCS is proposed. The mathematic model of the household appliances, EV and battery systems are introduced, and the FLC for the battery is designed. A demand response mechanism is built in the control approach as well, which provides the capability of joining the DR program to the users. The smart home EMS platform built in the lab, including EV, PV, dynamic loads and battery system, is introduced as well. The test result of the proposed control approach on the physical platform is discussed.

Chapter 5

A novel aggregator service for a residential apartment building is presented. With the assistance of central control platform in the aggregator, the aggregator alone is capable of managing the EVs, PV and battery system without the help of individual EMS installed in the apartments. Besides, as combining the apartments in the building as one utility, an inside trading mechanism is formed by the aggregator and different tariffs are offered to the residents. The cases presented in this chapter indicate that the aggregator brings benefits to both residents and stakeholders of the DERs under different electricity tariffs, and correspondingly shorten the pay-back period of the investment on DERs in the buildings.

Chapter 6

The summary of the entire thesis is presented, and the future research work is discussed in this chapter.

Chapter 2 Literature Review

2.1 Historical Development of Smart Homes & Buildings

The concept of smart homes/buildings has existed for many years, which comes from home/building automation, enabling people control the lights, gate, HVAC and other households through intelligent controller go-as-you-please [4]. However, due to the limitation of electric, electronic, communication, computer and control techniques, the smart homes & buildings were difficult to be established before early 20th Century [5]. Along with the widespread of electrical appliance such as TV, HVAC, wash machine, and cloth dryer during 1920s-1960s, the establishment of smart homes/buildings began to have a solid physical basis [6]. Correspondingly, X10, the first communication protocol for home appliances through power line, was established in 1975, aiming to help people easily control their household devices [7]. With the assistance of X10, the home appliances can be monitored and controlled using the 22-bit long data package transmitted on the power line. Since 1980, the realisation of operating home appliances through the assorted interface on the personal computer is regarded as the rudiment of Smart Home [8]. After 1990s, with the springing up of ICT, the telecommunication technique, wireless communication technique and Internet technique were able to integrated into the smart home/building systems in succession [9]. A number of wire/wireless communication protocols for household devices such as CEBus, LONWorks, IEEE 802.11 Wireless LAN, Bluetooth and Home RF, were invented during the last ten years in 20th century [9]. However, the prices of computer, microcontroller and communication components were too high to be used in smart home system during the last decade, which restricts the introduction of smart home system into normal people's life [10].

Started form the 21st Century, because of the rapid development of ICT and reduction in price of related electronic components, the smart home and smart home related products, such as wireless power socket, automatic lighting systems and thermal controllers, became affordable for ordinary customers [11]. In addition, the USA president Obama put forward the concept of smart grid in 2008, and aims at building a smart self-monitoring, cost-effective and environment-friendly power grid with the assistance of modern IT and renewable energy techniques, which makes smart grid become greatly attractive for both industry and academic [12]. In addition, as the integral factor of the smart grid, smart home has also received more attention than before [13]. It is worth noting that the modern smart home is tagged as the terminal link between customers and smart grid since the smart grid was proposed. Therefore, it will not only regarded as a home automation system but also as a manager of renewable energy resources or other distributed energy resources [14, 15]. With the integration of smart metering, IT technique and other advanced control techniques, the smart home will be able to promote the renewable energy systems and providing end users variable tariffs and other power services from the smart grid perspective [16-19].

According to the prediction of smart home market by market analyst companies ABI and Berg Insight, the market size of smart home products including smart metering, sensors and other components will reach $44 Billion in 2016 [20]. As an inviting market, a large number of leading companies, such as Google, Microsoft, Cisco, Apple and GE, have started to develop and launch their smart home products in order to occupy the smart home & building market.

2.2 EMS in Smart Homes & Buildings

Since the price rise of fuels and the pressure in reducing CO2 emission, the energy suppliers provide various tariffs and service to encourage their customers to reduce and manage their energy consumption efficiently, such as shifting the load or install their own DERs. Additionally, increasing installation of DERs in house and buildings, including solar system, small wind turbine and ESS, had made the energy consumption greener, but more difficulties have also appeared about their management than before. Although lots of efforts on the smart metering installation in distribution network have been made, the customers are still facing great challenges about managing the energy consumption efficiently since this new systems will change these energy using habits of them. Additionally, the energy bills have become heavy burdens to the residents. It has been reported by the OFGEM that the UK residential energy bills had reached £1200 per household per year in 2013 [21]. To exploit the opportunities for helping customers manage their devices and DERs in homes and buildings, more future investigations on design and development of HEMS and BEMS are required to be carried out in both industrial and academics areas

It was reported by [22] that the EMS market (HEMS, BEMS, enterprise EMS etc.) has achieved $17.4 billion in 2013, and this number is expected to increase to $38.49 billion in 2018, of which the Compounded Annual Growth Rate (CAGR) will be counted for 17.2%. The EMS products can provide various features and services to the customers. The most common function is to monitor the energy consumption of installed devices and control the operation states of the devices according to the environment and time factors. Some other functions (such as shifting the spare green energy to heat water) have been developed and realised in EMS as well. With the spread of the RTP, Demand Response Service (DRS) and other advanced tariffs or power services, more effective energy optimization functions, such like real-time monitoring & optimization functions, will be able to have core supporting techniques for further development.

2.2.1 Load Management

Served as a critical part of DSM, load management is an indispensable part for reducing peak load and back-up power plant. Hence, governments and EMS manufacturers' have drawn a lot of interests on its investigation and development. For load management, controllable loads such as air conditioning, space heater, water boiler, PHEV, EV and other residential appliances have been concerned as the main aspects. In addition, the rise of DERs drives the EMS providers to improve the capability of EMS in managing the loads with DERs.

On an economic level, the motivation of managing the loads by end users is to reduce the costs of energy consumption and increase the profitability of the installed DERs. Moreover, as a benefit of load management in distribution network, the energy market can act as main energy suppliers that could also reduce their risks of paying extra money for the balancing power. In order to promote the load management of Demand Side Management (DSM), the energy suppliers provide various tariffs with flexible prices rather than constant prices to customers. In this way, customers can be encouraged to make their energy consumption plans based on the electricity prices. Even though the electric prices of different tariffs vary from country to county, the electricity tariffs can be generally classified into three types – TOU, RTP and CPP (shown in Figure 2-1) according to the pricing mechanisms.

(1) The TOU tariff defines the electricity price according to specific time periods within a day, and each time period corresponds to a fixed price which is decided by the power grid demands level (e.g. Off-peak, mid-peak and peak). This kind of time-based pricing service is aimed at encouraging customers shift their energy consumption from peak time to off-peak through price incentive.

(2) The RTP price changes everyone or half hour, is determined by the real price in the energy wholesale market. The customers would obtain the predicted day-ahead RTP price to plan their energy use in advance.

(3) The CPP tariff is similar to TOU, but has a critical peak time with a higher price than the peak time price in TOU.

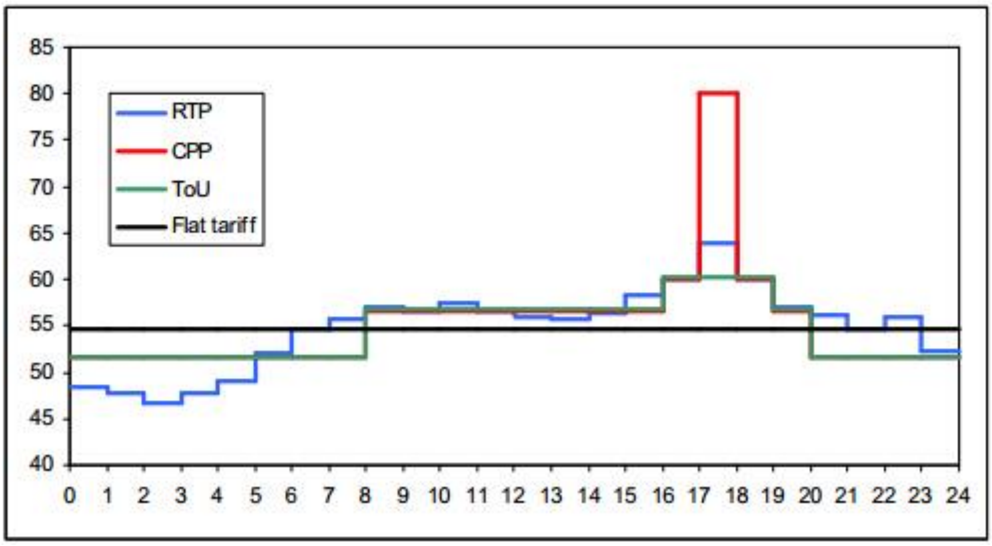

Figure 2-1 Examples of RTP, CPP and TOU [23]

According to the pricing principles of TOU, RTP and CPP, customers need to make estimations or measurements of utilities if they want get economic benefit from the flexible tariffs. However, it is difficult to make customers control their loads timely or change their energy consumption habits to response the changing tariffs. Therefore, the load management feature is developed as the important part of EMS to help customers manage their utility automatically and smartly with the assistances of the automatic monitor, plan and control systems. With the wide installation of smart meters and the adoption of Smart Home & Building systems, a solid platform is established for providing various modern electricity tariffs. The load management can be introduced as a service in EMS, which optimizes the load operation plan based on the collected data and request the device execute the plan through the physical area network.

A multi-strategy Load Management System has been proposed in [24], the stand-by power cutting and load shifting based on flattening and spot-price are provided to customers to give them multiple choices on managing their loads. Through the machine learning and pattern recognition methods, the loads can be managed based on the consideration of both living comforts and price information as shown in Figure 2-2 [25]. The multi-agent decision making method is another essential approach for managing the different types of loads and generators in building. It helps the DERs effectively interact with the loads, and thus improves the flexibility of the energy system in building and reduce the energy bills [26]. Furthermore, the fuzzy logic, neutral network and other modern control and optimization approaches are introduced to the load management in smart home, buildings and communities as well [27, 28]. An adaptive control of home environments (ACHE) system was proposed in [27], which maintains the living comforts of inhabitants and minimises the energy consumption with the assistance of neural network. In order to provide promising service of Demand Side Management (DSM) and Demand Response (DR) to the customers, [28] proposed a building energy management system (BEMS) using agent-based control strategy and fuzzy rule based decision making system. The agents can perform their duties to the corresponding parts of the building, and the decision making system can coordinate the agents to achieve the desired global goals, so that the BEMS can be optimized to exploit the demand flexibility of the buildings [28].

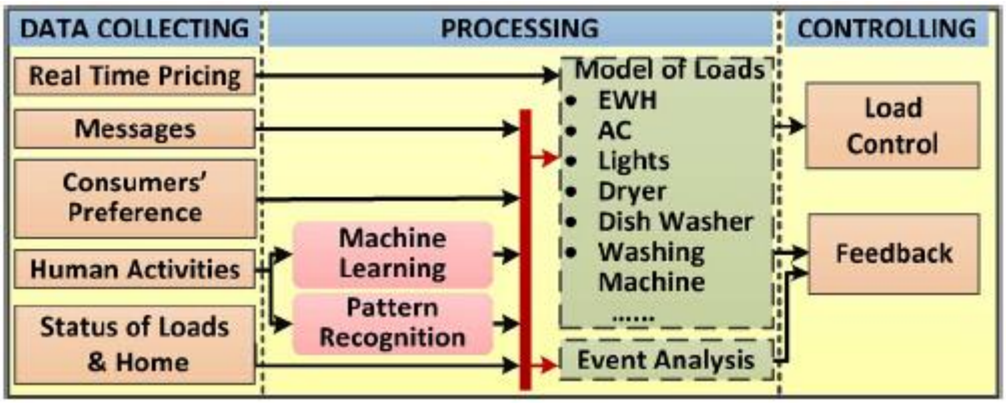

Figure 2-2 Load Management Process [25]

2.2.2 Emergency Demand Response

Even though load management can help the system operator balance the power grid in long term; the short-term imbalance between demand and supply still exists, especially in the condition of the wide installation of renewable resources. Large scale DR programs used for power plants or large energy consumers have been proved that such programs can improve the stability of the grid and reduce the energy cost for the customers [29]. As a consequence of the penetration of renewable generators in distribution network, the significant variation of renewable energy capacity output would increase the risk of network instability (e.g. Voltage Variation, Congestion). Therefore, the DR programs are introduced to the end user customers, such as residents and small commercial building owners, which supposed to solve the increasingly serious imbalance problems and formulate a ‘smarter’ grid.

UK has applied the DR program in the distribution network; a voltage-driven DR program has been presented in [30], which included hundreds of residential customers and a number of commercial and industrial customers. The Federal Energy Regulatory Commission of USA indicated that the growth of DR for residential uses has increased 13% from 2010 to 2012, reaching 8,134MW [31]. Most of the DR programs in USA for residential users are based on float rating tariff and DLC [31]. For instance, the float rating tariffs including the Real-Time Pricing (RTP), Critical Peak Pricing (CPP) and Time-of-Use (TOU) Pricing have been applied in US to encourage customers reduce their energy consumption to shift peak load from price incentive point of view. In Norway, the country which has successfully applied DR programs for large energy consumers, is considering the promotion of DR to residential customers [32]. The pilot study in [33] shows that the aggregated demand response from controlling the water heaters in half of the households, could reduce 4.2% of the registered peak load demand in Norway. As an emerging energy service, researchers have done a lot of research work in DR program as well.

[34] applies a two-state Markov Chain mode to predict both long-term and short-term energy consummation for 60,000 residential customers in USA in order to support the demand response estimation. In [35], a novel DR program has been introduced based

on coupon-incentive mechanism, which aims to help promote small-scale commercial and residential customers use flat tariff to join the DR service. The coupon-incentive mechanism targets at the retail customers who have equipped smart meters yet still use flat rate tariffs; the proposed mechanism offer coupon incentives to the customers through mobile communication or other similar methods to reduce their energy consumption when the electricity price in wholesale electricity market is high [35]. With the assistance of DLC approach, a DR response service for large-scale residential customers is proposed in [36]; the average consensus algorithm and multi-layer communication layer including aggregator service are utilized in the proposed approach to match the desired demands of the grid. In order to coordinate the loads and the DERs in different micro grids for DR service, [37] presents an agent-based EMS for the customers in the micro grids.

2.2.3 Short Term Operating Reserve Service

The operating reserve service is an electric market service, which reserves a certain amount of generation/demand capacity for power balancing, frequency regulation and voltage adjustment. The units included in the reserve service are defined as Balancing Mechanism (BM) and Non Balancing Mechanism (Non-BM) [38]. Traditionally, the BM refers to the power plants which can increase/decrease the power generation in order to response the reserve service. The Non-BM refers to the large energy customers (e.g. steel smelting factory) which can provide limited-period reserve service to system operators by interrupting the demand consumption.

Previously, the residential and small commercial customers are difficult to join the reserve market due to their small capacity. However, it became possible to coordinate the end users as an entirety across the space limit since the implementation of ICT devices in the modern power grid. There is potential to promote the relatively small energy users and the DERs join the operating reserve market through the modern communication and control techniques. Through aggregating the small customers and DERs and bidding in the reserve market, the residential and small commercial customers can join the day-ahead reserve service, fast reserve and standing reserve service as the Non-BM units; at the same time, the DERs in the distribution network can act as the BM to provide the service as well.

2.3 Distributed Energy Resources in Smart Homes & Buildings

DERs refer to the small power resources installed in distribution network, which can generate or store energy through grid-connected devices [39]. Since the DER systems are decentralized and mostly located close to the energy consumers (e.g. Homes & Buildings), the energy generated by or stored in the DERs can response the quick-change demands of the energy consumers in distributed network faster than the traditional centralized, long-distance and large-scale power plants [40]. With the implementation of DERs, the end energy consumers can get the potentially cheaper and greener energy from the DERs as an alternative way rather than depending on the centralized power supplier only [41]. Currently, the main stream commercially available DER systems are classified and introduced in [42-45], which are introduced in the following part as well.

2.4.1 Photovoltaic (PV) Systems

The PV system is a power system which converts the solar energy to electricity with the photovoltaic cells [46]. For a completed PV system solution, a DC-AC converter is usually included to convert the electricity from DC to AC, which can feed to the grid directly [47]. For some residential PV system such as standalone systems, the battery bank is necessary to ensure continuous power output during the night-time [48]. According to the scale and location, PV systems are categorized into three kinds: Residential roof-top, commercial roof-top and ground-mount utility-scale systems, which are shown in Figure 2-3 respectively.

Figure 2-3Three main kinds of PV systems [49-51]

Although the PV technique has already existed for more than twenty years, there is only little share of market for the PV systems because of the high cost in the early periods. After entering 21st century, the price of PV system kept dropping due to the continuous price reduction of PV array materials and the improvement of PV manufacturing efficiency [52]. From 2001 to 2012, the cost of PV system has dropped by more than 50%, i.e. $2.00 per watt (€1.52 per watt) [53]. Because of the price dropping of PV modules, the installation capacity of the PV system has increased correspondingly. As seen in Figure 2-4 and Figure 2-5, the U.S PV installation capacity had increased from 4MW to 1.15GW between 1997 and 2008 – nearly 300 times. At the same time, the 10-year CAGR of global PV showed a great growth rate which was close to 55% [54]. It should be noted that the remarkable increase of the PV system installation has not only benefited from the price drop of PV modules, but also from the government financial subsidies. For instances, US government provides 30% Federal tax Grant for PV system; UK government gives 13.88p/kWh FIT generation tariff to small solar PV system (capacity smaller than 4kW) and 6.38p/kWh generation tariff for stand-alone solar PV system (capacity larger than 50kW) and Chinese Government allows US$0.15 per kWh for PV system [55-57].

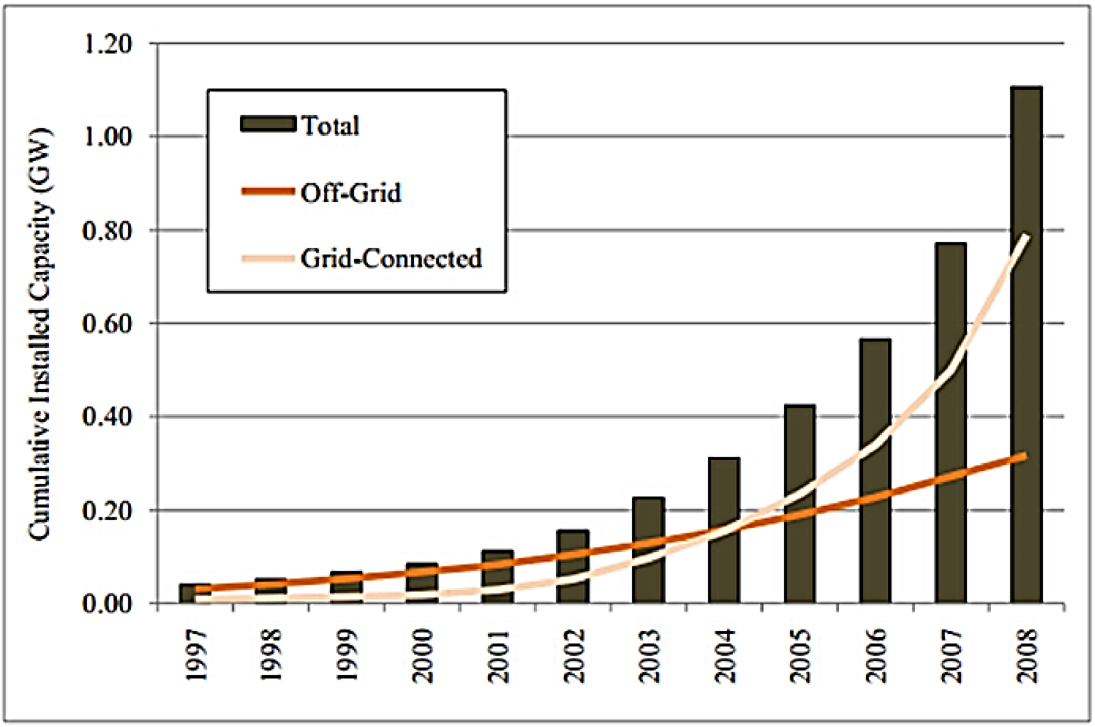

Figure 2-4 U.S. PV Installation Capacity [54]

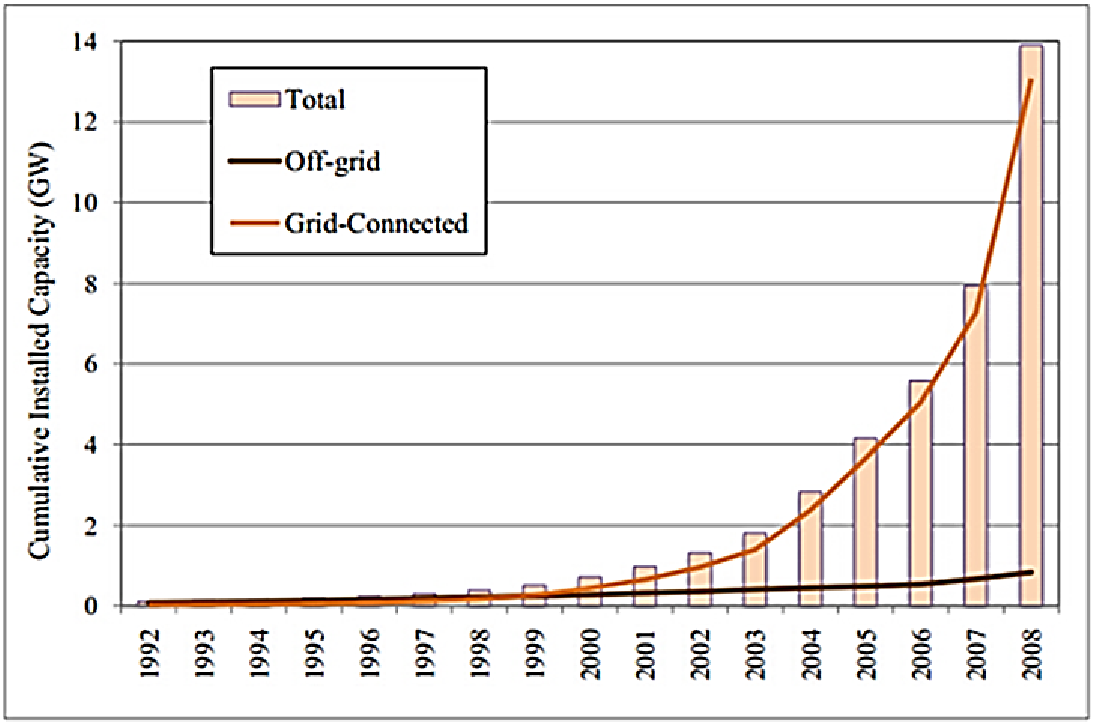

Figure 2-5 Global PV Installation Capacity [54]

Benefiting from the factors mentioned above, the installation capacity of PV system is expected to keep a sustainable and rapid growth in the predictable future [41, 58, 59]. For the small/medium scale roof-top PV systems in residential and commercial buildings, there is still great room for growth [60, 61]. Therefore, aiming to improve the monitor and control functions of such systems, the upcoming metering, control and optimization tools and components included in the smart home/ buildings solution will play an extremely important role for helping end users monitor and manage the PV systems [62, 63].

2.4.2 Small Wind Systems

Wind power has a long history of helping people in production since the adoption of the windmill for farm work [64]. After a wide-spread use of electricity since 1900, the wind turbine was designed and developed in order to convert the wind power to electricity based on the mechanism of electromagnetic induction [65]. Nowadays, the on-shore and off-shore wind farms have taken the leading positions in renewable energy generations [66]. Both large-scale wind farms and small wind turbine systems are exhibiting flourishing developments. Thanks to the miniaturization of the wind turbine system, an increasing number of residential and commercial buildings located in the windy areas are able to adopt the small (capacity between 2-10kW) wind system. Figure 2-6 proposes a typical small wind system for a residential house, including a wind turbine, underground cable, turbine controller box and a wind system inverter [67]. The customers, who installed the small wind system, can use the power generated by wind system directly and sell the spare electricity to the grid to get further payment according to the local FIT [68].

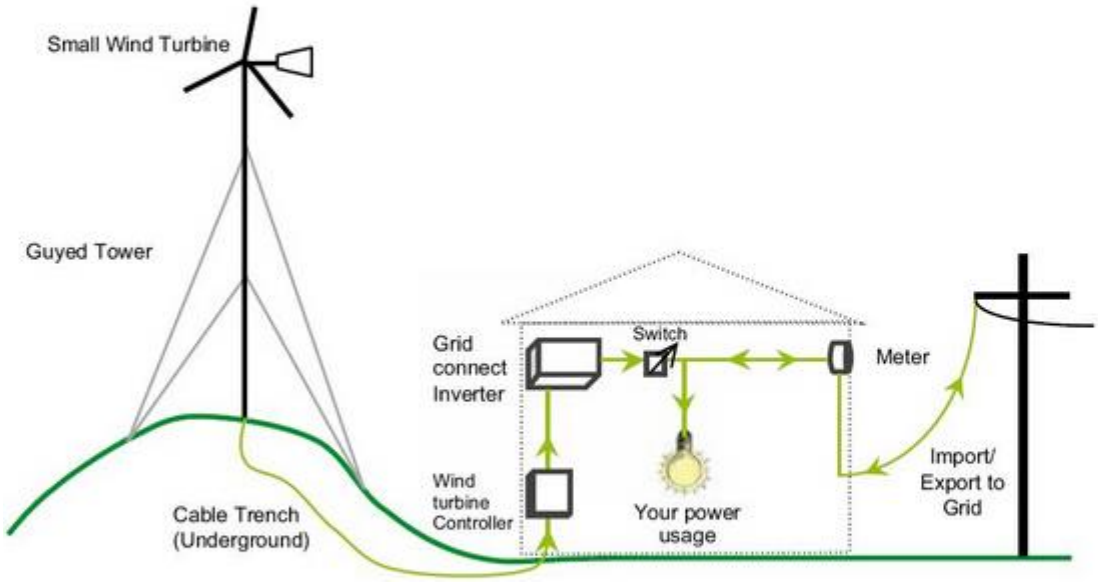

Figure 2-6 Small Wind System[67]

Once the wind speed is above the minimum speed, the rating generation power of small wind system ranges 200-10,000W according to the scale of wind turbine. Compared to the PV system, the advantage of wind power system is that it can still work during night time, thus can provide continuous power supply to the users once the wind speed is satisfied [69].

With the investigation of the UK small and medium wind system market, 19,854 Small & Medium Wind Systems have been deployed in UK between 2005 and 2011 [70]. Along with the decreasing difference on the cost between small & medium wind system (capacity up to 500kW) and large-scale wind power system (capacity larger than 500kW), the number of the wind systems with the capacity ranged 0-100kW will keep a fast growth rate [70].

2.4.3 Energy Storage System (ESS)

The ESS is the system to store the energy through physical media for later use. The ESS can satisfy the demands of different storage applications from residential users to the wholesale energy market. Since the smart grid aims to build an environment-friendly and decentralized power grid, the ESS can act as a coordinator in the network to help maintain the stability of the grid. Due to the instability of the generation of the renewable generators, such as wind turbine and PV arrays, the power output is always changeable and thereby difficult to predict accurately. The power generation have difficulties to satisfy the changeable power demands once the ratio of renewable energy resources takes high share in the entire power generations, and thus may result in power surge, frequency variation and other problems. With the assistance of ESS, the active/inactive power control, load shifting and excess energy storage can be achieved, and improve the stability of the power grid and the efficiency of energy use [71].

Currently, there are various techniques applied for the storage media in the energy storage systems, such as battery, flywheel, large capacitor, hydrogen and compressed air. Figure 2-7 gives several demonstration projects of energy storage systems with different techniques.

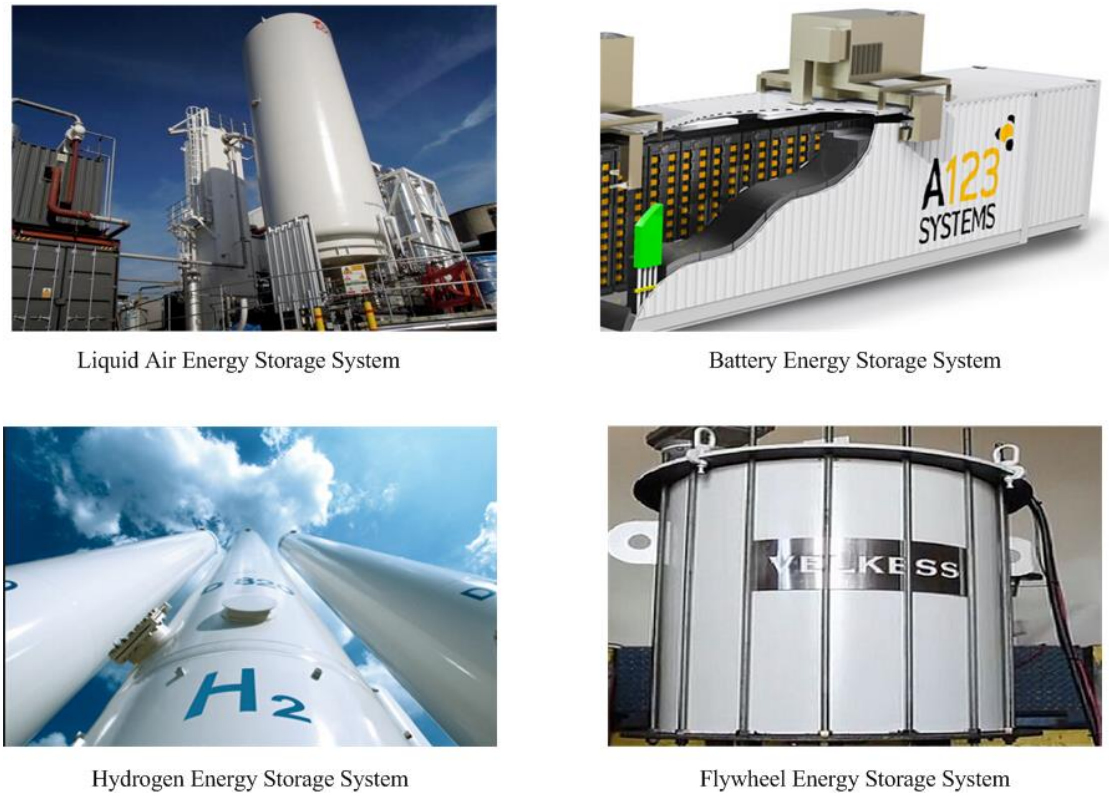

Figure 2-7 Energy Storage Systems [72-74]

In the low voltage (LV) distributed power network, with the consideration of cost and system working efficiency, the battery energy storage system (BESS) is recommended [75]. In Figure 2-8, the schematic diagram of a BESS system working with PV system is presented[76]. The presented BESS can store the spare energy generated by PV with the common DC bus and transmit the stored energy to residential house or grid through the DC/AC converter once necessary.

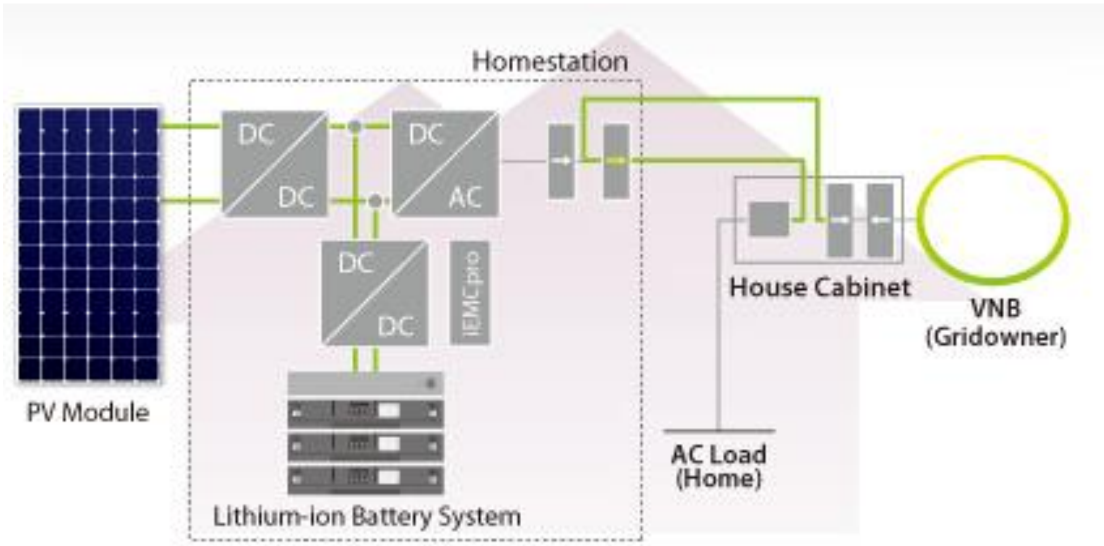

Figure 2-8 A Residential BESS integrated with PV system [76]

2.4.4 EV

The spread of EV and PHEV not only bring social and economic benefits, but also reduce the burden of electrical power system. According to [77], it has mentioned that over 20 million of EV will be on the road by 2020 worldwide. Correspondingly, Pike's research suggests that the number of EV charging stations will hit11 million globally by 2020 [78]. In USA, which is the largest EV ownership country, it is planned to build a huge amount of fast charging stations to satisfy the fast growing demands [79].

Along with the increasing number of EVs and accompanying EV charging stations, the relevant charging demands will increase either, which will significantly influence the stability and power quality of the distributed network. This is because of the high unit power rate of EV charging box/station and the generality of transportation user patterns (e.g. office workers have similar working periods during the week days).

As mentioned previously, the power grid operator will face new challenges in the power flows, grid losses, and voltage profile patterns once a large number of EVs are connected to the power system. [80-82] concluded that the power grid operator will face new peak loads caused by the EVs, and the existing grid equipment (e.g. Small Transformer in distribution grid) will have difficulties in handling the mass electric power, thus the power suppliers need to build more power plants to satisfy the increased demands. With the consideration of the proposed problems caused by the EVs, [83-88] specified a number of methods from the charging scheduling, centralized management, renewable energy integration and Vehicle-to-Grid (V2G) perspectives.

[86] proposed a smart charging method for the EVs in the distribution network based on the aggregator service, which can schedule the charging of the EVs by considering the prediction of required EV and the power grid loads. Moreover, [87] proposed a charging scheduling approach of EVs that can integrate with the wind system and other renewable energy systems in order to use the available capability of the distribution network efficiently. As shown in Figure 2-9, a home based EV smart charging system is presented, utilizing the Artificial Neural Networks (ANNs) to

forecast the load consumption, PV generation prediction and the electricity price and optimize the EV charging to minimize the energy bill [89].

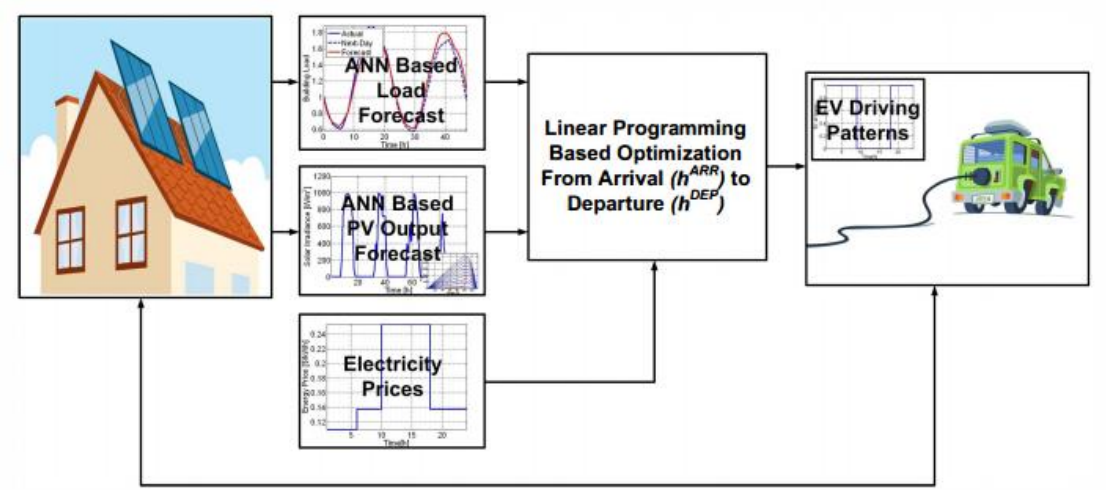

Figure 2-9 A Home Based EV Smart Charging System [89]

In view of the large battery capacity on EV and user pattern of automotive owners, V2G technique is introduced to maximize the using of the battery on EV and assist the power grid operation. The key component of V2G solution, bi-directional converter, can easily work with the EV DC charger in the market [90].

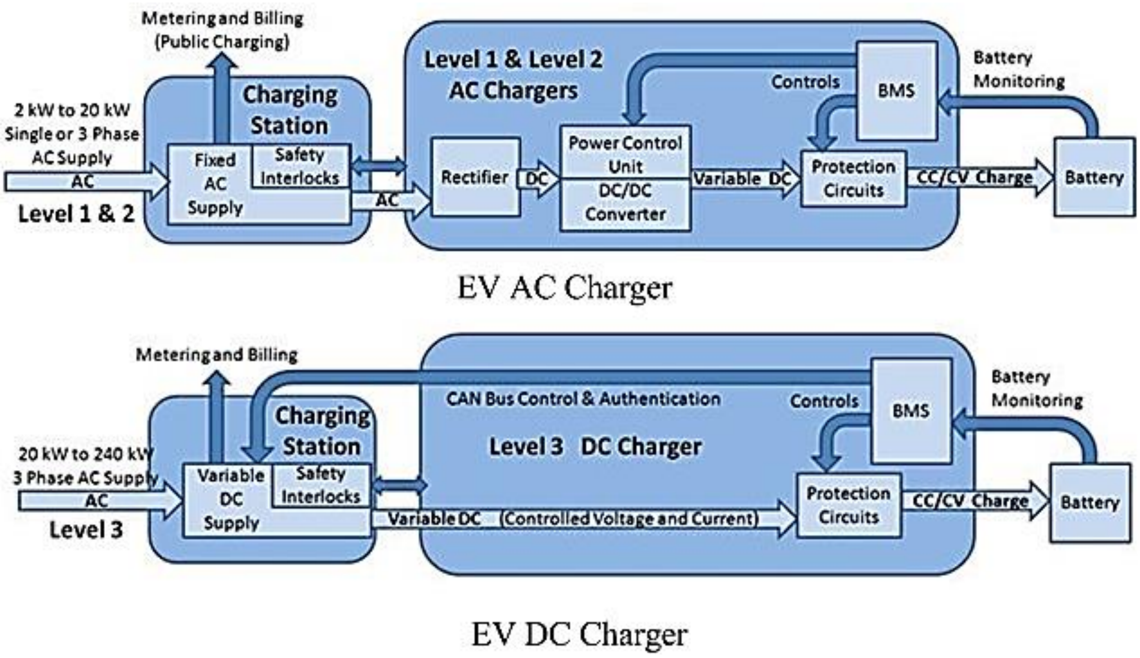

Figure 2-10 Two types of EV Chargers [90]

It can be seen that the EV DC charger is open to variable DC supplies. The V2G function can be achieved once the bi-directional inverter connects to the DC port of DC charger and follows the EV charging standards. It should be mentioned that the chargers shown in Figure 2-10 follow the SAE-J1772 standards, which is the North America EV charging standards. There are still other charging standards in other countries and areas, such as CHAdeMO for Japan, IEC 62196-1,2,3 for Europe. Fortunately, all these standards support the V2G technique.

With the assistance of V2G technique, the EVs and PHEVs can play an even more active role in the entire energy system such as joining DR program or VPP program. Figure 2-11 presents a complete Ecological Environment for EV and PHEV from bottom to top, including individual home, aggregator, ISOs and the energy power plants. Working though the across-grid communication and control network, the charging and discharging of the EVs and PHEVs can be coordinated by the upper level managers (e.g. DNOs or ISOs), so as to help maintain the stability of the grid, and at the same time provide financial benefits to the EVs and PHEVs owners [91]. A V2G VPP is presented in [85]; the study indicated that the grid-connected EVs can bring considerable benefits to the EV owners if the EV price can decrease as predicted. [88] proposed a V2G parking lot working with PV system. The results indicate that the proposed model can effectively improve the gain factor of PV and reduce the burden on the distribution network.

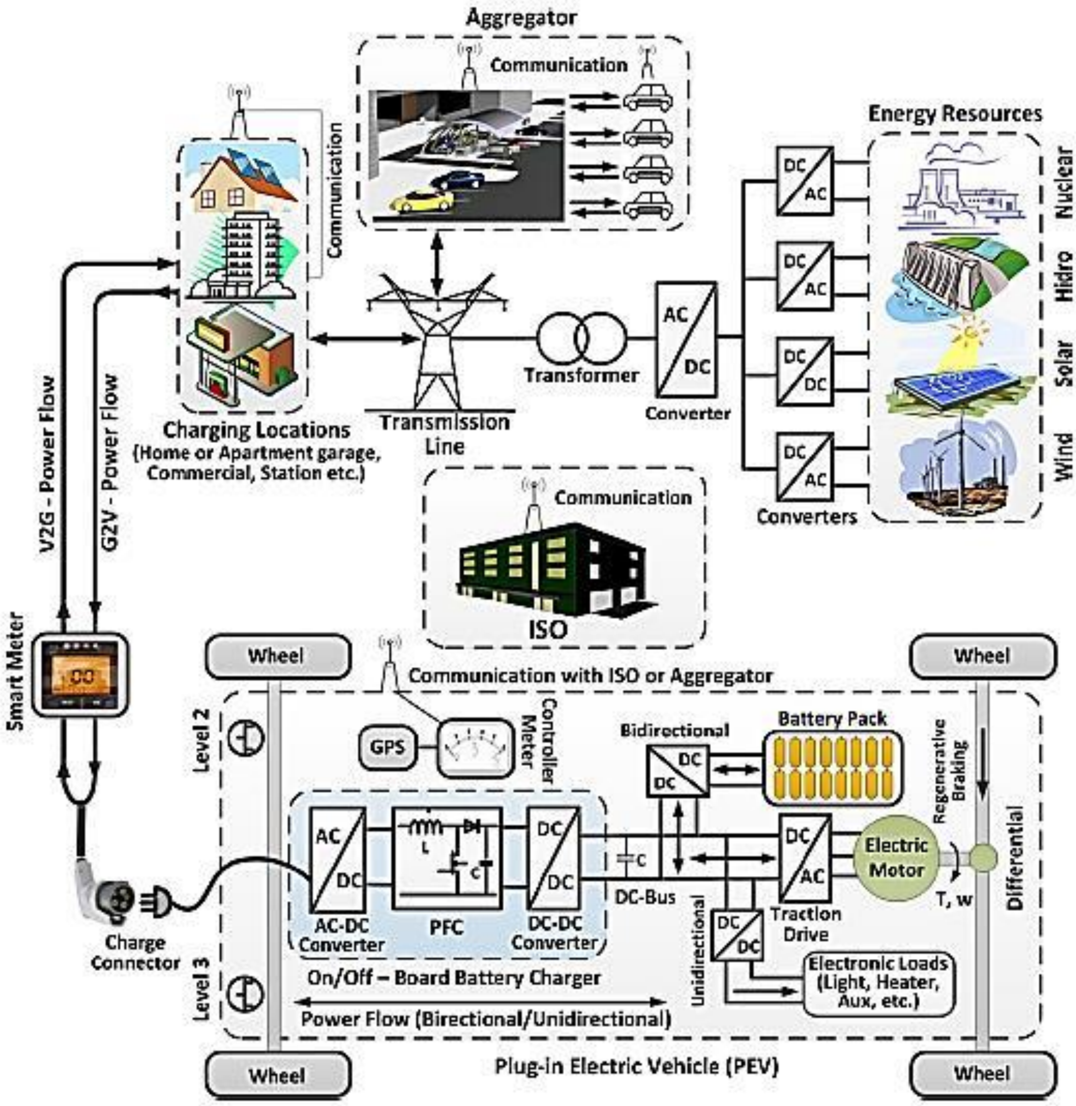

Figure 2-11 A VPP Model based on V2G Technique [91]

2.4.5 Other Systems

Apart from the DERs listed above, there are still a number of other DERs used with different techniques, such as CHP and Waste-to-energy. Those DERs mainly focus on the recycling and reusing of the wasted energy. For instances, the waste-to-energy system can collect the decomposers of the flora and fauna wastes and drive the turbine or fuel cells generating heat or electricity, and the CHP system reuses the exhausted heat from generation for heating or other purposes [92, 93].

2.4 Monitoring & Control Technique for Smart Homes and Buildings

For smart homes and buildings, the monitoring and control system is considered as its cornerstone, because it can take charge of communicating and managing the home appliances, renewable energy systems and any other equipment in the homes or buildings. Presently, there are a number of different techniques available in the market, which can plan the monitoring and control system for smart home and building. In this section, the mainstream communication technique for establishing monitoring and control system of smart homes and buildings will be introduced.

2.4.1 Wireless Personal Area Network (WPAN) Technique

WPAN techniques are recommended choices for establishing the monitor & control network in homes and buildings because of their cheap, easy-to-install and easy-to-maintain features. The network size and data flow transmission speed of most WPAN techniques can fully satisfy the requirements of individual house and small buildings. Currently, there are a number of WPAN techniques available in the market for smart homes/buildings, which are specified in the following table with their main characteristics.

	ZigBee	Z-Wave	WIFI	Bluetooth Classic	RuBee
Communication Standard	IEEE 802.15.4	Zensys	IEEE 802.15.1	IEEE 802.15.1	IEEE 1902.1
Working Frequency (Hz)	915M/2.4G	900	2.4/5G	2.4-2.485G	131k
Communication Distance (m)	Up to 100	Up to 100	Up to 92	Class 1- up to 100 Class 2- up to 30	15
Data Rate (bits/s)	Up to 250k	Up to 100k	Up to 96.3M in 2.4GHz	Up to 24M in latest version	Up to 9.6k
Number of Network Branch Nodes	64,000	232	255	7	8
Power Consumption	Approx. 1mW	< 1mW	Larger than > 20mW	>2mW	<0.1mW

Table 2-1 Main Features of different Wireless Communication Technique for Smart Homes & Buildings [94, 95]

- ZigBee

ZigBee is a wireless communication protocol used for building WPAN based on the standard IEEE 802.15. Thanks to the low power consumption and easy automatic networking characteristics, ZigBee has been widely applied in home automation, smart homes and smart buildings for monitoring and control purpose. Although the communication range of the nodes in ZigBee is between 10-100 meters, the communication distance can still be enhanced by proper design and implementation. For example, the mesh network topology can transmit the data through any attachable routers within the ZigBee network, which can consequently increase the communication distance of the network. In addition, one ZigBee network is large enough (support up to 64k branch nodes) to satisfy the requirements of home/buildings with a large number of devices. As different frequency channel required by different countries, the ZigBee network can work in 3 kinds of frequency: 868 MHZ, 915 MHz and 2.4 GHz, which correspond to the different maximum data transmission rate as well. It should be noted that the maximum data transmission rate of ZigBee is 250 Kbit/s, but is only suitable for the general communication among the devices not for entertainment purpose.

As reported by [96-98], many ZigBee based smart home systems have been proposed. With the help of ZigBee technique, a sensor network has been established in [96] aiming to monitor the operation of home appliances as well as the health & safety devices in a home (such as fire alarm and entrance guard system). Based on the behaviour of residents, modelled by the data of home appliances and in-home collected by ZigBee Sensor network, [98] had developed an energy saving solution for a smart home. In addition, the ZigBee technique has been involved in the solutions of smart buildings as well, which are proposed in [99-101].

- Z-Wave

Z-Wave is a wireless communication standard owned by Zensys Ltd, and licensed to the customers of Zensys Ltd. It was designed to meet the needs of remote monitoring and control features for home appliances in residential or small commercial places. Compared to the IEEE 802.11 standard based WPAN, the Z-Wave can only transmit up to 100kbits/s within its working frequency range, which is relatively small. In addition, a maximum of 232 nodes can be contained in a Z-Wave network and the maximum point-to-point communication distance in an open area is around 30 meters. Therefore, the smart home/building solutions developed by Z-Wave should not contain too complex data packages and too many devices, such as the case designed in [102] and [103].

- Bluetooth

The Bluetooth is the wireless technology originally implemented by telecom industry. The data rate of Bluetooth could only reach 1Mbps in the early period but about 24 Mbps in the latest version. Due to the developments in power consumption control and data rate, the Bluetooth technique can be implemented not only for the mobile system but also recently the entertainment, health & safety systems. Some researchers have presented the Bluetooth based smart home solution in [104] and [105] during the early 21st century. Because of the relatively high price, short communication distance and small capacity of networking devices, nowadays the Bluetooth technique is still difficult to compete with ZigBee, Z-Wave and other low power consumption & low cost RF techniques in smart home/building solutions. However, thanks to its wide use in mobile devices and good performance in entertainment system, it is still the must-have technique in the smart home solutions since it can integrate with entertainment features, such as the solution proposed in [106] and [107]. The Open Service Gateway initiative (OSGi) based smart home infrastructure proposed in [106] adopts the ZigBee communication technique to formulate the bottom layer wireless sensor network. In [107], a data collection model implemented by ZigBee technique is proposed; a mobile assisted-living and healthcare application is integrated with the model as well to improve the user experience.

- WIFI

WIFI is a high bandwidth wireless network technique based on IEEE 802.11 standard. Its data transmission speed can reach 300Mbps, and the communication distance is up to 35 meters indoor and 92 meters outside. In the smart home/building solutions, the WIFI technique is usually used by the coordinator with multiple-protocols, so as to transmit high load data to the gateway. The advantage of WIFI compared to other communication techniques is that it has been widely implanted in mobiles and other consumer electronics, in consequence, it is generally added in such devices in the smart home/building solutions as shown in [108].

- Other Wireless Communications Techniques in Smart Homes & Buildings

Beside all the communication techniques mentioned above, there are still other communication techniques such as RuBee, Enocean and Wibree available in the market, which can satisfy the various demands of smart homes/buildings with different requirements on working standards, operation frequency, communication distance and other factors. The detailed characteristics and features of the mentioned wireless communication technique are introduced in [109, 110].

2.5.2 Wired Communication Techniques

Limited by the communication distance, stability and other factors, the WPAN technique cannot satisfy all the requirements of smart homes & buildings. Especially for the large houses or commercial buildings with a large amount of network-connected devices, one WPAN cannot handle all the devices so that a number of sub-networks should be established. In order to coordinate the sub-network and handle the relatively large data packages, the wired communication techniques are recommended due to its high bandwidth and reliability.

- Ethernet

The Ethernet technique is a universal communication & information technology used for local area network (LAN). With the Fibre optic cables, the computers and any other devices containing Ethernet card can communicate with each other in the LAN with up to 10,000 Mbps speed. In the smart home & building solutions, the Ethernet is regarded as the information 'motorway' to collect/deliver the data packages from/to the sub-networks. An increasing number of office equipment and home entertainment devices, such as printer, scanner and media console, have equipped Ethernet features which can easily connect to the Ethernet-based smart home/building solutions without extra cost.

- Transmission Control Protocol (TCP) & Internet Protocol (IP)

IP is the most common protocol used for the communication among computing network. It defines the package size, header, hosting address and other information for data transmission within the network. With the assistance of TCP protocol, which defines the receipt of the data transmission above the IP protocol, the TCP/IP can formulate the completed data transmission solution through Internet. Among the Smart home & buildings, the TCP/IP plays the role of communicating with the external network to enable the smart home & buildings connect to the cloud platform and being monitored and controlled remotely. Moreover, along with the development of IP protocol, the latest version (IPv6) has become suitable for 'The Internet of Things' , and thus it is able to do more work in smart homes & buildings solutions rather than only working as the link between the smart homes & buildings and the external network. To make the machine-to-machine communication easier, each device in the smart homes & buildings needs to have their own IP address since that the IPv6 can allocate 3.4×10^{38} IP addresses. In addition, the improvement in authentication, data integrity and confidentiality allows the IPv6 to provide a secure communication environment in smart homes & buildings and so as to effectively protect the privacy of customers.

- PLC

For the customers who only require basic features of smart homes & buildings and pursue the relatively cheap solution, the PLC technique is recommended. The PLC uses the 50-50 Hz AC power line as the data carrier to transmit the data within the frequency 5-500 kHz. Because the whole world use the AC power cables in the houses and buildings, there is no need of upgrading or establishing communication network except some transceivers on AC power lines for the PLC implementation. To formulate a PLC network in homes & buildings, there are a number of networking technologies and related networking devices commercially available in the market now, such as INSTEON, X10, HomePlug, Ghn, IEEE1901 and PRIME. [111] and [112] have presented the smart home systems based on the PLC technique.

- BACnet

BACnet is the communication protocol focusing on building automation. For energy efficiency and security purposes, BACnet based communication network can monitor circumstance and manage the devices (such as HVAC, entrance guard and lighting in the building) intensively. BACnet was originally designed for HVAC control and has become the leading protocol in centralized HVAC system. With increasing demand of controlling other devices in the building, the BACnet provides different service for different objects in building automation. Thanks to its low maintenance cost and universality, the BACnet has been successfully applied in a great number of buildings.

- Fieldbus for Smart home & building

The Fieldbus is the class of communication techniques originally used for monitoring and controlling the devices in industrial environment. It can work in relatively extreme environment (e.g. High Temperature, dusty and damp) and provide reliable and real-time communication feature to the devices within the network. According to the various requirements in different industries, different Fieldbus techniques have been developed such as Controller Area Network (CAN), EtherCat, LonWorks and Modbus. With price reduction of the fieldbus modules, some of the fieldbus techniques are being implemented in the smart homes & buildings. For instance, [113] proposed a smart home system using the CAN bus as the backbone network. As CAN bus network consists only two communication cables 'CAN High' and 'CAN Low'; all the devices within the network are connected to the two cables in parallel, which makes the network structure simple and easy to maintain. The LonWorks, one kind of fieldbus techniques, has been applied in a building automation system for controlling the HVAC and managing the CCTV, which was presented in [114].

Chapter 3 A Space Heating EMS for Smart Home

3.1 Introduction

As a consequence of the fast development of smart metering and control units, the smart home/ is becoming mature in the market. From life comfort perspective, the smart home can bring great convenience to everyday life through the intelligent control of indoor temperature, lighting and door access. Moreover, due to the increasing energy shortage and greenhouse effect, governments are promoting the smart homes from energy savings and environment benefits points of view. Correspondingly, the modern electricity tariffs such as RTP are introduced by energy suppliers as an incentive mechanism for encouraging customers reduce their energy consumptions. In order to fulfill the requirements for living comforts and CO2 reduction, the EMS for smart homes is increasingly important.

To achieve the objectives in living comfort improvements and energy savings, the main work of EMS is to schedule the operation of controllable devices with the consideration of electricity price. According to the investigation in energy consumption of home appliances, the space heating/cooling systems are no doubt the largest energy consumes during summer and winter time in residential houses. According to the investigation of Balaras et al in sustainable-energy building, 57% of total energy in residential buildings is used for heating & cooling in Europe in 2003 and the percentage is supposed to increase continuously in the next decade [115]. Thus, the management of the space heating & cooling systems is critical to EMS. Currently, some of the space heaters in the market are equipped with basic controllers to control the temperature in house; the space heaters can start/stop when the in-house temperature reach the lower/upper bound. Meanwhile, some other space heaters are embedded with timers inside, which allow people configure the operation periods of the heaters. In case of taking RTP into account, the mentioned control methods for space heaters cannot work efficiently with the changeable prices, which may even cost customers more than the traditional electricity tariffs (e.g. Flat Tariff and TOU tariff).

Aiming to help the customers reduce the utility bills and balance the demands for the grid, an EMS for controlling the space heating system in smart home is proposed in this chapter.

3.2 Current EMS for Space Heating Systems

Figure 3-1 shows a basic circuit of space heater. As the current goes through the resistance, the heat can be generated on the resistance. This is the working principle of both space heaters and water boilers. The heating power can be calculated based on Joule Effect, which is described as $P=I^{2*}R$.

Where P represents the power (W), I represents the current (A) and R represents the Resistance (Ω).

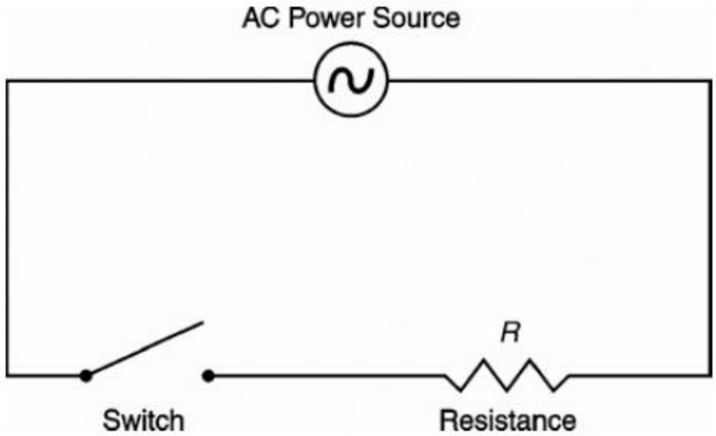

Figure 3-1 Basic Circuit of Space Heater

Since one house contains more than one space heater or other thermal devices, the central control unit, which is one kind of simple EMS, is developed for the central management of the space heating devices. For example, the radiators in house are located in different rooms; a central controller can turn on/off the radiators in specific periods through the relay in the radiators. As shown in Figure 3-2, a timer based control system for space heaters is presented: the residents get the access to configure the operation periods of the radiators through central control panel, so that the radiators can be turned on/off by the timers when the time signals are triggered.

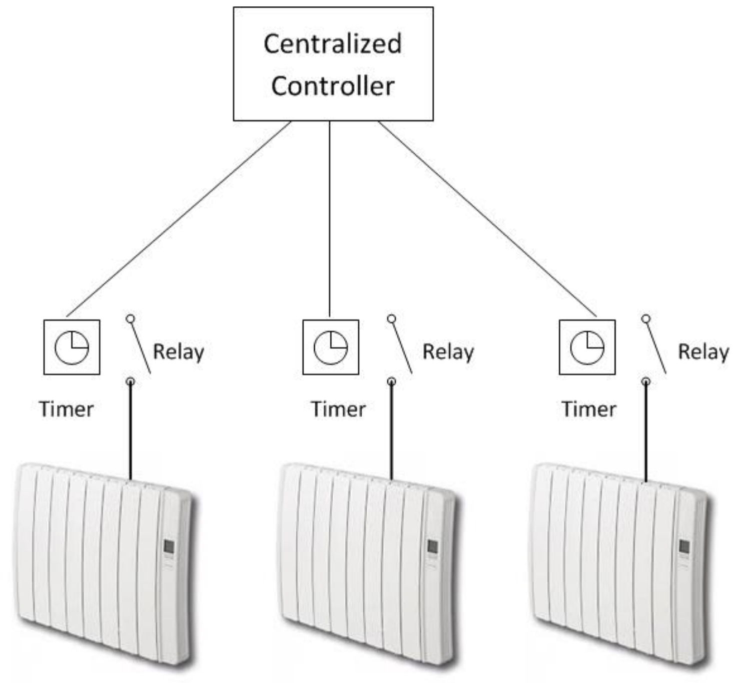

Figure 3-2 A timer based control system for Space Heaters

In some other solutions for space heating system, temperature sensor is equipped as shown in Figure 3-3. The users can configure the indoor temperature they prefer on the centralized controller panel, then the radiators will stop working automatically when the temperature reaches the pre-set value and restart working when the indoor temperature drops down to the lower bound of preset low-bound temperature. Consequently, the indoor temperature can be kept in a specific temperature range to avoid the waste of overheating and discomfort by lacking of heating.

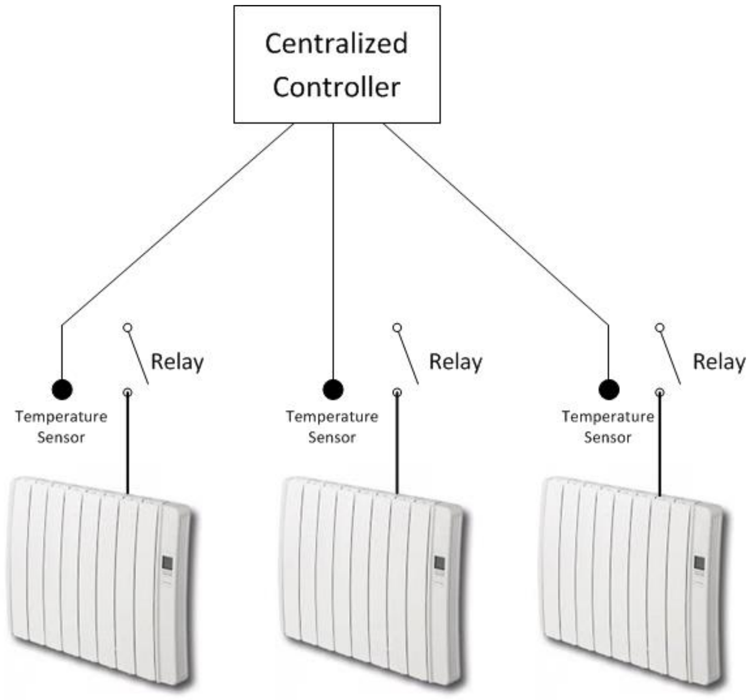

Figure 3-3 A temperature Sensor based control system for Space Heaters

3.3 EMS Solution for Space Heating & Cooling Appliances

3.3.1 Overview of HEMS Solution for Household Heating & Cooling Appliances

The proposed HEMS solution aims to reduce the energy costs of HVACs through scheduling the operation of the space heaters with the consideration of RTP tariff. Similar to the working periods of an oven, the working periods of space heaters can be classified into Pre-working (pre-heating) period and Stable working (heating) period. The pre-working period is the period that the space heaters heating the space to the desired temperature; the stable-working period is the period that the space heaters maintaining the temperature in the reasonable range according to the temperature configured by customers. In order to reduce the energy consumption and billing cost of space heating systems and other HVAC devices, a number of researchers have introduced various solutions such as temperature prediction and load shifting control approaches [116-118]. However, most of the solutions focus on the stable-working period of space heaters and other HVAC devices rather than the pre-heating period.

Furthermore, many countries have launched the policy for regulating the energy consumption of heating & cooling systems in buildings. In Sweden, the house heated by electricity devices is allowed to consume 55kWh per square meter per year [119]. Some other EU countries such as Spain and Denmark launched similar regulation policies to control the HVAC energy consumption as well. To fulfil the government policies, the construction materials for the new houses and buildings have been improved significantly, so that the thermal losses decrease correspondingly. Benefiting from the environmental friendly building materials, the EMS gets the potential capability in using the house as a temporary thermal accumulator, so that the radiators can heat the house in advance to avoid the peak time energy use.

Figure 3-4 presents the schematic diagram for the proposed EMS solution, which includes three monitor & control units, one outdoor temperature monitor node and one compact computer running the EMS program. The data transmission of the EMS system is based on the ZigBee wireless technique. Each space heater connects with a monitor & control unit, which is used to monitor the indoor temperature and energy consumption of the heaters and control the heaters' operation. The main function of the outdoor temperature monitor node is to collect the outdoor temperature and transmit the temperature information back to the EMS platform through a gateway. The EMS platform is operated on the EPC with an on-site communication gateway. It performs the work of data receiving, control optimization and control commands broadcasting.

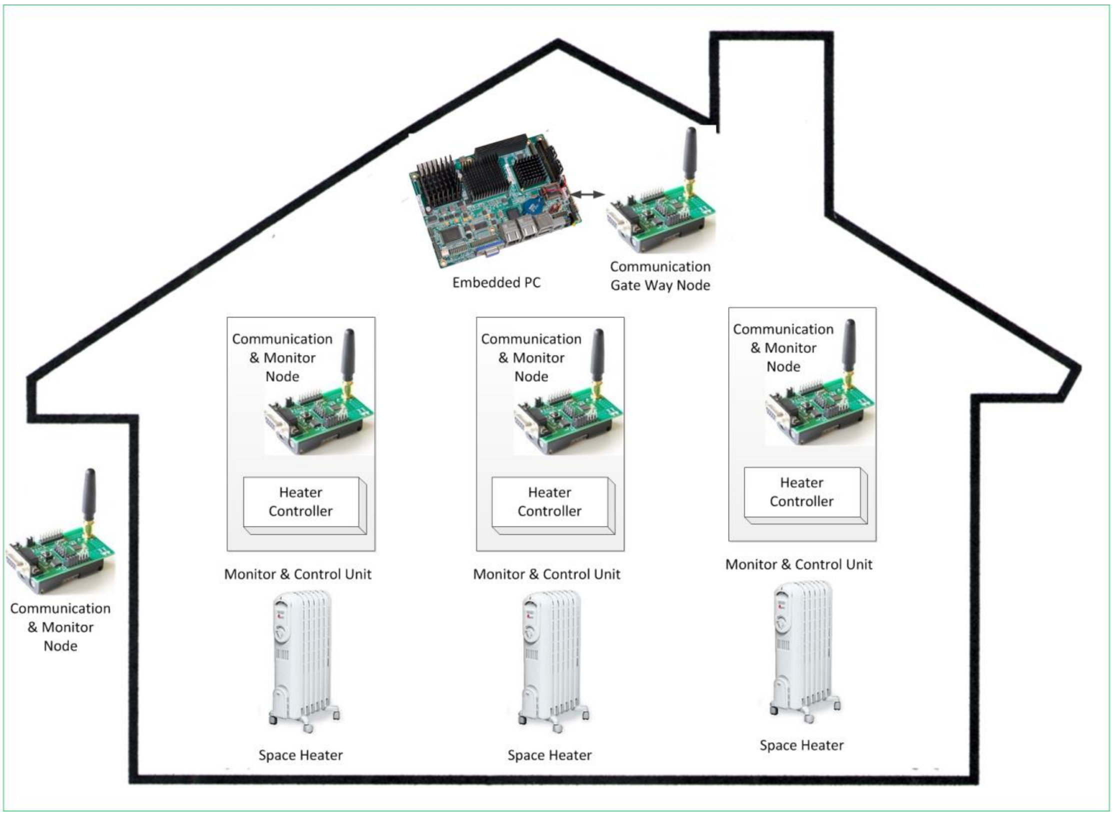

Figure 3-4 Schematic Solution Diagram

3.3.2 Design of the Monitor & Control Unit

The monitor & control unit contains five main components shown in Figure 3-5. The AC sensor and temperature sensor can monitor the power and the temperature respectively. The data transmission work is covered the ZigBee Module. The solid state relay next to the AC sensor can turn on/off the space heater based on the control commands from the EMS platform. The Monitor & Control unit is powered by a 100-240V AC to 5/12V DC converter.

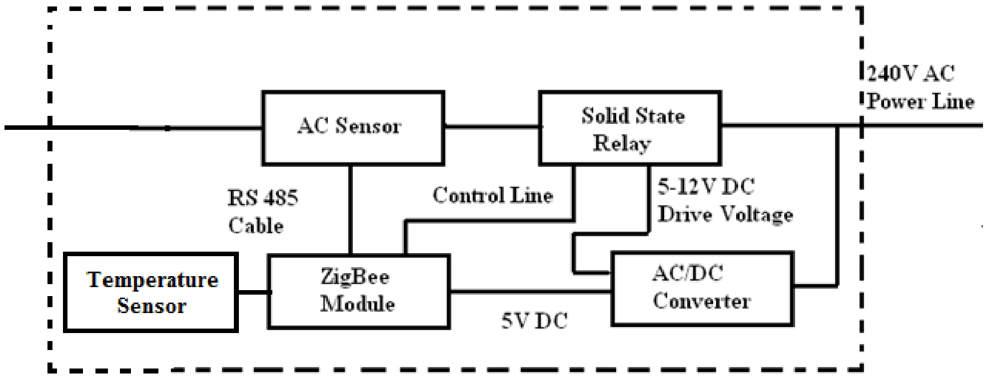

Figure 3-5 Design of the Monitor and Control Unit

3.3.3 Design of the Temperature Monitor Unit

The Temperature Monitoring Unit is a simplified version of monitor & control unit, which is shown in Figure 3-6. It is only equipped with one ZigBee module with a temperature sensor. The unit is powered up by three AA batteries rather than the AC/DC converter, which is convenient for outdoor installation and operation.

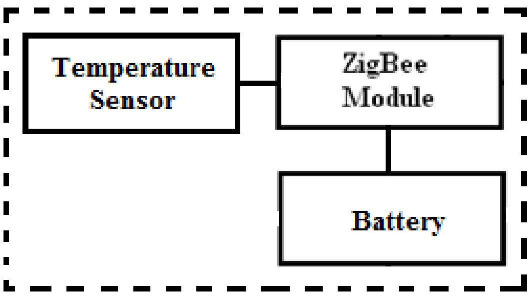

Figure 3-6 Design of the Temperature Monitoring Unit

3.3.4. Design of the EMS Program

The EMS program is designed as a back-end service running on compact computer, affording the communication and control work for the space heaters. It is developed on the Microsoft Visual Studio 2010 using C# language and .NET framework. A basic flow chart of the program of HEMS is given in Figure 3-7. The start-up part of the EMS program, from the starting point to connector A, indicates the process of the wireless network initialization. It should be noted that the ‘Initialize ZigBee Network’ in the first step refers to a series of configuration of the network (e.g. network topology and frequency). ‘Register ZigBee Branch nodes’ registers not only the 64-bit MAC address but also the 16-bit short address of the nodes on the network registration table, which can build a full and accurate network map for self-networking and re-connection of ZigBee network. The data reading part of the program is presented between connector A and B. It stores all the data to the log file with time stamps in XML format when the data is received. From connector B to C, the program uploads the required data to the designed solver and gets the optimized control strategy from the solver. The 5 seconds delay set in this part is the waiting time for the calculation of the solver. The last part of the program, from C to End, is to distribute the control commands to the space heaters. The way of ensuring the control commands successfully sent out is to check the command receipt signals from the branch nodes.

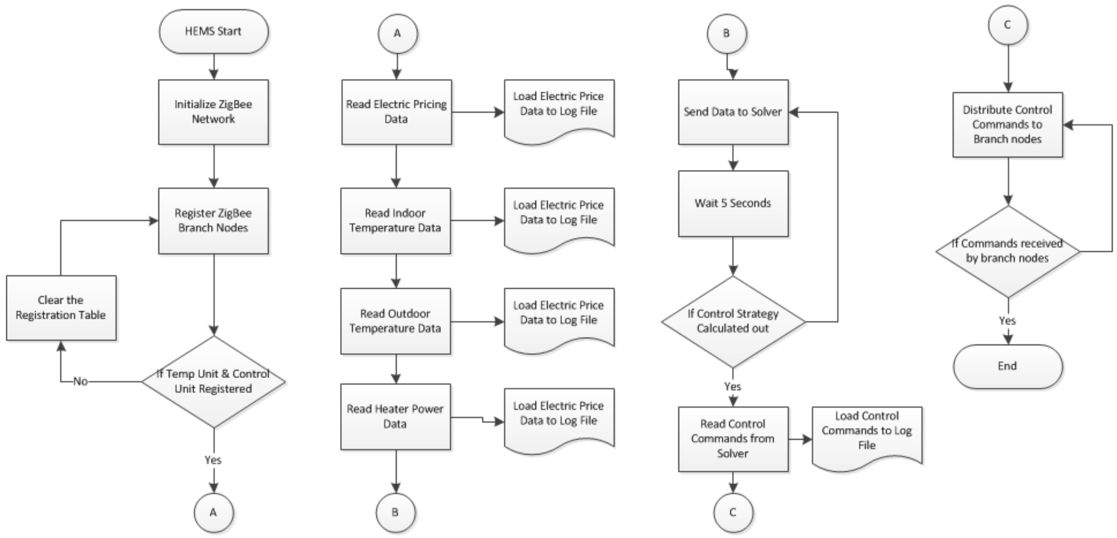

Figure 3-7 Design of the HEMS Platform

In view of the embedded program on the branch nodes (e.g. Monitor & Control unit), the operation mainly relies on the timer and external interrupt programmed on the chip. The outdoor temperature node broadcast the temperature data to the EMS every 10 seconds with the help of the internal timer. The monitor & control unit broadcasts the temperature and power data in the same way, and it also uses the external interrupt to receive and execute the control commands.

3.4 Mathematic Models

The thermal model of a house is applied in this part at first, aiming to provide accurate inputs to the EMS. Then the objective function and optimization approach of EMS for controlling space heaters are presented.

3.4.1 Indoor Thermal Model

The factors influencing the indoor thermal model are the power rating of radiators, indoor/outdoor temperature difference, specific heat capacity, air density, building construction materials and the size of house. The indoor temperature changing function in unit time under ideal situation is given in equation 3.1.

$$\frac{\Delta T}{\Delta t} = \frac{P_{Heater}}{S_A H_A \rho_A C_A} \tag{3.1}$$

where ΔT is the outdoor/indoor temperature difference

Δt is the unit time

P_{Heater} is the rating power of space heater

S_A is the heating space area

H_A is the home height

ρ_A is the air density

C_A is the specific heat capacity

It should be noticed that the thermal loss is not considered in the equation 3.1 for simplicity of considerations. It will be taken into account in formulation of the optimization model in this section. The rating power of the heater is assumed constant as well so that the temperature difference ΔT is constant in unit time.

In practise, no houses/buildings are in a perfect confined environment. Regarding to the building materials of the walls and windows, there are certain thermal loss to the indoor space when the radiator is running. The thermal exchange rate of the houses/buildings is closely related to the materials and size of the exterior wall and windows. The temperature change function considering the thermal loss is described as equation 3.2.

$$\frac{\Delta T_{change}}{\Delta t} = \frac{\varepsilon_{wa} S_{wa} + \varepsilon_{wi} S_{wi}}{S_A H_A \rho_A C_A} T_d \tag{3.2}$$

where ΔT_{change} is the temperature change

Δt is the unit time

ε_{wa} is the thermal exchange parameter of the exterior wall

S_{wa} is the area of exterior wall

ε_{wi} is the thermal exchange parameter of the window

S_{wi} is the area of the window

T_d is the indoor/outdoor temperature difference

In Equation 3.2, T_d is considered as a consistent value of the temperature difference between indoor and outdoor temperature. However, in practise, the T_d will change with the working conditions of radiators. The temperate difference changed in a unit time can be described as equation 3.3.

$$T_d(t) = T_{in}(t-1) + \Delta T - T_{out} \tag{3.3}$$

where T_{in} is the indoor temperature

T_{out} is the outdoor temperature

According to equation 3.1, 3.2 and 3.3 above, the practical indoor temperature characteristic can be deduced as follows.

$$T_1 = T_0 + \Delta t(-\frac{\Delta T_{change(1)}}{\Delta t} + \frac{\Delta T}{\Delta t})$$
$$T_2 = T_1 + \Delta t(-\frac{\Delta T_{change(2)}}{\Delta t} + \frac{\Delta T}{\Delta t})$$
$$T_3 = T_2 + \Delta t(-\frac{\Delta T_{change(3)}}{\Delta t} + \frac{\Delta T}{\Delta t}) \quad (3.4)$$
$$\ldots\ldots$$
$$T_k = T_{k-1} + \Delta t(-\frac{\Delta T_{change(k)}}{\Delta t} + \frac{\Delta T}{\Delta t})$$

Equation 3.4 indicates the changing process of indoor temperature by unit time when the radiators work steadily at home. It is easy to find that the thermal exchange will increase sharply along with the increase of temperature difference between indoor and outdoor. This is because the temperature increase $\Delta T_{increase}$ in unit time will decrease the indoor/outdoor temperature difference correspondingly as shown in equation 3.5. The indoor temperature will stop increasing when the temperature difference is too large to cover the thermal losses.

$$\frac{\Delta T_{increase}}{\Delta t} = \frac{P_{Heater}}{S_A H_A \rho_A C_A} - \frac{\varepsilon_{wa} S_{wa} + \varepsilon_{wi} S_{wi}}{S_A H_A \rho_A C_A} T_d \quad (3.5)$$

Therefore, it is easy to understand that the manual control of the EHs in home will waste energy when the Electric Heaters (EHs) keep working and make the indoor temperature in a high level. In addition, with the implementation of RTP tariff, the inefficient control of the EHS will probably lead to excessive energy cost in peak-time.

3.4.2 Control Strategy of EMS considering RTP Tariff

In order to reduce the energy cost under the implementation of RTP and provides more comfortable life to residents, it would be more efficient to arrange the operation of space heaters based on the price information, indoor thermal model and people's pattern. For instance, with the aid of cloud access to the EMS proposed earlier, the users can configure the arriving home time through their mobiles in advance, which leaves plenty of spare time - for the EMS to arrange the operation of radiators. The radiators can start working before people come back home. That means the radiators can avoid the peak-time operation and the indoor temperature can reach the preset value once people arrive home.

In order to get the optimization results of radiators, the control commands are involved in the indoor temperature function as shown in equation 3.6. The control commands are set as a matrix '$\boldsymbol{M}$' corresponding to the time axis. '0' in the matrix refers to the command 'switch off' and '1'refers to the command 'switch on'.

$$T_1 = T_0 + \Delta t(-\frac{\Delta T_{change(1)}}{\Delta t} + \frac{\Delta T}{\Delta t}\boldsymbol{M}(1))$$
$$T_2 = T_1 + \Delta t(-\frac{\Delta T_{change(2)}}{\Delta t} + \frac{\Delta T}{\Delta t}\boldsymbol{M}(2))$$
$$T_3 = T_2 + \Delta t(-\frac{\Delta T_{change(3)}}{\Delta t} + \frac{\Delta T}{\Delta t}\boldsymbol{M}(3)) \quad (3.6)$$
$$\cdots\cdots$$
$$T_k = T_{k-1} + \Delta t(-\frac{\Delta T_{change(k)}}{\Delta t} + \frac{\Delta T}{\Delta t}\boldsymbol{M}(k))$$

The proposed control strategy aims to minimize the energy costs by scheduling the operation of the space heaters before residents arriving home and maintaining the indoor temperature in the preset range. The objective function is given in equation 3.7. The restricted condition is presented in 3.8. The $s.t.T_k$ (temperature after residents arrive home) is restricted to be ±5% of the preset temperature. It is also worth mentioning that the outdoor temperature is assumed as a constant value to simplify the optimisation.

$$Min(Cost) = \sum_{t=0}^{k} M(k)P_e(k)\Delta t \tag{3.7}$$

where $\boldsymbol{M}$ is the matrix of control commands

P_e is the electricity price

$$s.t. T_k = T_{et}(1 \pm 5\%) \tag{3.8}$$

where T_{et} is the expected indoor temperature

According to the optimization model shown above, the proposed control solution is based on the Mixed Integer Programming (MIP). Currently, the main methods for solving the proposed problem are dynamic programming, branch and bound method, complete enumeration method, dynamic programming and GA [120]. In [121-123], three GA based energy management approaches have been proposed. In these literatures, all three GA based control strategies have shown the promising performance in load management, scheduling and responding to the Demand Side Management (DSM) programs. It is indicated that the GA based control approach shows aa high efficiency when the complexity of the calculation is relatively high. Compared to the dynamic programming, although GA cannot ensure to get the global optimal solution, the speed of GA is higher than the dynamic programming and it is easy to be achieved on the hardware system. As the space heating energy management system aims to be implemented on the physical hardware, GA is selected as the optimisation algorithm in this system. The GA based program is developed with MATLAB at first and then implemented in the physical hardware system. The performance of the GA based energy management system will be given in the following sections.

3.5 Case Studies

In order to reduce the energy cost and improve the living comforts for the residents, an effective EMS platform for space heating system has been proposed in the previous section. In this part, some cases are presented to verify the proposed solution.

3.5.1 Operation Characteristics of Space Heating System with basic Control functions

Most of the radiators in the current market do not have advanced control functions. As introduced in section 3.2, one traditional control function applied in space heaters is switching the heaters on/off through the built-in temperature sensors and relay to ensure the indoor temperature within present temperature range. Alternatively, the users can also set the operation period of the space heaters with the built-in timer on the control panel. Both of the control functions for the heaters are mostly based on the customer user experience, which is relatively inefficient.

The following case presents the operation characteristic curve of the space heating system applied in a 2-bedroom flat in UK during wintertime. In this case, a two bedroom flat is installed with one 3kW and two 2kW radiators to heat the living and the two bedrooms respectively. Based on the UK winter temperature data in the past thirty years[124, 125], the average temperature during winter time (Dec to Feb) is 4.5 ℃. Hence the outside temperature and the initial indoor temperature are configured as 4.5 ℃. The energy performance certificates (EPC) for the new built buildings in UK are mainly ranked between B (69-80) and C (80-91), thus, the mid value 80 is applied in the simulation (The value of EPC is determined by the net annual CO2 emission and the space of the building/houses) [126, 127]. Considering the flat area in UK, the area of the 2 bedroom area is configured as 60 m^2 based on the research of flat area in London and South England [128]. Regarding the thermal comfort in the flat, the best indoor temperature accepted by most people is 23.5 ℃, therefore, the indoor temperature range is configured between 22 ℃ and 25 ℃ (1.5 ℃ warmer and cooler than the best indoor temperature) for the space heating system [129]. According to the power rating of heaters, flat area and other factors, the 3 space heaters located in three rooms can heat the flat to the pre-set temperature range in 30 minutes as shown in both Figure 3-8 and Figure 3-9. Considering the living comforts of residents, the space heaters is usually turned on half an hour to one hour in advance (using the timer on space heaters or heating control panel) before people come back. Thus, the indoor temperature characteristic curves, one with half hour pre-heating and the other with 1 hour pre-heating, are shown in figure Figure 3-8 and Figure 3-9 respectively.

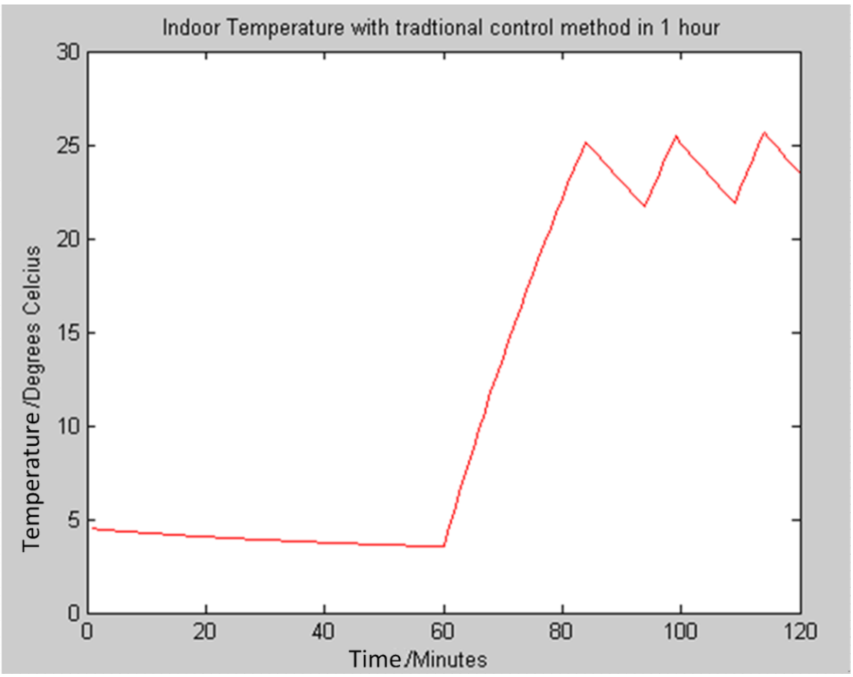

Figure 3-8 Indoor temperature of one hour preheating using traditional control method

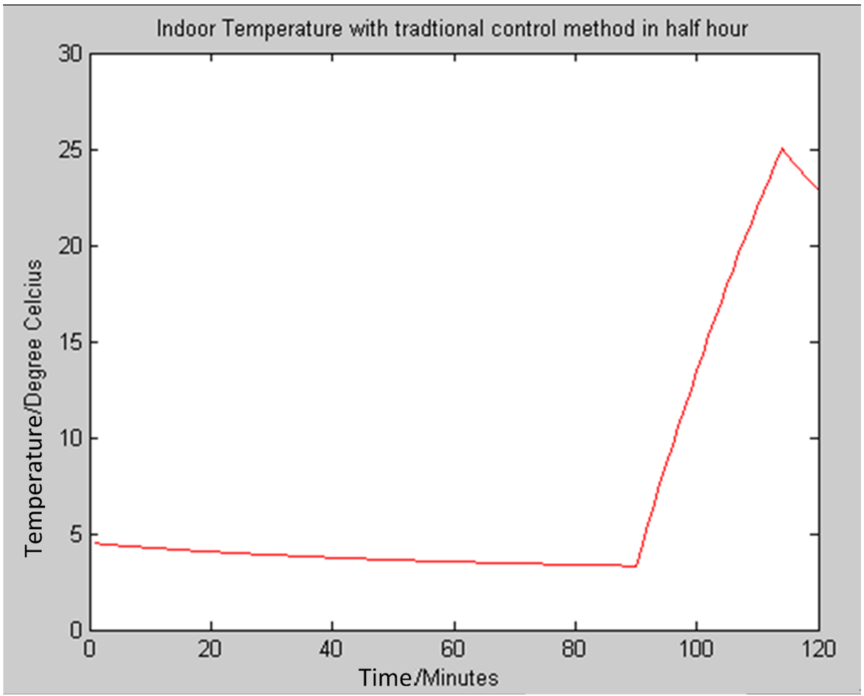

Figure 3-9 Indoor temperature of half hour preheating using traditional control method

As shown in the above two figures, the space heaters stopped working when indoor temperature reaches 25 ℃ and restarted when indoor temperature drops down to 22 ℃. It is easy to find that the energy cost for one-hour preheating is higher than the energy cost for half hour preheating based on the traditional tariff. The temperature for one-hour preheating scenario reaches the preset temperature 30 minutes before people come back home, which consumes more power than the half-hour preheating scenario. However, if the RTP tariff is used, the situation will be changed. For instance, if all the people turn on the radiators after work, the demand will increase at this period and the RTP price will increase correspondingly. Thus, the cost with longer preheating period could be cheaper than the scenario with shorter preheating period.

3.5.2 Operation Characteristics of Space Heating System with the Proposed Control Strategy

After taking the RTP tariff into account, the GA based EMS will optimize the radiators operation to achieve the cheapest cost and meanwhile satisfy the temperature requirements with optimized pre-heating periods. The 2-bedroom apartment is considered as a short-term thermal storage medium, which stores the heat in the period with low electricity price before people come back. Although there is certain thermal loss for the stored heat, the energy costs can reduced by the low price electricity as well. In addition, the desirable comfort level can be achieved in the proposed control strategy.

In order to verify the performance of the proposed control strategy under different electricity price , three 2-hour electric price sheets shown in Table 3-1 are used to test the proposed EMS. The reason for using the RTP price data for only 2 hours is because the thermal loss over 2 hours will be too large for the proposed 2-bedroom apartment with the proposed thermal factors.

Time Period (minutes)	Price List 1 (Pennies/kWh)	Price List 2 (Pennies/kWh)	Price List 3 (Pennies/kWh)
0-30	15	15	20
31-60	10	10	20
61-90	15	15	10
91-120	25	30	25

Table 3-1 Electric Price in Operational Period

It has been mentioned that the total power ratings of the three EHs in the 2-bedroom flat are 7kW. The price of the RTP tariff fluctuates from 10p to 30p. All the indoor temperature characteristics based on the GA control algorithms for the 3 RTP tariffs are presented in Figure 3-10..

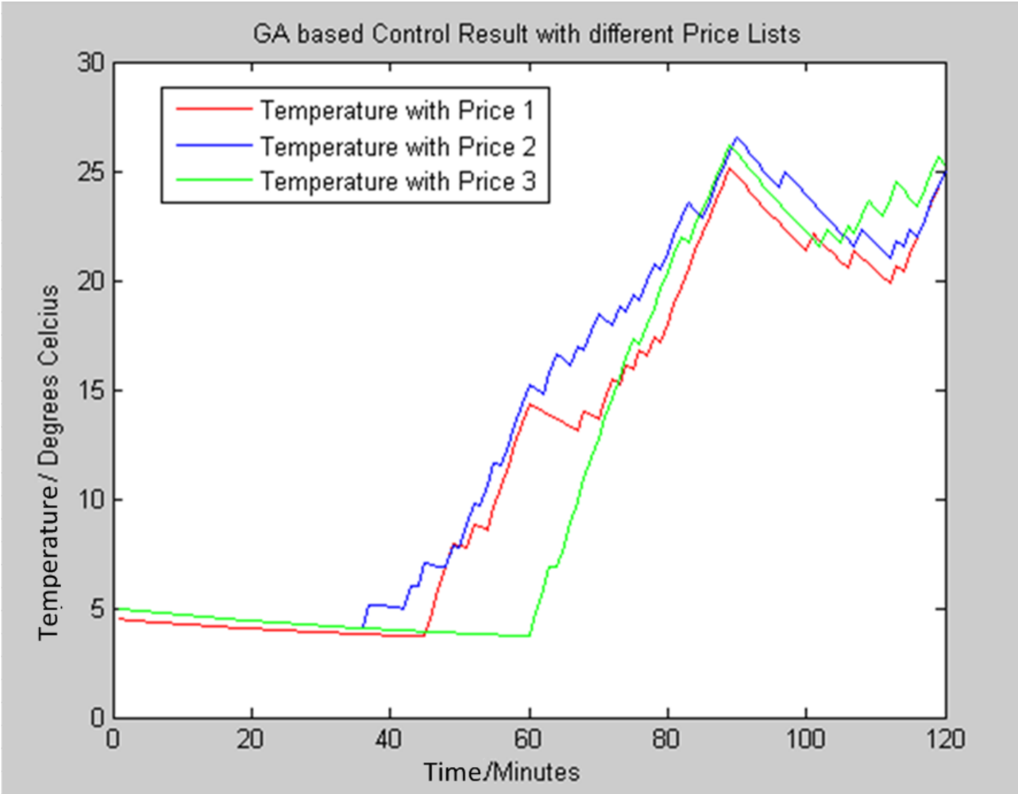

Figure 3-10 Results of GA based EMS with Three Price

Comparing the price list 1 with price list 2, the electricity prices are pretty much the same except the last 30 minutes in the time range. The electric price in the last 30 minutes of price list 2 is 5p higher than the price in price list 1. Therefore, in the first 90 minutes, the operation of radiators based on price list 1 works longer than the radiators based on price list 2, aiming to store more heat for peak time use.

Comparing the results using price list 3 and he results using price list 1, it is found that the radiators using price list 3 rarely work in the first 60 minutes, which aim to avoid the high-price period. They start working with full load after 60 minutes when the electric price enters into a relatively low interval. In order to provide required level of comforts to the residents when they come back, the radiators with price list 3 still works for around 10 minutes longer to reach the pre-set temperature range even though the electric price is high during that period.

The above figure has shown the characteristic curve of the temperature in different cases. In order to investigate the economic efficiency of the GA based control strategy, the comparison among the GA based control strategy, 1 hour preheating strategy and half hour preheating strategy are presented in Figure 3-11.

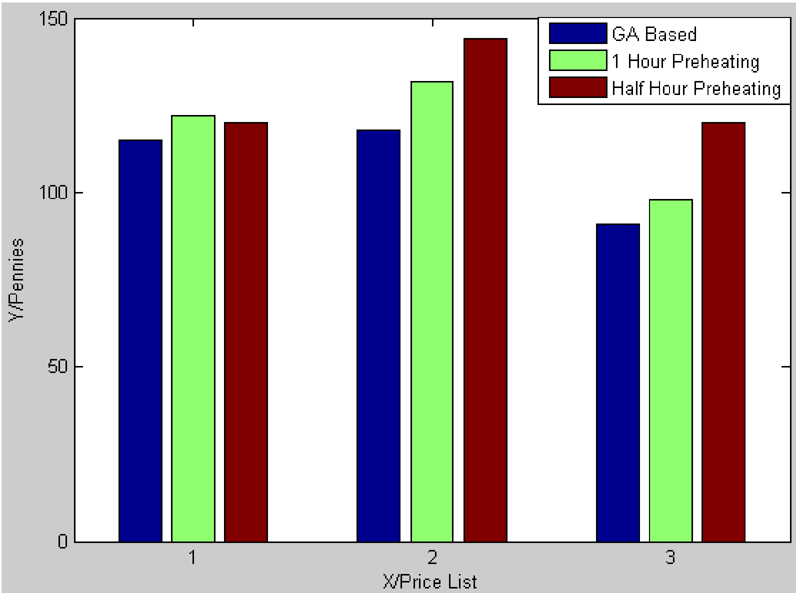

Figure 3-11 Cost comparisons between GA Based control and Traditional Control.

The histogram clearly indicates that the GA based strategy costs are lower than the other two strategies. In case 1 (implement Price List 1), due to the relatively small difference in electricity price, the cost differences of the three strategies are small as well. In case 2 and 3 (Implement Price List 2 and 3), the electricity prices enter into the high price interval in the last half hour. The scheduling of the radiators based on GA algorithm has much better performance in energy cost than the one-hour and half-hour preheating strategy. This is because the forward operation of radiators stores the heat in-home in the off-peak time, which reduces the energy use in peak time.

A detailed cost comparison among these three cases is given in Table 3-2.The energy bill for the space heating system using GA based strategy is taken as the reference value.

	Price List 1	**Price List 2**	**Price List 3**
GA	100%	100%	100%
1 hour preheating	106.1%	111.9%	107.7%
0.5 hour preheating	104.4%	122%	158.3%

Table 3-2 Cost Comparison on the Different Electricity Price Lists

Compared to 1-hour preheating and 0.5-hour preheating control approaches, the GA based EMS presents the best performance in all three price lists. Especially for the scenario with large price difference in last 60 minutes in price list 3, the EMS cost 58% less than the half-hour preheating strategy. It indicated that the proposed EMS can reduce the peak-time energy consumption to avoid high costs, and at the same time maintain the level of comforts for residents.

3.6 Physical Experiment System for Household Heating EMS

To verify the proposed EMS in real environments, a physical test bed has been established in the lab. The prototypes of the units used in the EMS are presented in Figure 3-12. A radiator connected with the monitor & control unit is shown in Figure 3-13 and the EPC with communication gateway for running the proposed EMS is shown in Figure 3-14.

(a)Monitor & Control Unit (b) Temperature Monitoring Unit

Figure 3-12 Hardware Prototypes for Proposed EMS

Figure 3-13 A Radiator with Monitor & Control Unit

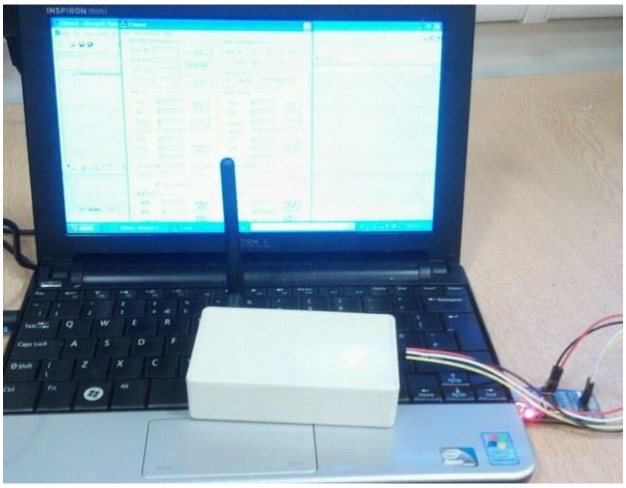

Figure 3-14 EMS Platform with Communication Gateway

The communication test, algorithm test and control commands execution test have been done on the test bed. The units authorization, networking and data transmission are proved by the communication test. In the communication test, the units in Figure 3-12 can be authorized by the gateway and join the network in 10 seconds after being powered up. The data of power consumption, indoor temperature and outdoor temperature are sent to the EMS every 20 seconds. The algorithm test indicates that the EMS program can generate the control commands matrix after receiving the external data and then distribute the control commands through the gateway. In control commands execution test, the interrupt on monitor & control unit is trigged by the control command broadcasted by the gateway, The monitor & control unit successfully turned on/off the connected radiator by the solid-state relay when control commands received. The above tests proved the feasibility of proposed EMS for space heating system in real environment.

3.7 Summary

In this chapter, a GA based EMS for residential space heating system was proposed. The modern electricity tariff, RTP is considered by the proposed EMS solution as well. Using the indoor space as the temporary energy storage medium, the EMS can schedule the heaters' operation to satisfy the customer demands in living comforts and bill savings. The performance of EMS was tested by three 2-hour data of RTP in case studies. Meanwhile, the cost comparison among proposed control approach, one-hour preheating and half-hour preheating control approaches was presented as well. The results proved the capability of the proposed EMS to improve cost saving and level of comfort. Furthermore, in order to verify the feasibility of the proposed EMS, a physical platform including control units, monitoring units and EPC has been established. A series of tests have shown that the proposed EMS can operate in a real environment.

Chapter 4 A Integrated Real-time HEMS Solution for Smart Homes

4.1 Introduction

In the previous chapter, an EMS system for optimizing the operation of residential space heating system has been proposed. However, considering other home appliances, distributed renewable energy generators and energy storage system, the EMS which only supports the heating & cooling system optimization cannot fulfill the increasing requirements of customers in energy savings and joining the emerging energy service (e.g. DR program). This chapter proposes a real-time control approach for HEMS, which manages the air conditioner (AC), clothes dryer (CD), Water Boiler (WB), photovoltaic generator (PV), electric vehicle (EV) and battery energy storage system (BESS). The proposed control approach uses 30-minute-ahead rolling optimization (RO) and real-time control strategy (RTCS) to manage the devices, in order to provide economic benefits to customers using RTP tariff. In addition, with the purpose of enabling Demand Response (DR) service for customers; a DR mechanism is developed in the proposed real-time control approach, which helps customers earn extra benefits from this emerging energy service. Moreover, in order to efficiently utilize the qualitative knowledge in managing the BESS, a fuzzy logic controller (FLC) is utilized to optimize the charging/discharging power; the rules of the FLC consider both electricity price and energy demands of the residents. The measure of the proposed control approach is presented in case studies. The full day imported electricity, EV charging rates, Battery operation characteristics and other key factors in different cases (including extreme case) are presented. The case studies also give the comparison of the energy cost between the houses with/without the proposed EMS for all the cases, which indicate the energy saving capacity and the effectiveness in executing DR program of the control approach. Lastly a physical test platform including battery ESS, PV and dynamic loads have been established in the lab for testing the whole system. The results of the tests completed on the test bed are given, and the feasibility of proposed control approach is proved.

4.2 HEMS System Model

4.2.1 Demand Response Mechanism and RTP Tariff

The modern electricity tariff and participation incentives are the mainstream methods to promote end users join the DR service because end users can achieve energy bill savings and get revenue from the electricity supply chain [130, 131]. Considering the current DR programs running in distribution work, most of the DR programs limit the peak loads of the households within the given threshold power value during the specific period when the total load of the grid is relatively high [131]. If the household loads can be limited as required during certain periods, the households can gain certain revenue or discount energy price from the DR Service suppliers. The RTP tariff is applied in the research as well, given the growth of modern tariffs. It provides relatively low but changeable price of the electricity to customers based on the real-time demands in the electricity market. The end users using RTP tariff can get the forecasted price information of RTP one day in advance from the energy supplier or distributors and plan their energy using based on the forecasted information. In addition, the charge of RTP has further divisions according to the energy consumption of households. The end users need pay extra money once their importation of electricity exceeds the limitation specified on the contract as well. Therefore, the maximum demands limitation in both common time and the DR events are taken into account to form the DR mechanism in the proposed control approach. In order to accurately process the proposed control approach, a contract is assumed to be signed between households and energy retailer or aggregators, and the restricted contexts are described as follows.

(1) The charge of household power in common time is based on the RTP C_{rt}^{t} when it does not exceed maximum power P_{grid}^{max}; the part in the excess of P_{grid}^{max} is charged with the price (1+δ_{pun}) C_{rt}^{t}.

(2) The households have the permission of selling electricity with the RTP C_{se}^{t} to the grid.

(3) Once the DR request is activated, the households should keep the amount of importation power under the agreed power limitation P_{DR}^{limit}.

(4) If the households do limit the power under the P_{DR}^{limit} during the period when DR event is activated, they will receive revenue with the amount equal to

$\delta_{ev} \cdot P_{DR}^{limit} \cdot \Delta t$.

(5) The households will face a punitive charge once the import power exceeds the power limit P_{DR}^{limit} when DR event is activated. Apart from the part of the import power under the P_{DR}^{limit} which is charged with the normal RTR C_{rt}^{t}, the excessive part of the import power will be charged at the rate $(1 + \delta_{DR}) \cdot C_{rt}^{t}$ when the total import power is larger than the P_{DR}^{limit} but smaller than P_{grid}^{max}. If the total import power is even larger than the common time limitation power P_{grid}^{max} during DR event, the punitive charge of the excessive part of import power over P_{grid}^{max} will be taken at the price $(1 + \delta_{pun}) \cdot C_{rt}^{t}$.

(6) The households will receive a notification of the 'start' and 'stop' time of the DR event from the retailer or aggregator with certain time period T_{DR}^{ad} before DR event starts.

(7) The number of DR events will not exceed the number N_{DR}^{max} within one day.

(8) The duration of one single DR event should be no longer than $T_{DR\_per}^{max}$; the total duration of the DR events in a whole day should be no longer than $T_{DR\_total}^{max}$; the time interval between any two DR events should be longer than T_{DR}^{inv}.

Based on the rules of the contract shown above, the mechanism of DR Service can be established as follows:

$B_t =$

$$
\begin{cases}
C_{rt}^{t} \cdot P_{grid}^{max} \cdot \Delta t + \left(\left(1+\delta_{pun}\right) \cdot C_{rt}^{t}\right) \cdot \left(p_{grid}^{t} - P_{grid}^{max}\right) \cdot \Delta t & p_{grid}^{t} > P_{grid}^{max} \\
\quad +\delta_{DR} \cdot C_{rt}^{t} \cdot \left(P_{grid}^{max} - P_{DR}^{limit}\right) \cdot \theta_{DR}^{t} \cdot \Delta t & \\
C_{rt}^{t} \cdot p_{grid}^{t} \cdot \Delta t + \delta_{DR} \cdot C_{rt}^{t} \cdot \left(p_{grid}^{t} - P_{DR}^{limit}\right) \cdot \theta_{DR}^{t} \cdot \Delta t & P_{DR}^{limit} < p_{grid}^{t} \le P_{grid}^{max} \\
C_{rt}^{t} \cdot p_{grid}^{t} \cdot \Delta t - \delta_{rev} \cdot P_{DR}^{limit} \cdot \theta_{DR}^{t} \cdot \Delta t & 0 \le p_{grid}^{t} < P_{DR}^{limit} \\
-C_{se}^{t} \cdot p_{grid}^{t} \cdot \Delta t - \delta_{rev} \cdot P_{DR}^{limit} \cdot \theta_{DR}^{t} \cdot \Delta t & p_{grid}^{t} < 0
\end{cases}
\tag{4.1}
$$

where ΔB_t represents the electricity bill between time t and $t + \Delta t$ ($); C_{rt}^{t} refers to the electricity price of RTP ($/kWh); Δt is the unit time interval (h); p_{grid}^{t} refers to the import/export power between the household and the grid (kW) (the value of p_{grid}^{t} is positive when households import/buy power from the grid; the value of p_{grid}^{t} is negative when households export/sell power to the grid); δ_{pun} denotes the factor of punitive charge rate for the excessive part of imported power P_{grid}^{max} in common time; δ_{DR} denotes the factor of punitive charge rate for the excessive part of the imported power exceeding P_{DR}^{limit} during DR event; δ_{rev} is the factor of earnings when the power of household is limited under P_{DR}^{limit}; θ_{DR}^{t} is a binary number which represents the status of DR event (1 = 'DR event active'; 0 = 'DR event inactive'); C_{se}^{t} denotes electricity sell/export price to the grid ($/kWh).

4.2.2 Constraints of Individual Appliances

The HEMS aims to optimize the operation of controllable devices in the home to achieve energy bill saving for customers. However, the HEMS should follow the operation rules of the devices when it is managing them. Hence, the operation constraints of the appliances, including the home appliance such as WB, AC, CD and

EV, the DERs such as PV system and BESS, are presented.

(1) Constraints of WB

There are only two working status for WB, which are 'on' and 'off'. 'On' refers to the status of EWH working with the rated power p_{EWH}. The temperature in the water tank is within the temperature range $\left[T_{outlet}^{min}, T_{outlet}^{max}\right]$. Thus, the temperature constraint of EWH can be concluded as equation 4.2.

$$T_{outlet}^{min} \leq T_{outlet}^{t} \leq T_{outlet}^{max} \tag{4.2}$$

where T_{outlet}^{t} denotes the temperature of water (℉) in the water tank at time *t*.

According to the mathematical model of WB built by Paper [132] , the water tank temperature is described as function 4.3.

$$T_{outlet}^{t+\Delta t} = \frac{T_{outlet}^{t} \cdot (V_{tank} - fr^{t} \cdot \Delta t)}{V_{tank}} + \frac{T_{inlet} \cdot fr^{t} \cdot \Delta t}{V_{tank}} + \frac{1gal}{8.34lb} \cdot [p_{EWH}^{t} \cdot \frac{3412Btu}{kWh} - \frac{A_{tank} \cdot (T_{outlet}^{t} - T_{room}^{t})}{R_{tank}}] \cdot \frac{\Delta t}{60\frac{min}{h}} \cdot \frac{1}{V_{tank}} \tag{4.3}$$

where V_{tank} denotes the water tank size (gallons); fr^{t} represents the hot water flow (gallons/minute); T_{inlet} represents the water temperature of tank inlet (℉); p_{EWH}^{t} denotes the EWH rated power (kWh); A_{tank} refers to the contact area of the water tank with the air (ft^2); T_{room}^{t} refers to the indoor temperature (℉); R_{tank}

refers to the heating core in the tank (℉·ft² ·h/Btu).

(2) Constraints of AC

Similar to radiators, AC has the 'on' and 'off' working status. It operates with the rated power p_{AC} (kW) once turned on. The temperature working range of AC can be described as $[T_{outlet}^{min}, T_{outlet}^{max}]$. Thus, the temperature constraint of AC is given by:

$$T_{room}^{min} \leq T_{room}^{t} \leq T_{room}^{max} \tag{4.4}$$

With the consideration of the thermal factors, the indoor temperature can be written as [133]:

$$T_{room}^{t+\Delta t} = \varepsilon_{air} \cdot T_{room}^{t} + (1 - \varepsilon_{air}) \cdot (T_{out}^{t} + \eta_{AC} \cdot p_{AC}^{t} / \kappa_{air}) \tag{4.5}$$

where ε_{air} refers to the air inertia; T_{out}^{t} represents the outdoor temperature (℉); η_{AC} denotes the AC working efficiency; κ_{air} represents the thermal conductivity (kW/℉).

(3) Constraints of CD

CD should operate for a certain period T_{CD}^{task} in certain time horizon $[T_{CD}^{start}, T_{CD}^{end}]$, which is configured by the users. p_{CD} (kW) is the power of CD . The operation constraints of CD are given by:

$$S_{CD}^{t} = 0 \; (t < T_{CD}^{start}, t > T_{CD}^{end}) \tag{4.6}$$

$$\sum_{t=T_{cd}^{start}}^{T_{CD}^{end}} S_{CD}^{t} \cdot \Delta t = T_{CD}^{task} \tag{4.7}$$

where S_{CD}^{t} is a binary data representing the working status of the CD (1='on', 0='off').

(4) Constraints of EV

The constraints of EV are similar to the constraints of CD because users need to configure the charging time horizon $[T_{EV}^{start}, T_{EV}^{end}]$ and the required charging period T_{EV}^{task} as well. The EV needs to complete the charging period T_{EV}^{task} during the time range $[T_{EV}^{start}, T_{EV}^{end}]$ with charging power p_{ev} (kW). The constraints of EV can be written as:

$$S_{EV}^{t} = 0 \ \ (t < T_{EV}^{start}, t > T_{EV}^{end}) \tag{4.8}$$

$$\sum_{t=T_{EV}^{start}}^{T_{EV}^{end}} S_{EV}^{t} \cdot \Delta t = T_{EV}^{task} \tag{4.9}$$

where S_{EV}^{t} is a binary data representing the charging status of EV (1='on', 0='off').

(5) Constraints of BESS

For all the lithium-ion battery systems, there is fixed stated of charge (SOC) range $[SOC_{min,} SOC_{max}]$, which protect the battery modules from over-charge and over-discharge. In addition, considering the energy transition efficiency and certain self-consumed power of the bidirectional inverters, the charging/discharging power of the inverter should be larger than a certain level but smaller than the maximum power of inverter. Figure 4-1 verifies the charging/discharging efficiency of the inverter in different charging/discharging power; the efficiency of the inverter is relatively low when the power is smaller than 300W. Thus, a threshold charging/discharging power value is configured for the inverter.

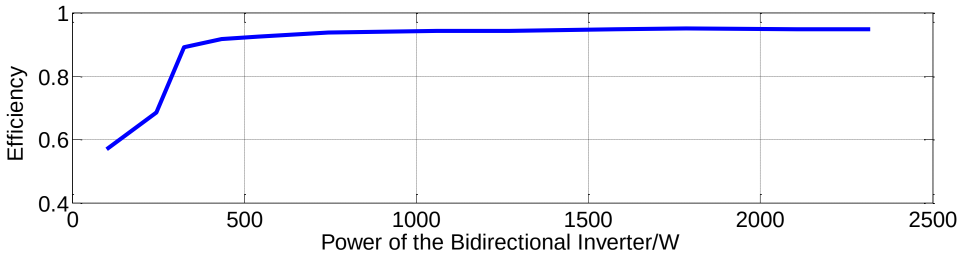

Figure 4-1 Working Efficiency of the Bi-directional Inverter

On account of the required operation conditions of the BESS discussed above, the constraints of the battery system are written as:

$$\mathrm{SOC}^t = E_{BT}^t / E_{BT}^{cap} \tag{4.10}$$

$$SOC_{min} \leq \mathrm{SOC}^t \leq SOC_{max} \tag{4.11}$$

$$P_{BT\_ch}^{min} \leq p_{BT}^t \leq P_{BT\_ch}^{max} \qquad \text{if } \ p_{BT}^t > 0 \tag{4.12}$$

$$P_{BT\_disch}^{max} \leq p_{BT}^t \leq P_{BT_{disch}}^{min} \qquad if \ \ p_{BT}^t < 0 \tag{4.13}$$

$$E_{BT}^{t+\Delta t} = \begin{cases} E_{BT}^t + p_{BT}^t \cdot \eta_{BT}^{ch} \cdot \Delta t & p_{BT}^t \geq 0 \\ E_{BT}^t + p_{BT}^t \cdot \eta_{BT}^{disch} \cdot \Delta t & p_{BT}^t < 0 \end{cases} \tag{4.14}$$

where SOC^t denotes the BESS SOC; p_{BT}^t represents the charging/discharging power of the battery system (kW) (positive value represents charging, where the direction of power flow is from grid to battery ; negative value represents discharging, where the direction of power flow is from battery to grid); The $P_{BT\_ch}^{min}$ and $P_{BT\_ch}^{max}$ represents the inverter min and max charging power (kW) ; $P_{BT\_disch}^{min}$ and $P_{BT\_disch}^{max}$ represent the inverter min and the max discharging power (kW); E_{BT}^{cap} represents the battery energy storage capacity (kWh), we assume the State of Health (SOH) of the battery is 100%, thus the SOH does not need take into account; E_{BT}^t represents the real-time energy stored in the battery(kWh); η_{BT}^{ch} and η_{BT}^{disch} denote the charging and discharging efficiency of the BESS respectively.

(6) Power Balance

The sum of the power consumed by household appliance, imported from grid, generated by PV system and transmitted by the battery system should be 0, which is given by equation 4.15.

$$p_{grid}^{t} + p_{\mathrm{PV}}^{t} - p_{EWH}^{t} - p_{AC}^{t} - S_{\mathrm{CD}}^{t} \cdot p_{CD} - S_{\mathrm{EV}}^{t} \cdot p_{EV} - p_{CL}^{t} - p_{BT}^{t} = 0 \qquad (4.15)$$

where p_{CL}^{t} denotes the CL power.

4.3 HEMS Optimization Approach

4.3.1 General Overview of the Optimization Approach

The control approach proposed in this chapter combines the half-hour ahead RO and RTCS to manage the devices in the household, which is shown in Figure 4-2.

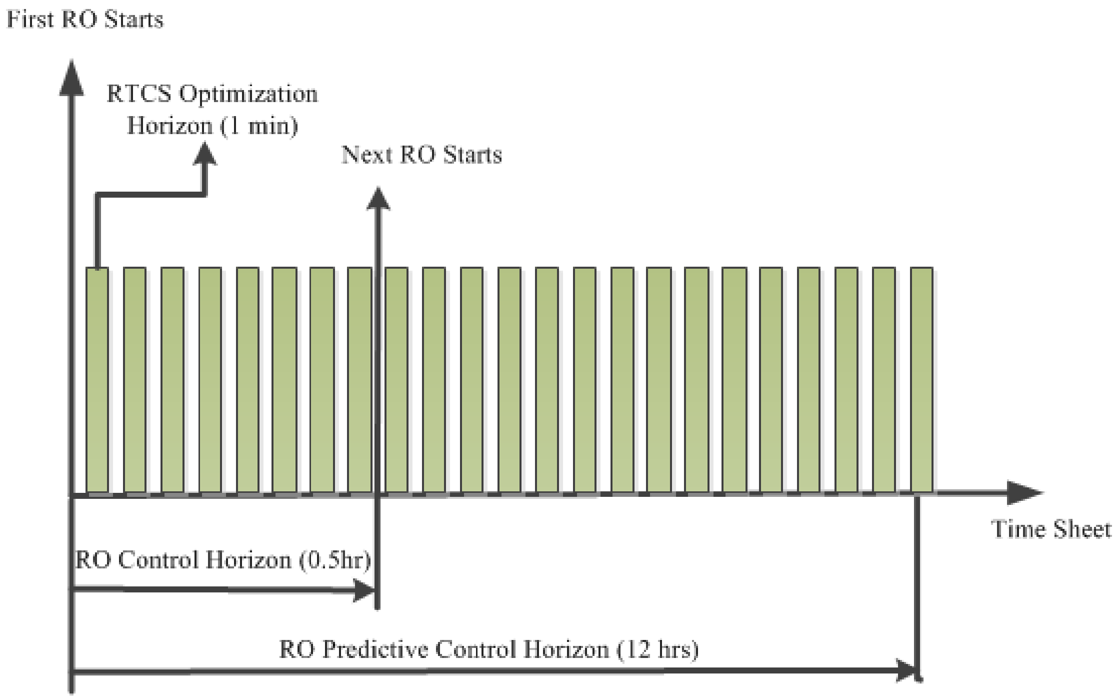

Figure 4-2 HEMS Optimization Approach

The RO starts optimizing every 30 minutes and will optimize the operation of the home appliances and DERs for a whole day. Considering the changes of the variables such as the working state of wash machine, water boiler and other home appliances, the optimization results of RO will be adopted for controlling the household devise for the next 30 minutes. Based on the operation mechanism of the proposed RO, the RO is also known as Model Predictive Control (MPC). After obtaining the computation results from the current RO, RTCS will start working during the time interval between two ROs. The RTCS will optimise the operation of household appliances and DERs every minute during the time interval between two ROs. The RO computation results will validate in the time interval before the next RO starts. However, during the 30-minute time interval of every two RO, the working state of the home applications included in the RO can still change, which will make the current RO result cannot perfectly fit the operation of the home appliances. In addition, due to the error between predicted information and real-time information of household appliance and DERs and the RO cannot adjust the optimization results during the 30-minute time interval, the optimisation result of RO cannot response the changing generations of the DERs. Thereby, the RTCS is integrated with the RO, which adjusts the optimization results of RO in real-time.

4.3.2 Rolling Optimization

The objectives of RO can be stated as: scheduling the controllable loads to reduce the energy consumption in peak time; charging the battery during the off-peak time; feeding the energy consumption of the household appliances through the BESS during peak time. The objective function of RO can be described as:

$$B_{RO} = B_1 + \sum_{j=2}^{N} B_j \tag{4.16}$$

where the B_{RO} represents the total energy bill calculated based on the RO; the $B_i = (i = 1,2, \ldots, N)$ represents the energy bill of household in the time interval i and it is calculated based on equation 4.1; N denotes the number of ROs have been taken.

The DR event occurs with random frequency and the period of DR event can be longer than the time interval of two ROs; thereby the DR event will not perfectly fit the RO as shown in Figure 4-3. To solve the DR optimization problem in RO, the method is introduced below.

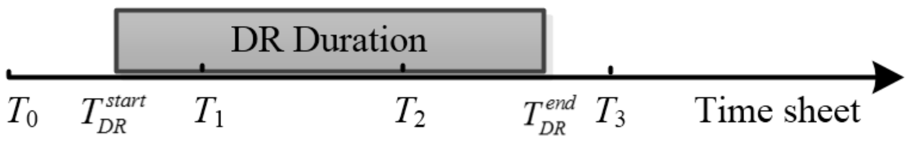

Figure 4-3 Illustration of the DR event

The two parameters T_{DR}^{start} and T_{DR}^{end} for the start/stop time of the latest DR event are informed in advance, hence the binary data of θ_{DR}^{i} representing the status of DR event in time interval *i* can be determined. Once the DR event takes up more than half of the time period of interval *i*, the θ_{DR}^{i} should be determined as 1; otherwise the θ_{DR}^{i} is 0. For instance, in Figure 4-3, there is a DR event across three time intervals. From T_0 to T_1, $T_1 - T_{DR}^{start} < 0.5 \cdot \Delta t$, hence $\theta_{DR}^{0} = 0$; from T_1 to T_2, the DR event is in operation during the whole period, so $\theta_{DR}^{1} = 1$; from T_2 to T_3, $T_{DR}^{end} - T_2 > 0.5 \cdot \Delta t$, so $\theta_{DR}^{2} = 1$.

In addition, it should be mentioned that both CD and EV are task-oriented devices. The working period of CD and EV cannot always be integral multiple of the RO time interval (half-hour) as DR event does, which means there will be non-integral value in the integral programming of RO. To solve this problem, the scheduling of CD/EV is calculated at the beginning of each RO and the result of the remaining duration divided by time interval is rounded to the nearest integer. However, the forced conversion from non-integral to integral will bring error in operation (e.g. the system may force the CD work 30 minutes although it only needs 20-minute operation), Thus, the adjustment of the start/stop working time will be achieved by the RTCS, which will be introduced in section 4.4.3.

Moreover, users could configure the time range of completing the EV's and CD's tasks longer than the default optimization time range of RO. In order to help the RO process such requirements properly, the method introduced below is adopted in the RO.

The default time length scheduled by RO for each round is configured as 12 hours. If the working time range of CD/EV is shorter than 12 hours, the RO will cover the operation of CD and EV in current round. If the time range is longer than 12 hours, the optimization of CD and EV will move to the next RO till the time range is shorter than the default length and be optimized by RTCS.

For the required data by RO, the information of appliances, PV and BESS can be collected by the metering units but the prediction data cannot be obtained locally. We assume that the forecasted RTP information are provided by retailer or aggregator; the temperature and weather data are provided by the meteorological department or other similar third-party organizations; the predicted data of solar generation and other home appliances are forecasted through the HEMS with ARIMA model based on the historical data [134].

4.3.3 Real-Time Control Strategy

The working status of the household appliance will not always be constant during the half-hour time interval of RO; that means the RO results will not perfectly fit the condition when the device working states change during the time interval. In order to obtain better scheduling results, a minute-based RTCS is applied in the HEMS too. The operation steps of the RTCS are given below:

(1) The working states of home appliances are initialized across the results from current RO.

(2) As the working states of appliances could change during the time interval between two ROs, the real-time data of appliance will be collected again to check with the RO results. If the working state and configurations are changed, the input data to RTCS will be updated.

(3) Once the states of all the household devices are updated, the household electric demands will be calculated.

(4) In the RTCS, the maximum power represents both P_{DR}^{limit} during DR event and P_{grid}^{max} during the common period. The RTCS will use the max BESS discharging power, PV power, residential loads (negative value) and maximum power (negative value) to calculate the power gap.

(5) Once the power gap is negative, it means the current scheduling plan cannot fulfill the limitation of import power. Then the RTCS will turn off some running devices based on the power gap. Thus, the priority should be configured for the home appliances, which helps RTCS to determine the turning off order of the appliances if the maximum import power cannot be

limited under the threshold value. The priorities of AC, WB, CD and EV are configured from high to low. The device with lowest priority will be turned off first.

(6) If the working states of home appliances do change in step 5 due to the maximum power limitation, the changed states will be updated in the RTCS.

(7) Later on, the BESS charging/discharging power will be calculated based on the FLC (The working mechanism of FLC for BESS will be explained in section 4.3.4)

(8) At last, all the states of household devices and BESS are determined by the previous steps; the control commands will be dispatched through the HEMS.

It is worth mentioning that the methods in solving the constraint violations or unstable regulations are still open. The Robust Model Predictive Control (RMPC) and Soft-Switching method can also be implemented to adjust the operations of the home appliances and DERs.

4.3.4 Fuzzy Logic Controller for BESS

The determination of the BESS operation is made in step 7 of the RTCS operation, which is the last determination among all the in-home devices. This is because the BESS can charge or discharge at different power rates, which is much more complex than the control of the home appliances. From the point of economic interests, the basic rule for the BESS is charging during low price period and discharging during high price period. However, the customers will face punitive charge if the import power cannot be limited below maximum power, and the punitive charge could be higher than the economic benefits gained by the BESS using the basic rules. Therefore, the control the BESS should not only consider the economic interests by trading the energy in the battery, but also the punitive charge of exceeding the maximum power. Moreover, the charging/discharging power of the BESS does not only rely on the power consumption and generation of household appliances and renewable generators but also the electricity price, working efficiency of inverter and the state of battery itself. All the mentioned factors above will influence the charging/discharging power of BESS and correspondingly the determination of the charging/discharging power is complex. Thus, a FLC is introduced to BESS to control the charge/discharge power of BESS.

The developed FLC for the BESS includes four components, which are fuzzification, interface, rule base and defuzzification [135]. The structure of the FLC is presented in Figure 4-4.

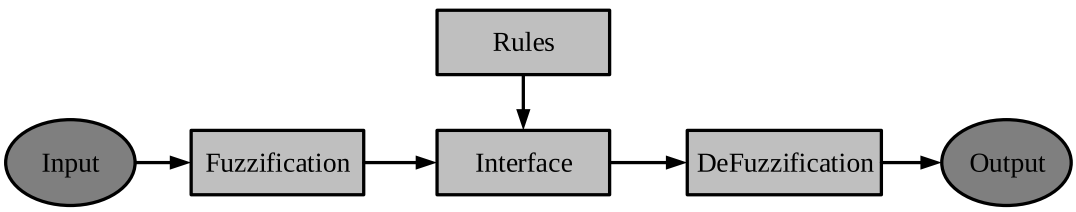

Figure 4-4 FLC Structure for BESS

The inputs of FLC are the electricity price and the SOC of battery modules in BESS; the outputs of the FLC are the determined charging/discharging power.

In the BESS, both the inputs (electricity price and battery SOC) are linguistic variables, which cannot be used in the FLC directly. In order to convert the non-fuzzy inputs to the fuzzy inputs, a trapezoidal membership function is applied in the FLC. The linguistic variable labels are defined as Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH) for both electricity price and battery SOC. The output (charging/discharging power of BESS) is fuzzified into six linguistic variables, which are Discharge High (DH), Discharge Medium (DM), Discharge Low (DL), Charge Low (CL), Charge Medium (CM), and Charge High (CH). The membership functions of the electricity price, battery SOC and the charging/discharging power of BESS in the FLC are presented in Figure 4-5, Figure 4-6 and Figure 4-7 respectively.

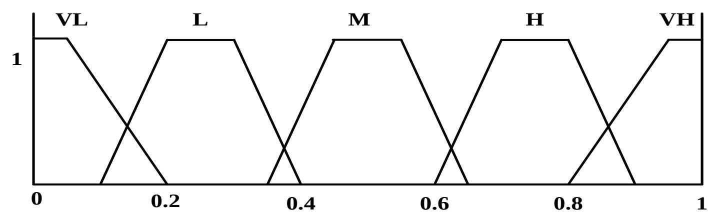

Figure 4-5Membership function of electricity price

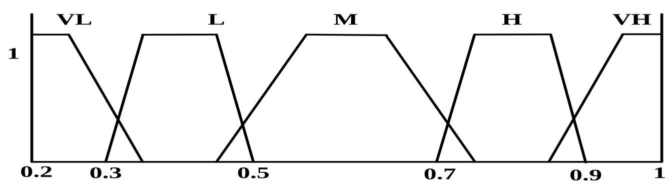

Figure 4-6Membership function of the SOC

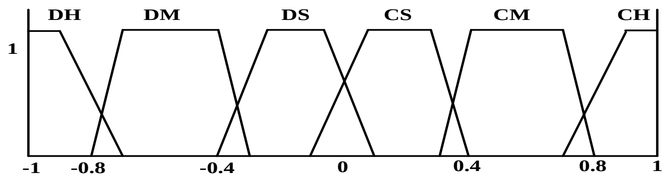

Figure 4-7Membership function of the charging/discharging power

The fuzzy inference adopts the Mamdani model; the implication of the rules utilizes the minimum function and the defuzzification of the FLC applies the largest of maximum method. The fuzzy rules of the FLC are given in Table 4-1. .

Price / SOC	VL	L	M	H	VH
VL	CH	CM	CL	DL	DL
L	CH	CM	CL	DL	DM
M	CM	CL	DL	DM	DH
H	CM	DL	DM	DH	DH
VH	CL	DM	DH	DH	DH

Table 4-1 The Set of Rules for FLC

In addition, except the FLC applied for optimizing the operation of BESS, some operation rules should be defined as well to ensure the economic benefits for the users who own the BESS. Considering the charging/discharging efficiency, PV spare energy storage and direct buying price from grid, the charging/dicharging price of the battery C_{BT}^{t} (\$/kWh) are given by equation 4.17, 4.18and 4.19.

The charging price of battery system using the spare power of PV:

$$C_{BT}^{t+\Delta t} = (C_{BT}^{t} \cdot E_{BT}^{t} + C_{se}^{t} \cdot p_{BT}^{t} \cdot \Delta t)/E_{BT}^{t+\Delta t} \quad (4.17)$$

The charging price of battery system using power from the grid:

$$C_{BT}^{t+\Delta t} = (C_{BT}^{t} \cdot E_{BT}^{t} + C_{rt}^{t} \cdot p_{\mathrm{BT}}^{t} \cdot \Delta t)/E_{BT}^{t+\Delta t} \quad (4.18)$$

The discharging price of battery:

$$C_{BT}^{t+\Delta t} = C_{BT}^{t} \quad (4.19)$$

According to the above equations, the operation rules for determining the charging/discharging power of BESS are given in Figure 4-8. The explanations are presented downside the figure.

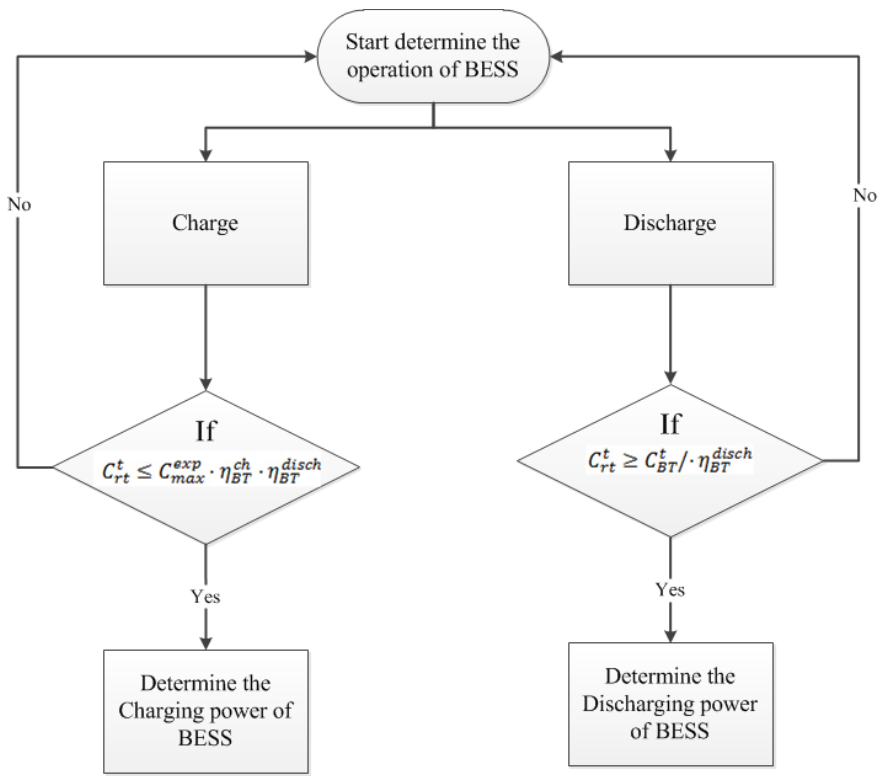

Figure 4-8 Operation Rules of BESS

(1) Due to the loss in charging and discharging process, the BESS can only be charged when the equation $C_{rt}^{t} \leq C_{max}^{exp} \cdot \eta_{BT}^{ch} \cdot \eta_{BT}^{disch}$ is satisfied, where C_{max}^{exp} is the maximum price in the forecasted RTP during a day ($/kWh).

(2) To ensure the economic benefits obtained by discharging the BESS, the equation $C_{rt}^{t} \geq C_{BT}^{t} / \cdot \eta_{BT}^{disch}$ should be satisfied with the consideration of discharging efficiency and the battery charging costs.

The two rules above regulate the charging/discharging activities of BESS and ensure the economic benefits to customers.

4.4 Case Studies

4.4.1 Simulation Results

In order to validate the performance of the proposed control strategy, a test bed is established in MATLAB. The constraints of the devices introduced in the HEMS model section are formulated based on the real devices running in home/lab and research papers.

The capacity of PV system is configured as 4.8kW, which refers to the residential PV kit introduced in paper [136]. The capacity of the battery system is configured as 24kWh, which is considered as a second-life automotive battery used in Nissan Leaf [137]. For the EV in the test bed, it is configured equal to the size of Peugeot I.ON EV; whose battery capacity is 16kWh. The parameters of home appliances refer to the parameters proposed in the literatures [132, 133, 138, 139]. The key parameters used in the simulation are listed in Table 4-2.

Parameters	Value	Unit	Parameters	Value	Unit
V_{tank}	100	Gallons	P_{AC}	2.352	kW
T_{inlet}	50	°F	P_{CD}	3.7	kW
A_{tank}	27	ft^2	P_{EV}	3.3	kW
R_{tank}	18	°F ft^2 h/Btu	E_{BT}^{cap}	24	kWh
p_{EWH}	4.5	kW	η_{BT}^{ch}	0.91	-
η_{AC}	3.5	-	η_{BT}^{disch}	0.91	-
ε_{air}	0.95	-	$SOC_{\min}$	0.2	-
κ_{air}	0.25	kW/ °F	$SOC_{\max}$	1	-
$P_{BT\_ch}^{min}$	0.3	kW	$P_{BT\_ch}^{max}$	4	kW
$P_{BT\_disch}^{min}$	-0.3	kW	$P_{BT\_disch}^{max}$	-4	kW

Table 4-2 Key Parameters of Devices

Furthermore, the HEMS model should satisfy the living comfort requirements of customers and the contracts between residents and energy suppliers. Thus, some parameters related to living comforts and the contracts are configured. The water temperature of WB is limited within the range 108 °F-122 °F. The indoor temperature is configured within the range 72 °F - 82 °F. For the DR mechanism, the key parameters are configured as: p_{grid}^{max}=10kW, p_{DR}^{limit}=4kW, $C_{se}^{t} = C_{\mathrm{rt}}^{t}/2$, $\delta_{pun} = 1$, $\delta_{DR} = 0.5$, $\delta_{rev} = 0.2$, $T_{DR}^{ad} = 0.25$, $N_{DR}^{max} = 4$, $T_{DR\_per}^{max} = 1h$, $T_{total}^{max} = 4h$ and $T_{DR}^{inv} = 1.5h$.

The price information is the critical factor in the proposed control approach, which will determine the operation of the devices and the DR events. The RO and RTCS require the forecasted price data and real-time data of RTP to execute the optimization respectively. The one-day real-time price and forecasted price of RTP are presented in Figure 4-9 based on the price data in [140]. In the case studies, it is assumed that the HEMS can get the next half-hour real-time electricity price and the next 24 hour forecasted price data every half hour from the DNOs or energy retailers.

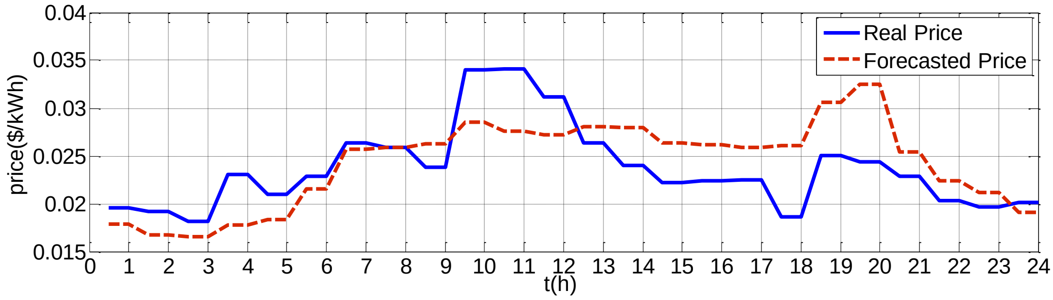

Figure 4-9 Forecasted RTP and actual RTP

Three cases are established to test the performance of the proposed control strategy for the household devices. The running conditions for all three cases are the same except the activation periods of DR events and the power of critical load (CL) in certain periods. The one-day power rates of critical load are given in Figure 4-10. In order to analyse the performance of the real-time control approach in extreme conditions, additional 4kW critical load is added temporarily in Case C during 17:00 – 18:00, which is shown in Table 4-3.

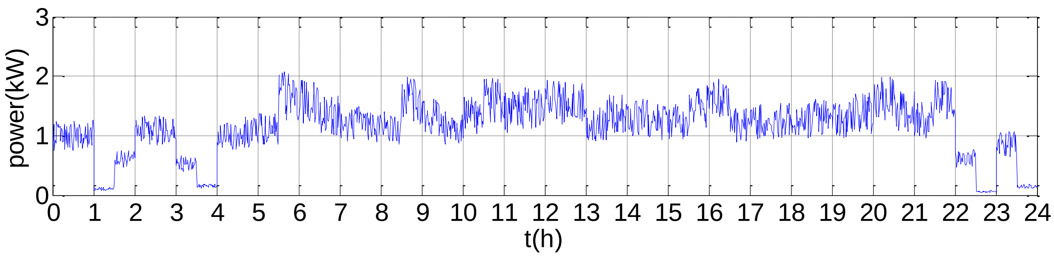

Figure 4-10 One-Day Power Curve of CL

The information of DR events are introduced in Table 4-3. The DR events of the three Cases are distributed in different peak-time periods. Each of the cases has some shared DR event periods, which makes commonality among them. For the task-oriented devices CD and EV, the EV is required to be charged for 4 hours during 17:30 – 24:00; the CD is ought to work for 2 hours between 17:00 and 21:00.

	DR Event Time Periods	Power of CL
Case A	8:45-9:45; 11:45-12:45; 21:00-22:00	Basic CL
Case B	11:45-12:45;17:00-18:00;21:00-22:00	Basic CL
Case C	11:45-12:45; 17:00-18:00;21:00-22:00	Basic CL, additional 4kW during 17:00-18:00

Table 4-3 Overview of Three Cases

Based on the above configuration of the household devices and DR events, the results of all three cases between 17:00 – 24:00 are presented in Figure 4-11, Figure 4-12and Figure 4-13 respectively. The yellow areas in the three figures refer to the DR events activation periods. The Case A and B have same critical loads and same devices except the running time of DR events, which aims to evaluate the performance of the proposed control strategy in different DR event time periods. The Case C has additional critical loads during DR events and one more DR event compared to Case C during 17:00 – 24:00, which helps evaluate the performance of the control strategy in extreme conditions. The functional state of all the devices for all three cases are listed in Table 4-4, where '√' refers to 'on' and '×' refers to 'off' for the household devices.

	Case A				Case B				Case C			
Time	WB	AC	CD	EV	WB	AC	CD	EV	WB	AC	CD	EV
17:00-17:30	√	√	×	×	√	√	×	×	×	√	×	×
17:30-18:00	√	×	√	√	×	×	×	√	17:40-18:00	×	×	×
18:00-18:30	×	√	×	×	×	√	×	×	×	√	×	×
18:30-19:00	×	×	×	×	×	×	×	×	×	×	×	×
19:00-19:30	×	×	×	√	×	×	√	×	×	√	√	×
19:30-20:00	×	√	√	×	×	√	√	×	×	×	√	×
20:00-20:30	×	√	√	×	√	×	√	×	√	×	√	√
20:30:21:00	√	×	√	×	√	×	√	√	√	×	√	√
21:00-21:30	×	×	×	√	×	√	×	√	×	√	×	√
21:30-22:00	×	×	×	√	×	×	×	√	×	×	×	√
22:00-22:30	×	√	×	√	×	√	×	√	×	√	×	√
22:30-23:00	×	√	×	√	×	√	×	√	×	√	×	√
23:00-23:30	×	×	×	√	×	×	×	√	×	×	×	√
23:30-24:00	×	√	×	√	×	√	×	√	×	√	×	√

Table 4-4 Device Operation List of All Three Cases after Optimization

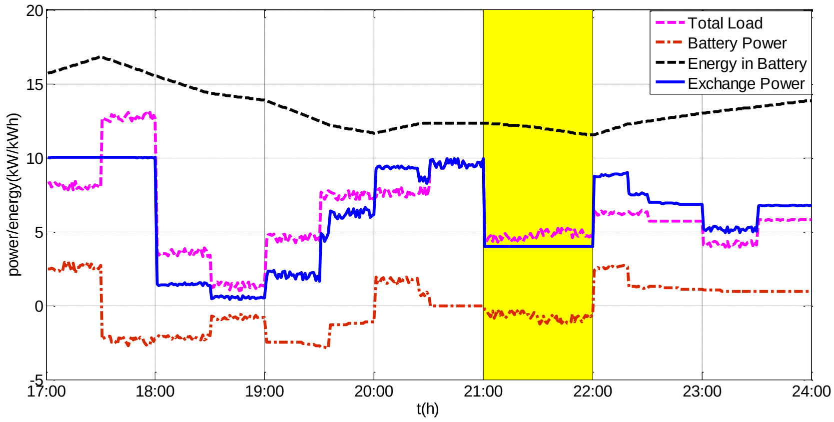

Figure 4-11 Case A Results during 17:00-24:00

According to the results of Case A shown in Figure 4-11, the import power of the household does not exceed the contracted maximum power 10kW during the entire period, which avoids the punitive charge of exceeding the import power limits in normal time. Because of the relatively low price period during 17:00-18:00, the household power is kept at maximum power 10kW, which ensures the customers can get full benefit of low price energy. In addition, the battery system is being charged in the first half hour of 17:00-18:00 to store energy for peak-time use. However, in the other half hour of 17:00-18:00, the power flow of battery system changes from charging to discharging immediately to compensate the power demands of CD and EV, elsewise the householders will face the punitive charge of exceeding the 10kW threshold. During 18:00 – 20:00, the import power is kept at a low level with the assistance of battery discharging and load shifting when the electricity price is high. Although there is serious forecasting error of the electric price during 18:00 – 20:00, the RO and RTCS kept the battery discharge at a reasonable level rather than discharge the battery with maximum power to offset the energy cost calculated by mistakenly forecasted price. During the DR event from 21:00 to 22:00, the import power is regulated under the threshold power rate successfully; the power suspected to be consumed in this period is shifted to the later time periods with low electricity price.

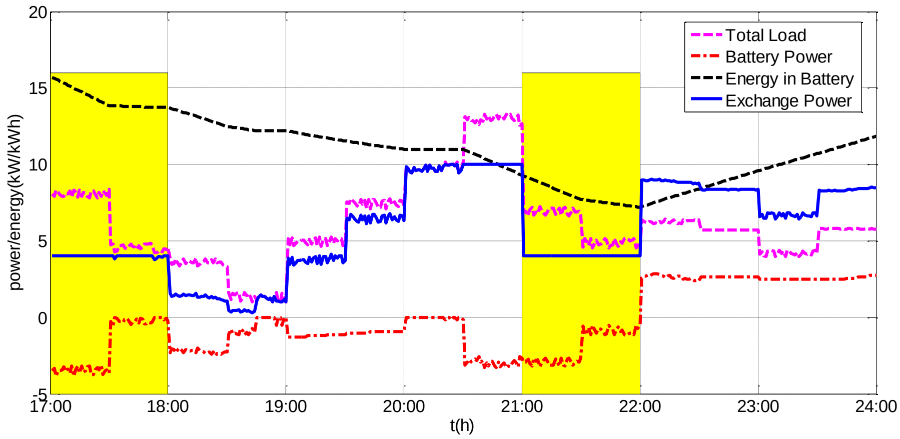

Figure 4-12 Case B Results during 17:00-24:00

Case B has the same pre-set configurations as Case A except the DR events. As shown in Figure 4-12, there is one more DR event existing in Case B, which occurs during the period from 17:00 to 18:00. It is noted that the import power rate is limited under the threshold power for both DR events. Because of the import power limitation during DR events, the load of WB and CD are shifted to night time to avoid the punitive charge. From 18:00 to 21:00, the import power was limited in low level during 18:00 and 20:00 but jump to a high level during 20:00-21:00. This is because the power consumption are limited by two DR events for two hours; some of the controllable loads have to be shifted to the relatively high price time periods. However, benefit by the stored energy in the battery system, 8.5kWh energy is contributed to fit the gap during the two DR events, which effectively reduce the energy cost of customers during the high price period.

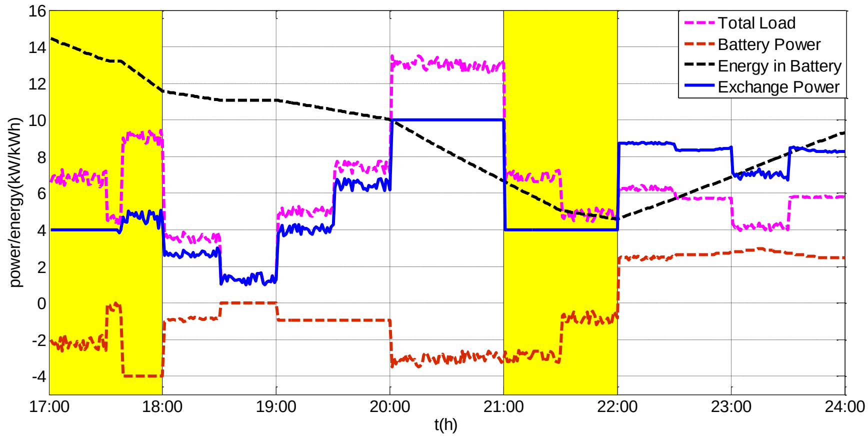

Figure 4-13 Case C Results during 17:00-24:00

Case C has two DR events and 4kW additional power on CL loads as shown in Figure 4-13. Due to the extreme condition in Case C, the system fails to satisfy the DR events during 17:40-18:00. This is caused by the sudden large amount of hot water usage and the WB is forced to start working immediately to provide hot water to the customers. Although the battery has discharged with maximum discharging power and the controllable loads are shifted to the other time periods during the DR events, the import power can still not be limited under the contracted power rate. It indicates that the uncontrollable factors such as sudden hot water usage, cooking and rain/snow would lead to failure to satisfy the DR events. One potential way of solving this problem is to increase the inverter and battery size of BESS, which can provide customers larger and longer power supply to fit the sudden demands during DR events. Additionally, increasing the size of BESS can also reduce the electricity bills for customers further and even make the household operate independently without importing power from grid.

The three cases shown above give the operation results of the proposed RO and RTCS during the period from 17:00 to 24:00 in different conditions. However, the given operation time of the three cases are all in night time, which is the time period when PV generation is lacking. Thus, to analyse the performance of the proposed control approach in day-time, whole day test results based on Case A is given in Figure 4-14 except the 17:00-24:00 part which has already been shown in Figure 4-11. From Figure 4-11 and Figure 4-14, it can be seen that the import power is limited under the threshold power rate in both common time and DR events. The BESS keeps charging during 0:00-3:00, when the electricity price is low, and then discharge a little bit to reduce the import power when there is a big forecasted error of the price from 3:00 to 4:00. After the price enters into the relatively high price range between 9:00 and 12:00, the BESS start releasing the stored energy with high power rate to feed the power demands, which can reduce the electricity bills for the customers. In addition, it can be found that the import power equals to 0 during several time periods (10:30-11:30, 12:00-13:00, 14:00-15:30) in the day time. It is because the PV generation is large during these periods, and the household devices cannot fully consume the power generated by PV. Consequently the battery enters into charging mode, which stores the excess power from the PV. It should be noted that the battery may not charge even if there is spare power from PV but smaller than 300W because of the low charging efficiency in low power and specific self-consumption of the BESS.

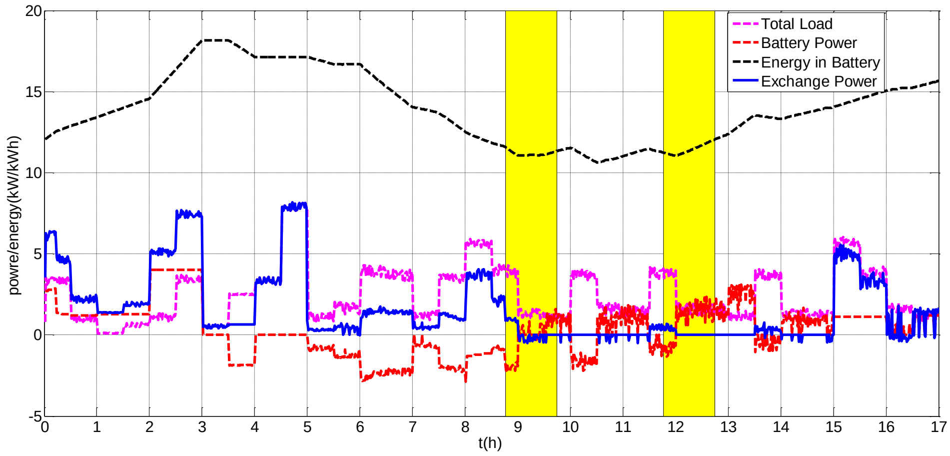

Figure 4-14 Results of Case A between 00:00-17:00

In addition, to get the detailed bill saving capability of the proposed control approach, the bill of the house using the proposed control approach is compared with the house without using any control approach based on the conditions of the three cases. The bills with control of the three cases represent the electricity bills consumed by the house which applies the proposed real-time control approach during 17:00-24:00. The bills without control represent the electricity bills consumed by the house without using any home energy management systems. The bills are calculated based on the amount of the exchange power with the grid, the real-time electricity price and the profits of joining the DR program. The comparison is given in Table 4-5. The results indicated that the proposed control approach can save up to 19% of energy bills compared to the house without using any control systems.

	Case A ($)	Case B ($)	Case C ($)
Bill with Control	1.39	1.43	1.43
Bill without Control	1.71	1.70	1.72

Table 4-5 Bill Comparison

4.5 Lab Test bed Implementation

The performance of the proposed RO & RTCS control strategy has been proved by the simulation results shown in the previous section. In order to evaluate the feasiblity of the proposed system, a hardware based test bed is established in lab and presented in Figure 4-15. The PV simulator connects with a Sunny Boy 5000TL inverter (Maximum Power 5000W), in order to simulate an entire 4.8kW PV system. The battery system is built up with a 24kWh second-life automotive battery and a 4kW bi-directional inverter. A Peugeot EV connects to the AC grid through a 3.3kW AC charging point; the capacity of the EV battery is 16kWh. The CLs and CD are simulated by three dynamic loads in the lab. The measurement & control units and assorted HEMS are included in the test bed as well.

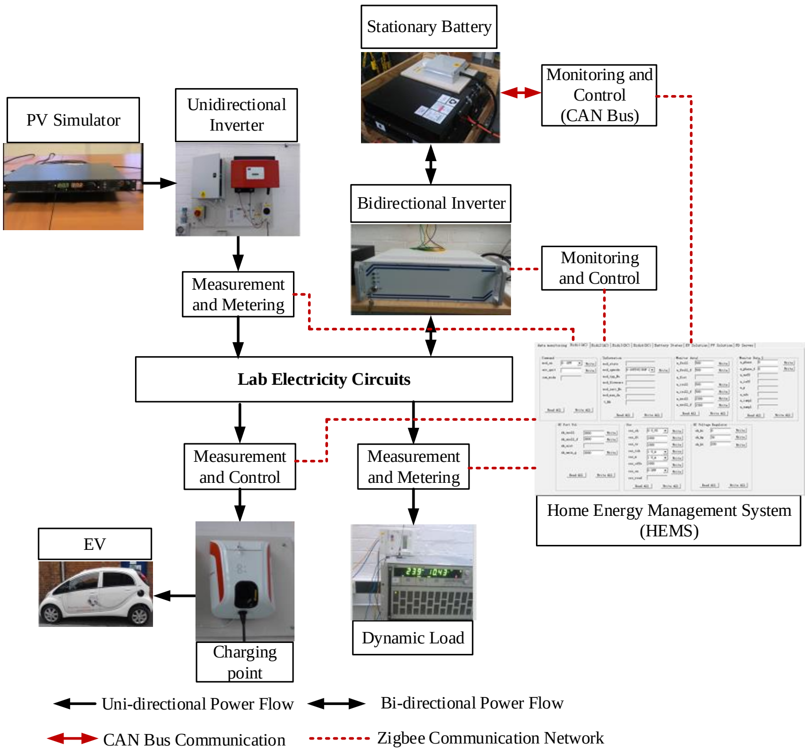

Figure 4-15 The structure of HEMS test bed

To monitor the operation state of devices and run the control commands wirelessly, the communication network in the test bed is established by ZigBee technique based on IEEE 802. 15.4 Protocol. The topology of ZigBee network uses a star network; the coordinator connecting to the EPC is the ‘core’ of the ‘star’ and all branch monitor & control units exchange the data with the only ‘core’ in the network. Selecting the star-topology is because of its clear structure, easy-to-maintain and easy for networking characteristics. With the assistance of the branch monitor & control units, the EV, PV, battery, inverter and other devices in the test bed can be monitored and controlled through the HEMS. In addition, in order to avoid the interference of other wireless network signals from WIFI, Bluetooth and other ZigBee network, the network communication channels, host name and MAC address are configured and registered in advance. To exchange the data with the local devices (e.g. Automotive Battery, PV and other household appliances), CAN bus, RS232 and RS485 communication standards are implemented in the monitoring and control units for machine-to-machine communication. Moreover, the solid state relay (32A max, 200V~240V AC) is installed in some of the units for controlling the home appliances simulated by dynamic loads.

The HEMS system is running on an EPC with Windows Embedded Compact OS. The HEMS system consists of two parts: one is a C# based platform for collecting the data from physical devices and distributing control commands from the solver to the devices, the other is the RTCS & RO integrated optimization solver on MATLAB, used for making the control strategy of the devices based on the input data from the C# platform. In the practical test bed, the operation information of the home appliances (CL and CD), EV and PV including voltage, current, power and historical energy data are collected every 10 seconds but broadcast every 30 seconds by the monitoring & control units. The information of the battery modules including voltage, battery cell temperature and SOC are collected and broadcasted every 20 seconds. The information of the bi-directional inverter in the battery system is collected every 5 seconds, which includes AC and DC terminal voltage, charging/discharging current, temperature of the AC/DC and DC/DC modules and the common bus voltage. The control commands will be broadcasted to the physical devices after the control strategy has been determined. The interrupt on the monitor & control units will activate and execute the control commands immediately through the solid state relay or machine-to-machine communication function on board. As a result of the limitation in experimental conditions, the WB and AC are simulated by the MATLAB according to their mathematical model.

During the test run on the test bed, the operation information of all the devices can be collected and transmitted to the HEMS at the right time. The optimization solver of the HEMS completes the calculation in 20-30 seconds after receiving the data from C# platform. The C# based platform of HEMS will distribute the commands to the monitor & control units through the ZigBee Coordinator when the control strategy is ready in the solver. The response time of the branch units for executing the switch on/off commands ranges between 20ms and 50ms, depending on the data transmission distance and network environment. Aiming to protect the bi-directional inverter, the power changing speed of the inverter is limited to 230-250W/s. Within the test, the inverter takes 5 seconds to increase the charging power from 0 to 1kW after receiving the control commands. According to the test results, the proposed real-time control approach for smart home operates properly in practical. All the devices on the test bed are under the management of EMS as expect.

4.6 Summary

In this chapter, a real-time control approach was proposed for HEMS aiming to solve the load shifting, energy bill saving and DR program response problems. The mathematical models of multiple home appliances and DERs were designed in first place. Based on the mathematical models, the RO optimized the operation of CLs and DERs every half hour. To ensure the effectiveness of optimization and reduce the influence of prediction error and working states change, a RTCS was applied during the time interval between every two ROs, which adjusts the control strategy every minute. The DR response mechanism was considered in both RO and RTCS as well.

Regarding to the characteristics of the bi-directional inverter, a FLC was designed to determine the charging/discharging power of BESS, which helps customers reduce the energy consumption in peak-time and ensure the execution of DR program.

To validate the performance of the proposed HEMS control approach, one virtual test bed in MATLAB and one physical test bed in the lab have been established. In simulation tests, three different cases were implemented and the extreme condition (larger prediction error, more critical loads in average and more frequent DR events) was considered in case C. The results indicated that the proposed HEMS can optimize the load using and response DR events successfully in case A and B, but it was failed to response the first DR event in case C. The failure in case C was caused by large critical loads and larger prediction error, which the HEMS did not have enough capability in reducing the power to satisfy the DR requirements. The solution is to enlarge the inverter and battery size, which allows larger control capability to HEMS. The bills comparison in the case study also demonstrated the strong energy cost saving capability of the proposed control approach. In order to validate the feasibility of the proposed control approach in practical conditions, the communication test and control test for the proposed HEMS solution have been carried out on a hardware based test bed. The test results indicated that the proposed HEMS have the capability to manage and control the physical devices in practice.

Chapter 5 A Novel Aggregator Service for Residential Apartment Buildings

5.1 Introduction

As introduced in Literature Review chapter, an increasing number of DERs are being installed in residential houses; modern tariffs such as TOU and RTP are launching the market by energy suppliers and DNOs. People living in houses get enough motivations to join the emerging energy service by the incentive mechanism for DERs and multiple choices in tariffs. However, due to the complex ownership and management problems, the promotion of DER installation in residential building is still lagging behind. The residents in residential apartment building do not have rights to install DERs, and the estate management companies or building owners do not have enough driving force to do so.

In order to solve such problems, a novel aggregator service for residential apartment building is proposed in this chapter. Compared to the traditional aggregator service, the proposed aggregator service focuses more on the profitability improvement of the aggregator without changing residents' energy use habits. The proposed aggregator service helps both aggregator and customers gain benefits from the DERs installed in the building, thereby achieve a win-win situation.

A new trading mechanism, similar to inside trading in stock market, is implemented in the aggregator, which enables the aggregator sell electricity to the residents directly by central metering system. A series of incentive mechanisms are proposed in the aggregator service for encouraging residents to join the service. In addition, a centralized management system for optimizing the operation of EV, PV and BESS is employed to increase the profitability of aggregator and bring benefits to the residents as well.

5.2 Aggregator Service Model for Residential Apartment Building

5.2.1 Overview of the Aggregator Service

With the investigation of aggregator reviewed in chapter 2, it is indicated that the aggregator can effectively maximize the savings for customers and reduce the risk of energy suppliers in emerging electricity market. Nevertheless, the aggregators which use DR program or Frequency Regulation program will more or less influence the user habits. In addition, the customers who do not install the HEMS system are difficult to join the aggregator service only if they pay extra money to install it. Thus, to promote the customers joining the service, the proposed aggregator provides a generic service to customers no matter if they install the HEMS or not. Additionally, in order to improve the driving forces of estate owners or other investors in installing DERs in residential buildings, the aggregator will manage the DERs to gain considerable profits for the stakeholders.

Figure 5-1 presents the schematic diagram of the proposed aggregator. The aggregator in the diagram affords two main works: one is managing the PV, EV and BESS; the other one is selling electricity to residents. The aggregator purchases electricity from energy suppliers at the wholesale price and sells the electricity to the residents with relatively low retail price. The aggregator makes the settlement with the energy suppliers as a whole, so that the aggregator can trade electricity from PV or BESS with the residents internally with a higher price than selling price in Feed-in-Tariff (FIT). In order to promote residents to join the aggregator service, multiple tariffs will be provided by aggregator and Low Price Guarantees (LPG) will be made with the residents.

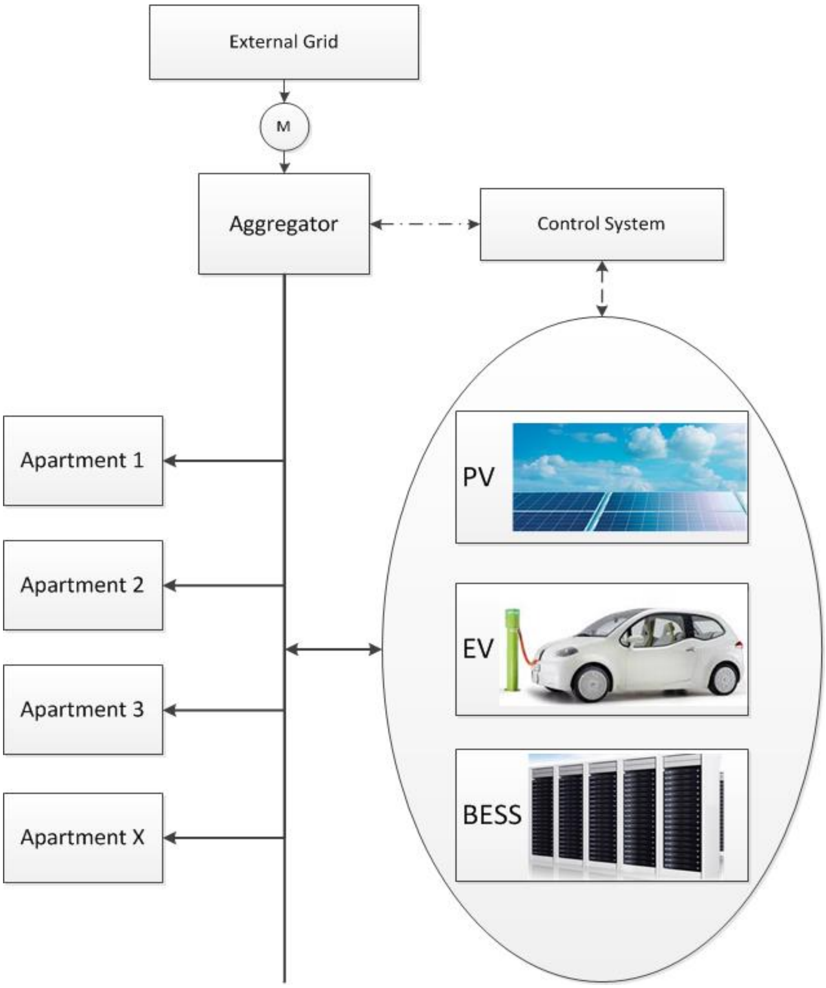

Figure 5-1 Schematic Diagram of Proposed Aggregator

5.2.2 Customer Incentive Mechanism

1) Lower Price Guarantees (LPG)

Currently, the incentive mechanism applied in aggregator service can be classified into three kinds: discount price for off-peak time, direct refunds of energy bills and specific rewards for responding to DR program or other similar programs [145-148]. In order to encourage the customers to join the aggregator service, the proposed aggregator uses LPG to attract customers as the promotion strategy. It guarantees customers to obtain the lowest price from the aggregator compared to other main energy suppliers. The effectiveness of LPG in customer acquisition has been proved in [149].

2) Participation Bonus

The roof PV and BESS will take up the public space in the buildings, so that the aggregator will allow participation bonus to the residents for subsiding the use of the public place. The participation bonus is divided into two parts: one part is the exemption of the 'daily standing charge', which is usually 10-30 p/day; the other part is the dividend of the profits gained by aggregator depending on the net margin.

3) EV Savings

Furthermore, a central management platform is proposed in the aggregator service for managing the EV, PV and BESS. The EV owners can receive the automatic charging scheduling service for their EV for free (Users should configure mooring time and departure time of the EV by themselves).The aggregator will schedule the charging of EV based on the configured data and the price information.

5.2.3 Aggregator Profitability Mechanism

1) Inside Trading

The new trading mechanism, similar to ‘inside trading’, enables customers purchase energy from the aggregator rather than the public retailers with relatively low price. At the same time, the negotiation power of aggregator is much stronger than the individual residential customers, which is possible to get a discount price from energy suppliers [150]. The aggregator can even bid in the electricity market if the size is large enough to get a more competitive price [81]. Benefit by the relatively low purchasing price, the aggregator is able to gain certain price difference by selling the electricity to residents.

2) Central Management Platform for EV, PV and BESS

As the central management platform is implemented in the aggregator, the operation of EV and BESS can be optimized based on the PV generation and residential energy consumption to reduce the power import from grid during peak-time, which can reduce the electricity procurement cost of the aggregator. In addition, the inside trading mechanism enables the aggregator to sell the PV and BESS energy to the residents with contracted price rather than the grid at a low price (The export rate of DERs is only 4.77p/kWh in UK) [151].

3) EV Scheduling

Although EV owners can reduce their cost in charging the EV with the assistance of central platform, they still need to pay for the electricity for charging. As the aggregator schedule the EV charging to the off-peak time, the aggregator can obtain lower price during the off-peak time than the residents. Therefore, the aggregator can get the profits from EV scheduling as well. In addition, EV is large task-oriented resources in the building, the aggregator has the potential to get further profits from EVs through joining the DR program [150].

5.2.4 Physical Structure

Figure 5-2 presents the physical structure of a residential apartment building including PV, EVs and BESS. To implement the proposed aggregator service, the physical electric wiring and connections of the buildings remain the same as for installation of some smart meters and controllers. A PV system is installed on the rooftop of the residential building, the BESS is located in basement or storage rooms and EV chargers are installed in the original building car park. The PV, BESS and EV chargers will connect to the main power line of the building, so that the whole building can work as an entirety including the residential apartments.

To enable the monitoring and control function for PV, EVs and BESS in aggregator, smart meters and controllers which have the functionalities of bi-directional metering, remote reading and control are expected to be installed. The Bi-directional smart meters are installed at the junction between the building power line and distributed network. The aggregator can monitor the import and export electricity from/to the grid through the bi-directional meter, so that the aggregator can make settlement with the energy suppliers. Moreover, with the assistance of the smart meters installed in each apartment and the PV system, the consumption of each apartment and the generation of PV system can be monitored, which helps the aggregator to optimize the operation of BESS and EV. The control units will be installed in BESS and EV chargers. The control unit in BESS can adjust the charging/discharging power of the inverter and the control units in EV chargers can turn the charger on/off to control the charging state of EV. Therefore, all the equipment in the building in the building can be monitored and controlled by a central management platform (e.g. a aggregator) after installing the smart meters and controllers. According to the PV generation, apartment energy consumption and the electricity price, the controllable devices such as EV chargers and BESS can help the aggregator reduce the peak-load of the whole residential building and use the renewable energy as much as possible.

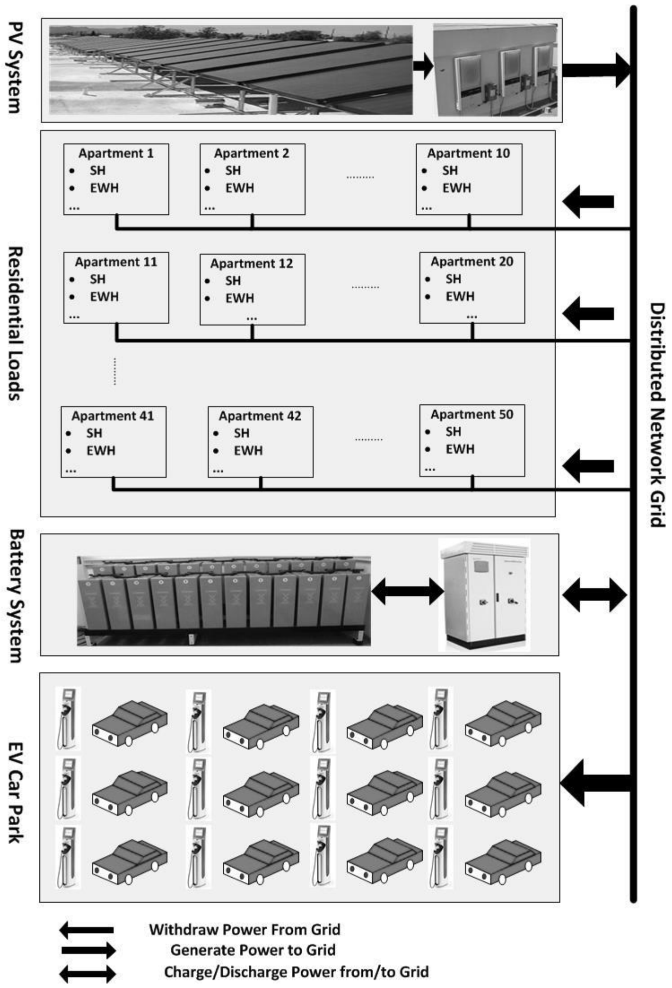

Figure 5-2 Physical Structure of a Residential Apartment Building

5.2.5 Communication Structure

The communication network of the aggregator affords the data monitoring and device control functions in the residential apartment building. With the assistance of the communication network, the real-time energy consumption of each apartment, PV generation data and BESS working states can be monitored and transmitted to the aggregator; the control commands can be distributed to the BESS and EV chargers correspondingly.

To establish the communication network of the aggregator, there are plenty of choices such as Zigbee, Z-Wave, WIFI CAN Bus, Ethernet or PLC, which have been introduced in chapter 3. On account of the floor space of the residential apartment building the communication network is designed as a wire/wireless mixed network. The ZigBee network is implemented to build the wireless network in the building; the Ethernet is selected as the local communication standard in wired network. As shown in Figure 5-3, the communication network includes 8 sub-networks, and all the sub-networks connect to the master server through the Switch. Each sub-network is in charge of the data transmission and processing work in certain areas. For instance, all the smart meters of the apartments located at the Ground Floor will form an individual ZigBee Network; the data transmission is confined to the formed network and specific slave server. The slave server will repack the data at first and then transmit them to the master server, which can reduce the working load of master server efficiently. With the assistance of sub-network, the disturbance of the data transmission among different end devices can be decreased and the communication stability can be improved correspondingly.

The master server is a more powerful server than the slave server, which acts as the ‘brain’ of the aggregator. From data transmission perspective, the master server affords not only the data collection work from the local devices but also the commands distribution work to the sub-network. From data processing perspective, the central management platform is operated on the master server, which optimizes the operation of the EV and BESS. In addition, although all the slave servers and the master server can communicate with external platform or service centers through the router, to ensure the security of the network, only the router port connecting the master server is enabled for external communication. The master server will get the electricity pricing data or other notices from the energy suppliers or DNOs with the router. Moreover, a data storage system is working with the master server as well, which helps the master server store the necessary data locally to support the bill calculation, devices operation optimization and consumer behavior analysis.

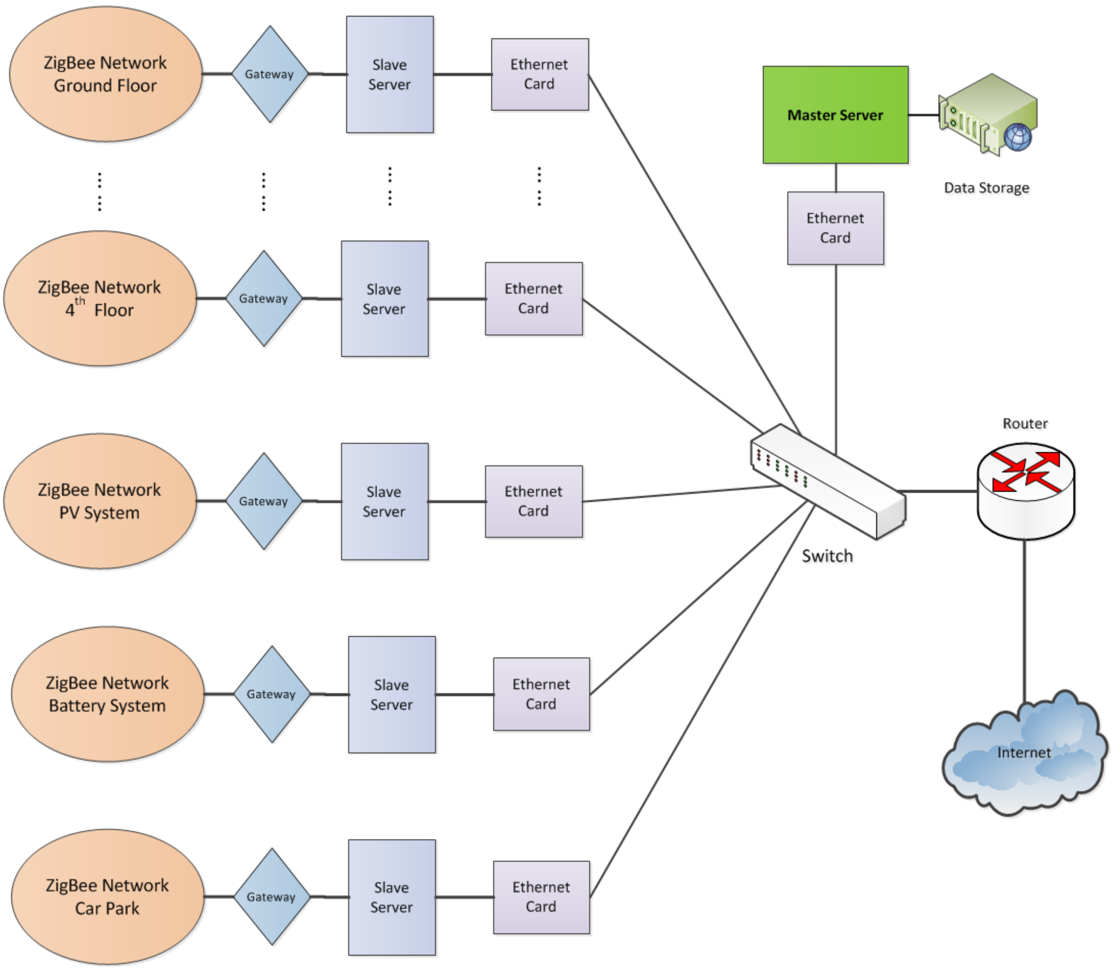

Figure 5-3 Communication Structure for Proposed Aggregator

In addition, from Figure 5-3, it can be seen that a ZigBee network is adopted in the sub-network for monitoring and controlling the local devices. Eight ZigBee networks are responsible for monitoring and controlling the devices in different areas respectively, which can reduce the complexity of wireless network structure and the data transmission flow. For the topology of the ZigBee network, the mesh topology is selected. Compared to the star and cluster topology provided by ZigBee network, the mesh topology is more stable and robust, which can provide solid communication network in the residential building with lots of walls and doors. As shown in Figure 5-4, any routers and coordinators in the mesh ZigBee network can communicate with each other without fixed routing path. That means the data within the network can still be transmitted even if some of the routers in the network are broken down or stop working.

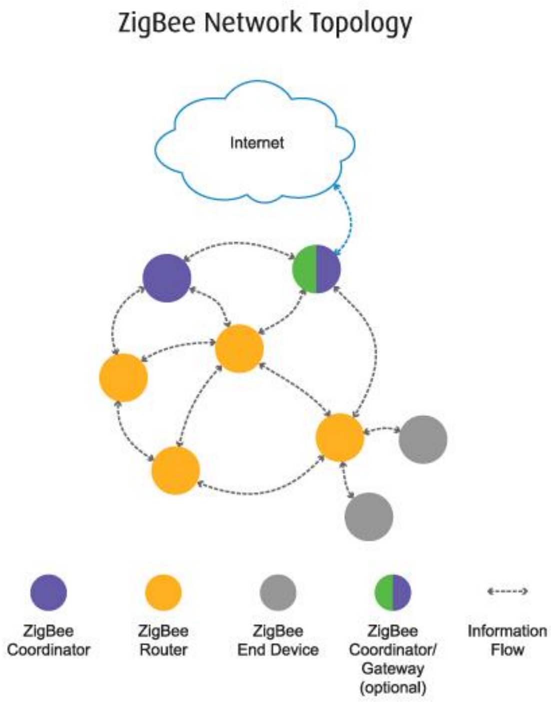

Figure 5-4 Mesh Topology of ZigBee Network [152]

5.3 Tariffs Provided by Aggregator

The formulation of the tariffs will influence the profitability and promotion of the aggregator. According to the electricity tariffs in UK and other European countries, three kinds of electricity tariffs (Flat Rate, TOU and RTP tariffs) are expected to be provided by the aggregator service. All three tariffs follow the incentive mechanisms proposed in section 5.2.2. The residents in the building can select any tariff they prefer. The detailed information of the three tariffs is given in the following paragraphs. It is worth mentioning that all the tariff information of UK energy suppliers are collected from UKPOWER.CO.UK.

- **Flat Rate**

The flat rate applied in UK market consists the daily standing charge (like the feline rental fee) and the constant price of electricity (£/kWh). Regarding to the flat rate tariffs provide by three UK main power suppliers for West Midlands, UK, the flat rate tariff will follow the lowest price tariff to fulfill the LPG strategy. In addition, the daily standing charge is exempted as the participation bonus to the customers. The price data of the flat rate tariff of the main UK power suppliers and aggregator are presented in Table 5-1.

Electricity Supplier	Standing Charge (excl. VAT)	Day Rate (excl. VAT)
EDF	18p	13.03p
EON	15.64p	13.06p
SSE	14.09p	12.43p
Aggregator	N/A	12.43p

Table 5-1 Flat Rate Tariff

- **Time-of-Use (TOU) Tariff (Economy 7 Tariff)**

An increasing number of smart meters have been installed in UK; thereby the TOU tariff is becoming more and more popular. The TOU tariff, also named as Economy 7/10 tariff in UK, provides Peak-Time price and Off-Peak time price to customers. People who use TOU tariff can use electricity with lower price for 7/10 hours during night time. The off-peak time defined by Economy 7 tariff in UK usually takes 7 hours between 10pm and 8:30am. The formulation of the aggregator TOU tariff is same as the aggregator flat rate tariff. As shown in Table 5-2, three TOU tariffs for West Midlands area provided by three UK main power suppliers as well as the aggregator TOU are given.

Electricity Supplier	Standing Charge (excl. VAT)	Day Rate (excl. VAT)	Night Rate (excl. VAT)
EDF	18p	14.57p	5.26p
EON	15.64p	16.11p	6.56p
SSE	14.09	14.89p	6.83p
Aggregator	N/A	14.57p	5.26p

Table 5-2 TOU Tariff

- **Real Time Pricing (RTP)**

The RTP tariff charges the retail customers with the electricity price changed every hour/half hour. Currently, few RTP tariffs exist in UK market for residential customers. Therefore, the RTP tariff data is established based on the RTP data provided by GDF Suez in US [153]. It should be noted that the price data has been modified based on the UK average domestic electricity price and US average domestic electricity price (Data obtained from the referenced government report) [154, 155]. After modifying the electricity data, a one-day Aggregator RTP tariff is given in Figure 5-5.

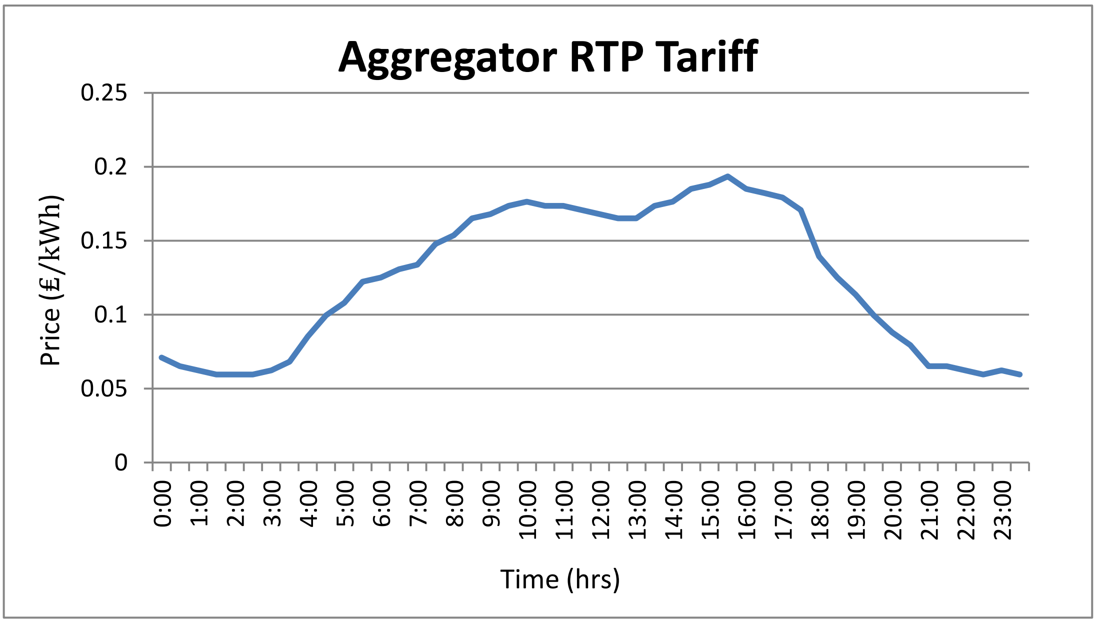

Figure 5-5 One-Day Aggregator RTP Tariff

5.4 Mathematical Model

The mathematic model and optimization approach for the central management platform in the aggregator is introduced in the following paragraphs.

5.4.1 Optimization Objective

The aggregator aims to minimize the costs of importing electricity from the grid. The objective can be expressed as follows:

$$\text{Min} \sum_{t=1}^{T} B_t = \sum_{t=1}^{T} (S_t + O_t)$$

$$S_t = p_t^{ag} \cdot C_t^s \cdot \Delta t \text{ if } p_t^{ag} < 0 \tag{5.1}$$

$$O_t = p_t^{ag} \cdot C_t^o \cdot \Delta t \text{ if } p_t^{ag} > 0$$

where B_t is the costs of aggregator during the time period *t*;

S_t is the benefits the aggregator should get for selling energy to the grid.at time *t*;

O_t is the cost the aggregator should pay to buy energy at time *t*;

p_t^{ag} is the power the aggregator buys from or sell to the grid at time *t*;

C_t^s is the price the aggregator exports energy to the grid at time *t*;

C_t^o is the price the aggregator imports energy from the grid at time *t*;

5.4.2 Constraints of BESS and EV

The power from the BESS, PV and grid should equal to the power consumption, including residential consumptions and EV charging. The power balance can be expressed as equation 5.2. It should be mentioned that BESS is charging when $p_t^{bt}$is positive and BESS is discharging when p_t^{bt} is negative.

$$\sum_{m=1}^{N_h} p_t^m + \sum_{n=1}^{N_{EV}} p_t^{EV,n} + p_t^{bt} - p_t^{ag} - p_t^{pv} = 0 \tag{5.2}$$

where p_t^m is the power of m^th apartment at time *t*; $p_t^{EV,n}$ is the power of n^th EV at time *t*; p_t^{bt} is the charging/discharging power of BESS at time *t*; p_t^{ag} is the power the aggregator buys from or sells to the grid at time *t*; p_t^{pv} is the PV generation at time *t*.

(1) BESS

A BESS is assumed to be installed in the residential building with second-life automotive batteries. . The operation of the BESS should follow the constraints as below.

$$P_{BT\_ch}^{min} \leq p_t^{bt} \leq P_{BT_{ch}}^{max} p_t^{bt} > 0 \tag{5.3}$$

$$P_{BT\_disch}^{max} \leq p_t^{bt} \leq P_{BT\_disch}^{min} p_t^{bt} > 0 \tag{5.4}$$

$$E_{BT}^{t+\Delta t} = \begin{cases} E_{BT}^t + p_t^{bt} \cdot \eta_{BT}^{ch} \cdot \Delta t & p_t^{bt} \geq 0 \\ E_{BT}^t + p_t^{bt} \cdot \eta_{BT}^{disch} \cdot \Delta t & p_t^{bt} < 0 \end{cases} \tag{5.5}$$

where $P_{BT\_ch}^{min}$ and $P_{BT\_ch}^{max}$ are the minimum and maximum charging power (kW) of the battery system. $P_{BT\_disch}^{max}$ and $P_{BT\_disch}^{min}$ represent the maximum and minimum discharging power (kW) of the battery system. The p_{BT}^t denotes the charging/discharging power (kW) of the inverter at time t. The E_{BT}^t denotes the capacity of the battery at time t.

For the second-hand automotive batteries in the BESS, we assume all the batteries have the same SOH and the original capacity E_{BT}^{Ori} of each automotive battery is the same. The battery modules in the BESS should follow the equation5.6 and 5.7.

$$E_{BT}^{cap} = N \cdot E_{\boldsymbol{BT}}^{Ori} \cdot SOH \tag{5.6}$$

$$0 < \mathrm{SOC}^t = E_{BT}^t / E_{BT}^{cap} \leq 100 \tag{5.7}$$

where N is the number of the automotive batteries, SOC^t denotes the SOC of the battery modules at time *t*.

(2) EV Charging

In view of the current EV chargers in the market, the modern EV charger has built with multiple EV Charging Standards and provides a number of customized functions on the interface. For instance, the EV owners can set the preferred charging period, the charging amount once they connect the EV with the EV charging points. With the assistance of CAN bus communication cables on the EV charging gun in some Chargers, the EV charging point can also get the SOC information of the EV.

We assume that the EV chargers in the proposed residential building car park have equipped the customized configuration function and worked with fixed charging power. The EV owners can set the departure time and certain charging amount after connecting their EV with the chargers. The operation of EV charging should follow the constraints below.

$$\sum_{t=T_{EV}^{start,n}}^{t=T_{EV}^{end,n}} S_t^{EV,n} \cdot p^{EV} \cdot \Delta t = E_{EV}^n \tag{5.8}$$

$$T_{EV}^{start,n} \leq \mathrm{t} \leq T_{EV}^{end,n} \tag{5.9}$$

$$S_t^{EV,n} = 0\ or\ 1 \tag{5.10}$$

where p^{EV} refers to the fixed power rate of EV charger; $S_t^{EV,n}$ denotes the working state of n^{th} EV charger at time t, 0 refers to 'off' and 1 refers to 'on'; $T_{EV}^{start,n}$ and $T_{EV}^{end,n}$ refers to the EV mooring and departing time respectively; E_{EV}^n refers to the total charging demand of n^{th} EV.

5.4.3 Optimization Approach

It can be seen from the mathematical model, the variable for the EV is integer valued, and the other variables are continuous. So this model is a mixed-integer linear programming (MILP). Nonetheless, when the number of EV is large, the large number of integer brings difficulties to solve the problem. The optimization will take long time to schedule the charging of EVs. It will be difficult to apply aggregator to manage the EVs in the building efficiently. A comparison among the continuous relaxation method, fuzzy logic control and the MILP method for optimising the energy management has given in [156]. According to the results of the comparison, the continuous relaxation method showed a promising performance in energy management with great higher speed than the MILP. Thus, to tackle this problem, an optimization approach based on continuous relaxation is applied. The optimization approach is divided into two stages as follows.

In the first stage, the integer variable is taken as a continuous variable, varying between [0, 1]. And the problem is solved as a pure linear problem. The values for the integral variables (varying between [0, 1]) can be determined, and they are compared with a threshold, to determine the final value (0 or 1). So the integral values are determined by a continuous relaxation method.

Since values for the integral variables have been determined in the first stage, the other values need to be determined in the second stage, which is to solve the linear problem.

The process of the proposed optimization approach is shown in figure 5.6. The optimization runs every half hour in the aggregator to schedule the charging of EV and operation of the BESS.

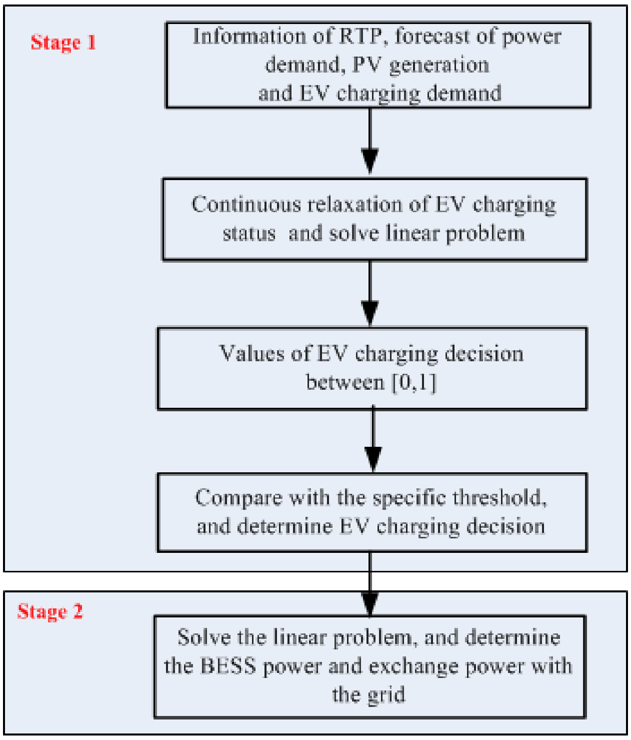

Figure 5-6 Control Approach Process

The control algorithm is coded with YALMILP (a modeling language for advanced modeling) and utilised by CPLEX (an optimization software package).

5.5 Case Studies

The mechanism and model of the residential apartment building aggregator service have been given in the previous section. In order to validate the performance of proposed aggregator service, the parameters applied in the aggregator are firstly introduced; then the test of the aggregator using the proposed parameters in MATLAB is given; finally the profitability of the aggregator with the provided tariffs is discussed.

5.5.1 Input Parameters of Aggregator Service

- **Residential Building Information**

A five-floor residential building with 50 apartments (30 2-bedroom apartments and 20 1-bedroom apartments) located in West Midland UK is used for the simulation (Map data shown in Figure 5-7 and the red box is the proposed building). The roof area is 900-1200 m^2 and basement area is around $120m^2$. 50 parking place are available in the building.

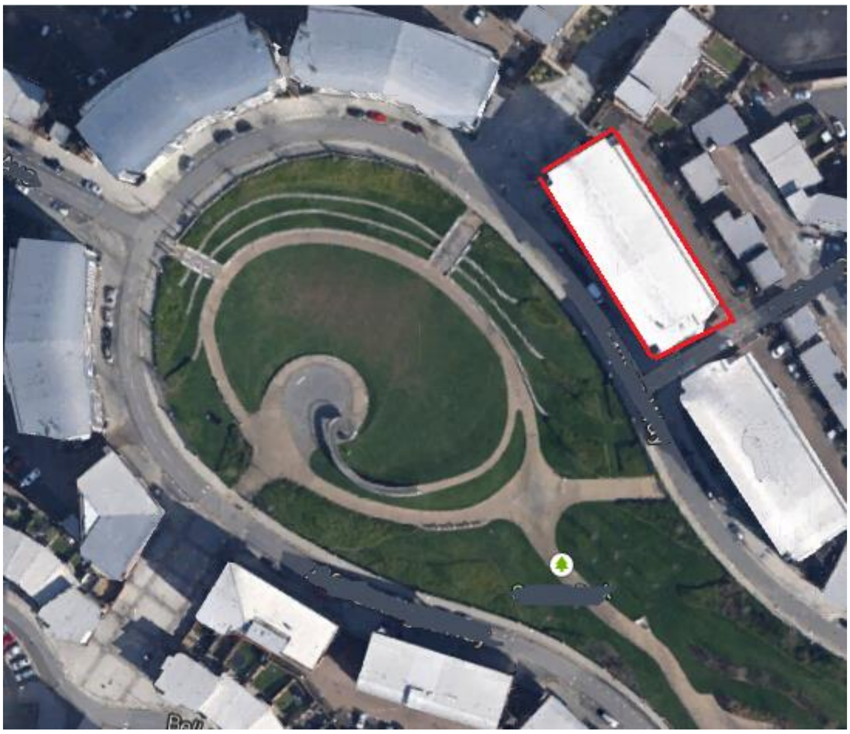

Figure 5-7 Residential Apartment Building for the aggregator Service

(Map data: Google Maps/Google Earth APIs © 2014 Google. All rights reserved)

- Energy Purchase Agreement

In UK electricity market, larger energy consumers can get cheaper energy because of their negotiation power with the supplier. The Department of Energy & Climate Change (DECC) had reported that the large/Medium/Small energy consumers can purchase the energy 46.2%/38.8%/32.6% cheaper than the domestic customers during 2012-2014 in UK [157]. The aggregator forms the energy consumption of the building as an entirety, so that a power purchase agreement can be signed between aggregator and power suppliers and the aggregator can get relatively lower price than the retail price. In the case study, we assume the aggregator signed the RTP tariff with energy supplier as a small/medium size energy consumer and can get 35% discount off the RTP tariff proposed in section 5.4.

- PV Generation

The PV generation size is determined by the roof area. Based on the roof space of the building, a 100 kWp solar system is assumed to be installed. One-day generation data of the solar system is given in Figure 5-8 from 12:00PM to next day 12:00PM based on the real-time data from Newquay Weather Station [158].

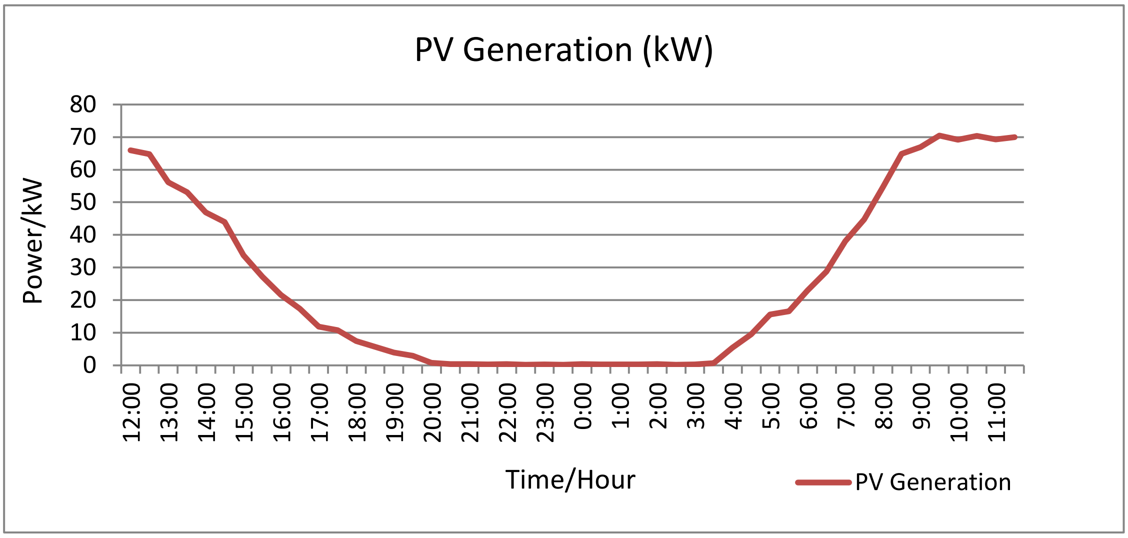

Figure 5-8 One-Day PV Generation Data

- BESS

A 150kWh BESS is assumed to be installed in the building. The maximum charging/discharging power of the BESS is defined as 50kW. Both of the charging and discharging efficiency are defined as 95%, which has been introduced in section 5.5. It should be mentioned that the final state of BESS will follow the original BESS state by the end of optimization.

- EV Charging

The EV car park in the building is assumed to have 50 chargers rated at 3.3kW per charger. The capacity of each EV is configured as 24kWh (same as the Nissan Leaf battery size). The arrival time, departure time and battery charging time are estimated based on the EV user pattern data obtained from E.ON demo project. The EV one-day charging curve of 50 EVs is given in Figure 5-9.

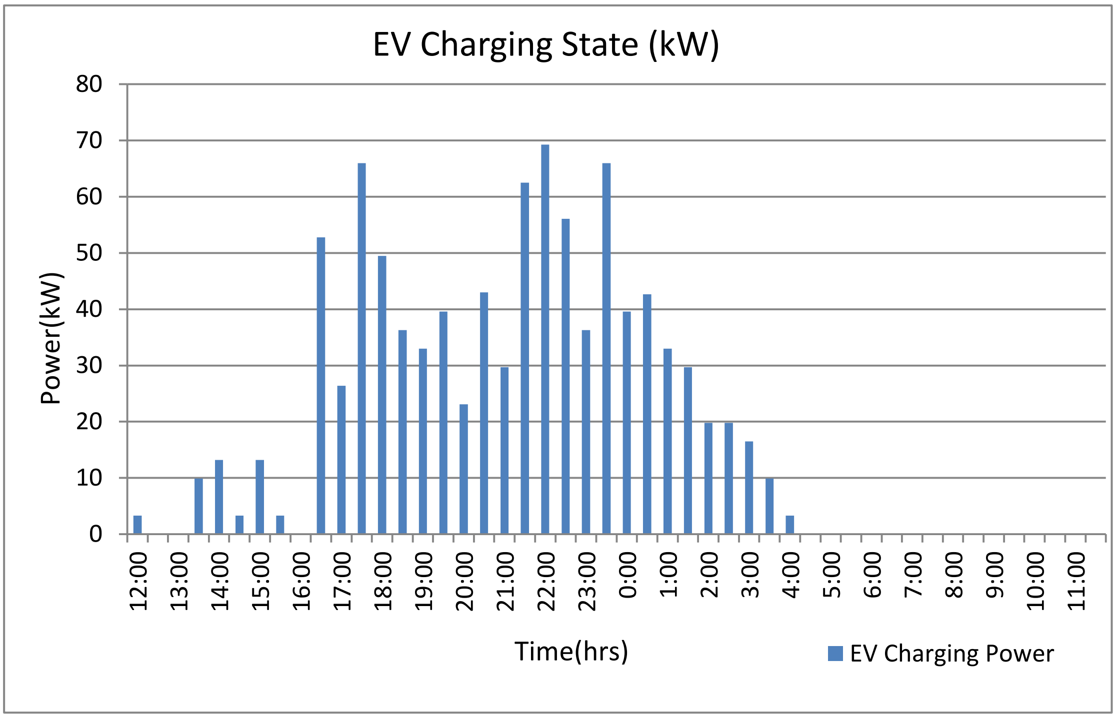

Figure 5-9 One-Day EV Charging Curve

- Residential Energy Usage

The residential energy usage of 50 apartments for one-day is given in Figure 5-10. The energy consumption is estimated with the data from E.ON Demo project.

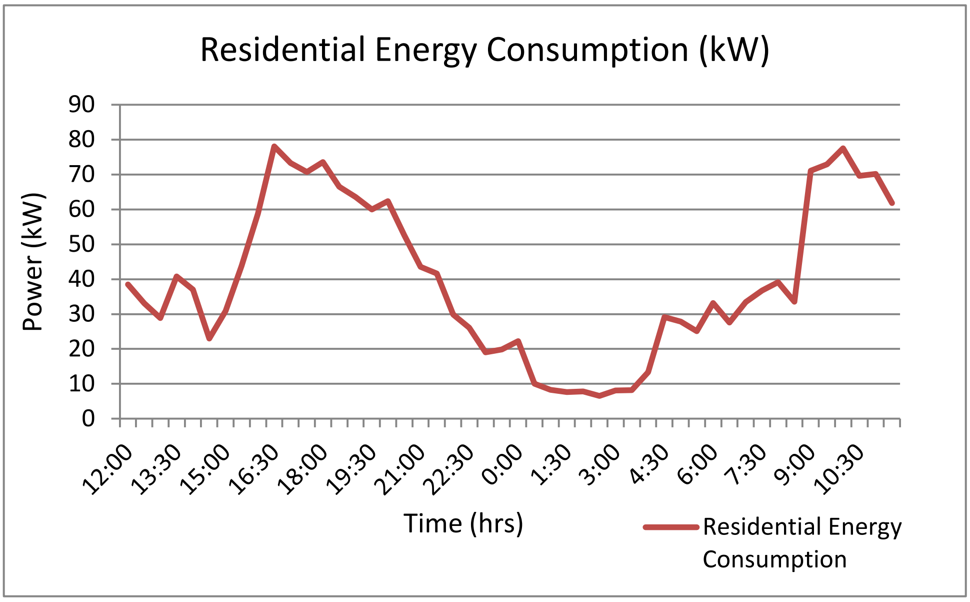

Figure 5-10 One-Day Residential Energy Consumption

It should be noted that the optimization of EV and BESS requires the predicted data. We assume the predicted data are provided by energy suppliers, the meteorological department and other related organizations. In the simulation, a $\pm$15% random error is added on the required data to form the prediction data.

5.5.2 Operation Results of Aggregator Service

The results are presented in this part after importing the above data to the aggregator developed on MATLAB. Related analysis and discussion are presented with the results as well.

- General Performance

As shown in Figure 5-11, a whole day operation results of the residential building using the aggregator service is given. The purple curve represents the price of electricity imported from the grid; the blue curve represents the forecasted electricity price; the green bars are the PV generation power; the blue bars refer to the total energy consumption (Home energy consumption and EV charging power) and the red bars represent the import energy amount from the grid.

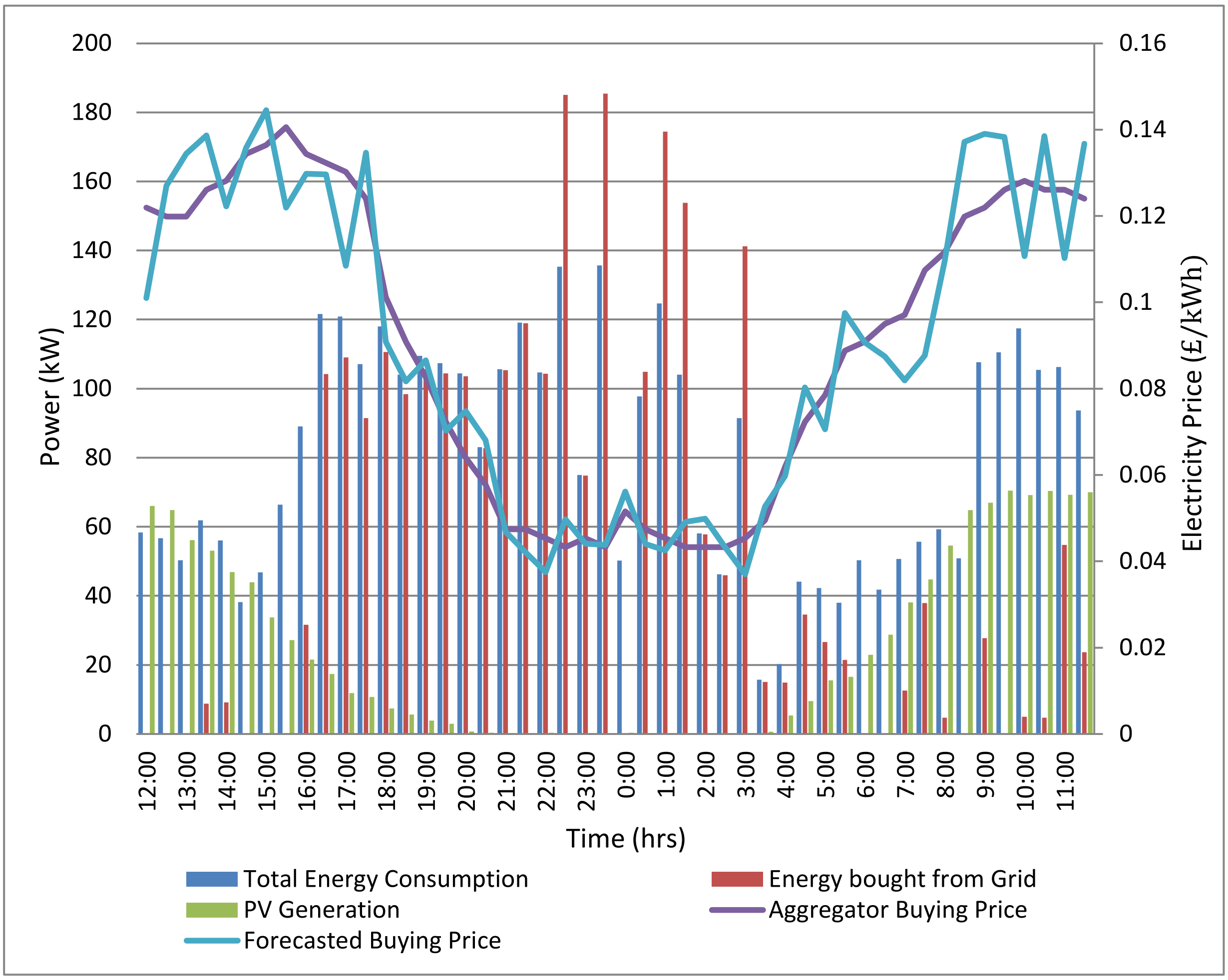

Figure 5-11 Performance of Aggregator Service in 50-Apartment Residential Building

It is found that the import price is relatively high during the day time between 9:00AM and 6PM; the price entered into the relatively cheap range during 6:00PM-10:00PM and 3:00AM-8:00AM; the import price is extremely cheap during 10:00PM-3:00AM. Due to the cheap price during 10:00PM-3:00AM, the electricity bought from grid is even higher than the total residential consumption power, which means the cheap energy is bought and stored in the battery system to supply the energy demand during peak time. The PV system exports considerable power to cover the residential energy consumption when the import electricity price is high during 9:00AM-4:00PM. The PV generation during this period contributes great profits to the aggregator. In addition, with the assistance of BESS, the stored electricity is discharged as well to feed the energy consumption during the peak time, so that the stored energy can be sold in a relatively high retail price. Thanks to the PV and BESS, the energy imported from the grid (Red Bar) during the high price period (8:00AM-4:00PM) has been controlled effectively to a low level effectively. In addition, it is worth mentioning that the forecasted prices, shown as the blue curve, have certain forecasted error during 7:00AM – 4:00PM. Nevertheless, the import energy is still controlled in a relatively low level, which indicates that the optimization approach of the central control platform in aggregator effectively reduces the influence by the forecasted error.

- EV Scheduling Results

Figure 5-12 presents the EV scheduling results after applying aggregator service in the residential building. The blue bars refer to the original charging state of the EVs. It can be seen that around 30% of the original charging energy of the EVs is allowed in time period between 4:00PM and 8:00PM. However, the electricity price is still in a high range during this period, which increases the cost of charging the EVs. With the assistance of aggregator, most of the charging power of the EV during 4:00PM -

8:00PM has been successfully shifted to the low price time period 9:00PM – 3:00AM, so that the charging cost of the EV can be reduced effectively. Due to the significant flexibility of EV charging period, the forecasted error existed in peak time (12:00AM-18:00PM) does not influence the EV charging scheduling very much.

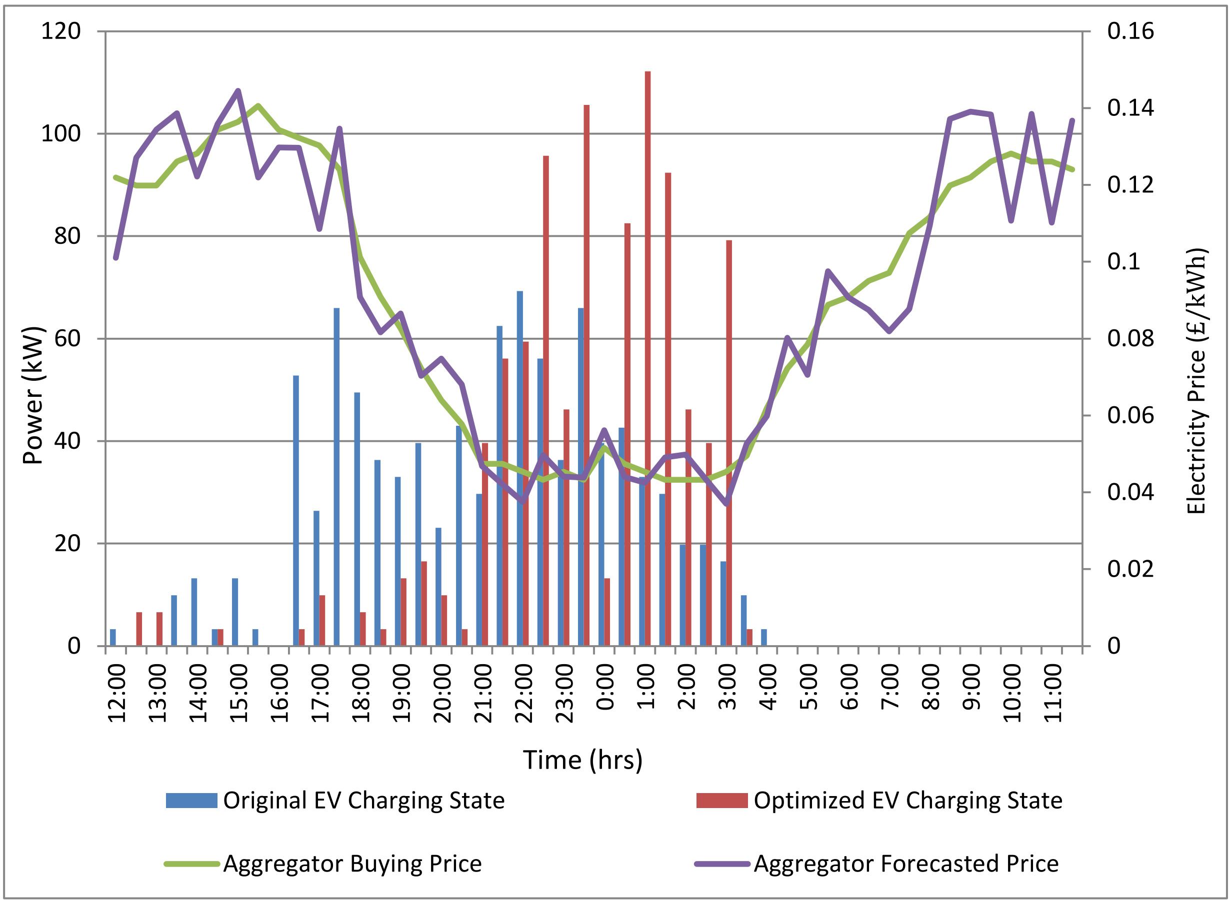

Figure 5-12 EV Scheduling Results

- BESS Operation Results

Figure 5-13 presents the charging/discharging states of the BESS within one day. According to the detailed charging/discharging activities of the BESS it can be seen that the BESS discharges power to the apartments during the high price period to feed the residential energy consumption; the total discharged energy during this period is calculated as 120.5 kWh, which means 80.3% of the stored energy in the battery system has been used during the high-price period. With the comparison of the discharging power during the high price period and charging power during low price period, it can be concluded that most of the stored energy during the cheap price period is used during the high price period, which essentially helps the aggregator gain profits through the price difference.

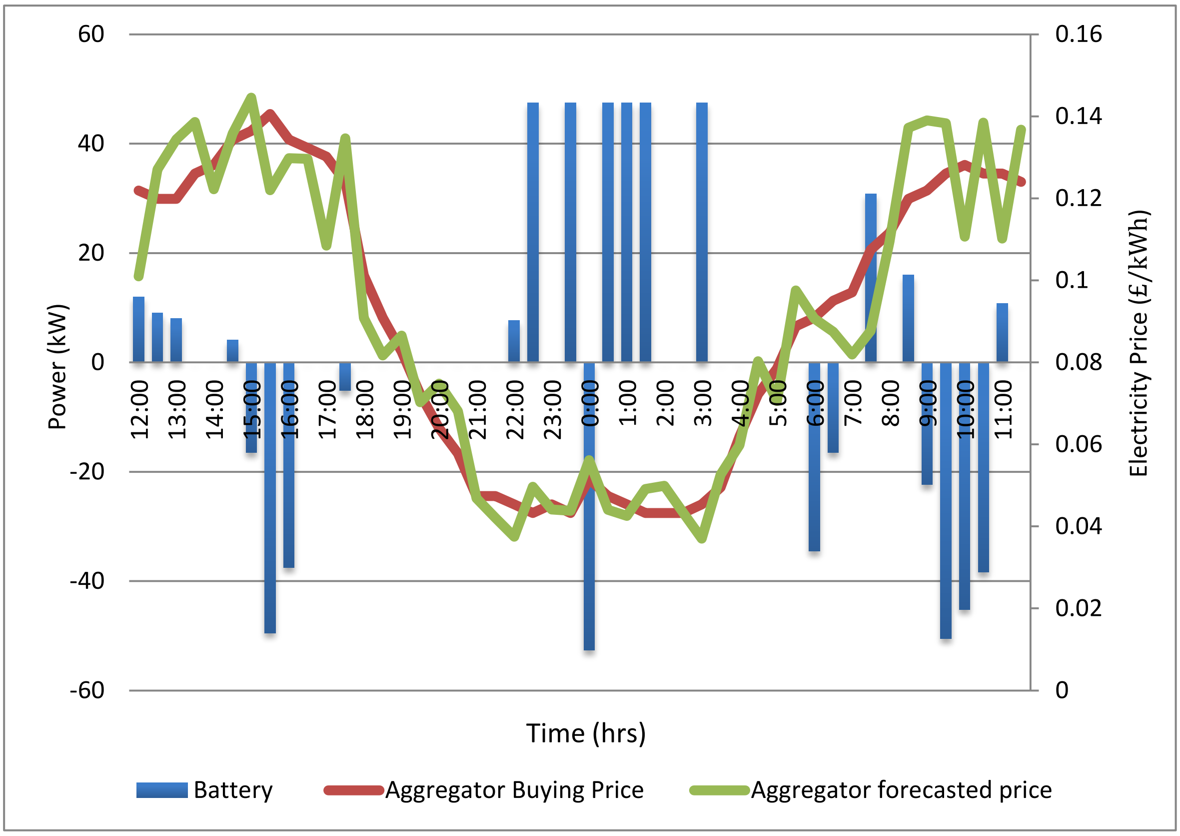

Figure 5-13 Operation States of BESS

5.5.3 Profitability Performance of Aggregator with Different Tariffs

- **Aggregator Profitability**

Table 5-3 gives the detailed profits of the aggregator service for three different tariffs and the analysis is given as below.

Time	Total Energy Usage (kWh)	Imported Electricity (kWh)	Aggregator Purchasing Cost (£)	Constant Tariff Payment (£)	TOU Tariff Payment (£)	RTP Tariff Payment (£)
12:00-12:30	35.00	0.00	0.00	2.18	2.55	2.94
12:30-13:00	36.65	0.00	0.00	2.28	2.67	3.02
13:00-13:30	32.84	0.00	0.00	2.04	2.39	2.71
13:30-14:00	37.11	5.25	0.33	2.31	2.70	3.22
14:00-14:30	33.65	5.51	0.35	2.09	2.45	2.97
14:30-15:00	24.21	0.00	0.00	1.50	1.76	2.24
15:00-15:30	28.10	0.00	0.00	1.75	2.05	2.64
15:30-16:00	39.82	0.00	0.00	2.47	2.90	3.85
16:00-16:30	53.45	22.71	1.53	3.32	3.89	4.94
16:30-17:00	74.28	63.85	4.22	4.62	5.41	6.76
17:00-17:30	76.50	69.39	4.52	4.75	5.57	6.86
17:30-18:00	64.25	55.38	3.43	3.99	4.68	5.48
18:00-18:30	73.47	69.01	3.49	4.57	5.35	5.12
18:30-19:00	63.75	60.35	2.74	3.96	4.64	3.99
19:00-19:30	70.99	68.64	2.84	4.41	5.17	4.04
19:30-20:00	71.00	69.24	2.50	4.41	5.17	3.53
20:00-20:30	66.58	66.12	2.12	4.14	4.85	2.93
20:30-21:00	51.15	50.96	1.47	3.18	3.73	2.03
21:00-21:30	79.22	79.03	1.87	4.92	5.77	2.59
21:30-22:00	93.94	93.80	2.22	5.84	6.84	3.07
22:00-22:30	86.57	90.36	2.05	5.38	6.31	2.70
22:30-23:00	119.46	144.34	3.12	7.42	8.70	3.56
23:00-23:30	63.50	63.35	1.44	3.95	4.63	1.98
23:30-0:00	123.62	148.51	3.21	7.68	3.25	3.68
0:00-0:30	33.43	8.23	0.21	2.08	0.88	1.19
0:30-1:00	91.65	116.49	2.76	5.70	2.41	2.99
1:00-1:30	119.71	144.54	3.28	7.44	3.15	3.74

Time	Total Energy Usage (kWh)	Imported Electricity (kWh)	Aggregator Purchasing Cost (£)	Constant Tariff Payment (£)	TOU Tariff Payment (£)	RTP Tariff Payment (£)
1:30-2:00	99.38	124.25	2.69	6.18	2.61	2.96
2:00-2:30	53.33	53.15	1.15	3.31	1.40	1.59
2:30-3:00	45.54	45.42	0.98	2.83	1.20	1.36
3:00-3:30	86.57	111.44	2.53	5.38	2.28	2.70
3:30-4:00	10.75	10.37	0.26	0.67	0.28	0.37
4:00-4:30	12.14	8.94	0.28	0.75	0.32	0.52
4:30-5:00	26.45	20.76	0.75	1.64	0.70	1.32
5:00-5:30	25.34	16.00	0.63	1.58	0.67	1.37
5:30-6:00	22.79	12.84	0.57	1.42	0.60	1.39
6:00-6:30	30.17	0.00	0.00	1.88	0.79	1.89
6:30-7:00	25.07	0.00	0.00	1.56	0.66	1.64
7:00-7:30	30.40	7.55	0.37	1.89	0.80	2.03
7:30-8:00	33.38	22.76	1.22	2.07	0.88	2.47
8:00-8:30	35.58	2.83	0.16	2.21	2.59	2.73
8:30-9:00	30.52	0.00	0.00	1.90	2.22	2.52
9:00-9:30	64.62	13.81	0.84	4.02	4.71	5.42
9:30-10:00	66.29	0.00	0.00	4.12	4.83	5.75
10:00-10:30	70.46	7.49	0.48	4.38	5.13	6.22
10:30-11:00	63.28	2.83	0.18	3.93	4.61	5.49
11:00-11:30	63.75	27.84	1.76	3.96	4.64	5.53
11:30-12:00	56.22	14.23	0.88	3.49	4.10	4.80
Total	**1347.96**	**998.79**	**65.43**	**167.55**	**155.91**	**154.85**

Table 5-3 Profitability Performance of Aggregator

According to the results in Table 5-3, the billing detail can be calculated as shown in Table 5-4. It can be seen that the bills of three different tariffs are similar in a whole day, which indicates that the proposed billing mechanism is fair to all the customers who choose different tariffs. The Flat Rate tariff is slightly higher than the bills of other two tariffs; this is because the EV owners cannot get the savings on the EV charging scheduling due to the constant price. The method to solve this problem is allowing certain amount of subsidy to the EV owners who choose constant tariff. In addition, it can be seen that the PV system contributes more than 300 kWh electricity to feed the energy consumption, that is why the imported power is much less than the total energy usage. The detailed billing information of the three tariffs is presented in in table 5.4 and introduced below:

	Purchasing Cost (£)	**PV Contribution (£)**	**Battery System Contribution (£)**	**Imported Electricity Trading Contribution (£)**	**Total (£)**
Flat Tariff	65.4	44.57	11.9	45.68	167.55
TOU Tariff		47.11	11.1	32.3	155.91
RTP Tariff		58.9	18.0	12.55	154.85

Table 5-4 Billing Detail

Among the payment detail, the contribution of PV system and battery system counted in RTP tariff is obviously higher than the Flat and TOU tariffs. This is because the higher electricity price in peak-time brings larger price difference to the aggregator and the PV and BESS energy can be sold at a higher price. The relatively high imported electricity trading contribution in flat tariff is because the aggregator can shift the EV charging to the low price period, so that the EV owners using TOU and RTP tariffs will pay less than the owners using flat tariff.

- **Payback Period Comparison**

It is assumed that the residential apartment building in this case study has already installed 100kWp PV system and 150kWh battery system. The estimation of PV and battery system cost is calculated based on [159] and [160]. The input data for the payback period calculation includes the PV generation, electricity price and the EV charging information. The PV generation data is obtained from [158] with the whole year data of 2013. The electricity price and the EV charging information are assumed as the same as the data used in the case study and applied in whole year optimization repeatedly for calculating the payback period evaluation. The equations of payback period calculation are given as below.

$$Payback\ Period\ (Year) = \frac{\text{BESS Investmen+PV Investment}}{\text{One Year Profit of Aggregator}} \tag{5.11}$$

$$One\ Year\ Profit\ of\ Aggregator = \sum_{k=1}^{n} P_k \tag{5.12}$$

where $n = 365$ represents the day number of one year and P_k represents the profit of aggregator in day k. It is worth mentioning that the maintenance charge and the efficiency reduction caused by aging of PV and BESS are not included in the calculation.

The investment, payback period and optimized payback period is shown in Table 5-5 and discussed below. It should be mentioned that the battery modules used in the BESS are considered as the second-life automotive batteries, so that the BESS cost only includes the purchase of inverter. .

Tariff	PV System Investment (£)	Battery System Investment (£)	General Payback Period (Years)	Payback period after using aggregator (Years)
Flat Tariff	195000	18000	12-20	7.08
TOU				6.94
RTP				5.72

Table 5-5 Payback Period of PV and Battery systems

The general payback period for the PV and battery system is estimated based on the investigation of UK solar payback period made by O'Flaherty [161]. The payback period of the PV and battery system used by the aggregator is calculated from the data of PV contribution, battery contribution shown in table 5.4 and the UK solar PV feed-in tariff [151]. Compared to the general payback period, all three tariffs can significantly reduce the payback periods. The utility management companies or investors will have much more driving forces to install DERs in the residential buildings.

5.6 Summary

In this chapter, the design of the aggregator service for residential apartment building has been proposed. Both physical and communication structures have been developed to support the implementation of the aggregator in the building. The bill mechanism and incentive mechanisms employed in the aggregator were discussed as well. The LPG and participation bonus promised by aggregator service can effectively motivate residents to join the aggregator service.

To ensure the effectiveness of the aggregator, three billing tariffs: flat rate tariff, TOU and RTP are tested with the aggregator in the case studies. The results have shown that the proposed aggregator can get considerable profits even it provide the low price energy to the residents. The PV system and BESS play a critical role in the aggregator service and contributes up to 78.7% margin profits of aggregator service (when residents choose RTP tariff). Compared to the general payback periods of DERs, the aggregator can reduce the pay back periods down to 5.72 years, which is 71.4% shorter (if general payback period is 20 years).

Chapter 6 Conclusions and Future Research Plan

6.1 Major Conclusions

As a consequence of the fast development of the smart grid in recent years, an increasing number of DERs, smart meters and other ICT based devices have been installed in the grid, especially in the distribution network. This vast deployment leads to significant reduction of carbon emission, but the inherent intermittence of DERs also brings new challenges such as demand and supply unbalance to the grid. The smart home and building solutions provide not only the living comforts improvements and energy optimisation to the end users but also the interaction service to the power grid operators. The EMS, which bears the energy management work in smart homes & buildings, contributes great power in solving the new challenges caused by the increasing DERs and loads.

EMS helps delivering a necessary coordinating platform for the controllable loads, DERs and the advanced tariffs to schedule their operations. This thesis has proposed a range of solutions for individual device, individual home all the way to residential buildings.

The conclusion of this thesis covers the following aspects

1. As a large energy consuming devices in residential house and commercial buildings, the space heating & cooling system is one of most valuable loads to be controlled and optimised by EMS. However, the current system in the market only provides the basic control features such as timer and constant temperature control, which is not compatible with the smart tariffs such as RTP. A GA based EMS for space heating system has been proposed in chapter 3, fully considering the house thermal models, residents' living comforts and the float tariffs. With the pre-configuration of the proposed EMS, the space heaters can operate in-advance according to the price signals; the residents' house will acts as a temporary thermal storage media, which store the low-price electricity for a short-period before people come back home, so that people can enjoy the warm environment once they get home but spend less. The results within different prices scenarios indicate that the proposed solution can cut the energy bills up to 36.8% for the customers without sacrificing living comforts compared to the heaters equipped with basic control features. A hardware based test bed has been established in the lab and the performance of the proposed GA based EMS has been validated on the test bed.

2. For a complete EMS solution of a residential house, all the controllable loads such as clothes dryer and water boiler, and the DERs should be taken into account. Regarding the quick change of the loads and the DERs' states, the optimisation speed and accuracy of the EMS are the critical factors to be considered. In order to improve the speed and accuracy, a novel real-time control approach of the EMS has

been proposed in chapter 5, which combined both RTCS and RO, so that the load scheduling will rely on not only the predicted data but also the real-time information collected by the sensor network. In addition, the DR programs are promoted by the energy suppliers in the distribution network, giving incentives for an increasing number of residential houses to join the programs to earn extra benefits. Therefore, the DR automatic response and control mechanism were embedded in the proposed EMS control approach in order to fulfill the requirements of the customers to join DR programs. It should be mentioned that the BESS and PV systems, considered as the DERs installed in the home, are taken into the optimisation as well. The numerical results presented in chapter 5 indicated that the proposed control approach can schedule the loads such as WB and EVs to operate during the relatively low price period and fulfill the DR events at the same time. The BESS performs excellently in assisting the optimisation of energy consumption, through storing spare energy of PV generation and purchasing cheap energy from the gird in off-peak time based on FLC.

3. Compared with the EMS for a single residential house, the management of the loads and DERs in building by aggregator tends to be more intricate. The complexity lies in heavy scheduling work of load and DERs as well as the variety of user requirements and conditions. Especially for the residential apartment building, the complex property rights and profit allocations make the promotion of PV and other DERs difficult, which seriously shrink the installation capability of the DERs in the

distribution network. In order to solve the problem, an aggregator service for the residential building was proposed in chapter 5, which coordinates and optimises the DERs in the building. According to the predicted information of renewable energy generation, EVs' using pattern, electricity price and the load consumption in the building, the aggregator generated the control plan for the EV and BESS. This mechanism minimized the cost of electricity imported from the grid and brought profits to the stakeholders of the DERs and residents in the building. Considering the cheap energy exporting price of the Feed-in tariff, the inside trading of PV generation and BESS energy proposed in chapter 5 no doubts provided much better financial benefits to the stakeholders. The case studies in chapter 5 have given the performance of the proposed aggregator service for the residential building with three different kinds of tariffs. The results in all three cases validated the effectiveness of the proposed aggregator service in shortening the pay-back periods of the DER investments and provide cheap energy to residents.

6.2 Future Research Work

Three control approaches of EMS have been proposed in the thesis, from optimising the single space heating system in the home, to controlling the devices in the complete residential house and residential building. The physical EMS platform for residential house has been established in the lab, which aids in carrying out case studies in chapter

3 and 4. As for the research of EMS, some further studies shown below are necessary to be investigated.

1. Due to the limitation of the lab space and hardware, a physical platform for the building aggregator has not yet been established. Since the control and communication platform is critical to both the research in BEMS and the aggregator service for building or community, a small-scale but fully equipped physical based simulation platform for Building Energy Management System (BEMS) would offer great assistance to the evaluation, development and research of the smart building solutions.

2. The communication network for wireless control only applies ZigBee in the lab. Nevertheless, some other communication methods such as X10 and Z-Wave, are also the mainstream options for home control system and sensor network, which can satisfy different requirements for households. Additionally, the building automation standardised communication systems such as building fieldbus are not equipped in the lab either. In order to fulfil the different requirements for the smart home and building research, some other communication systems can be established in the lab to cover the research in the communication stability and efficiency areas for smart homes and buildings.

3. The performance and effectiveness of the BESS for home and building have been evaluated in chapter 4 and 5. The battery systems can improve the flexibility of the

energy management, and also enhance the working efficiency of DERs in the home and in buildings. At the current stage, the research proposed in the thesis mainly focused on the small-scale energy storage system in homes and buildings. With the consideration of increasing PHEVs and EVs on the road, the increasing number of second-hand automotive batteries will be available in the market in the next decade. The research in the middle or large scale energy storage systems for the communities and distribution network will shape the modern power network.

4. The Virtual Power Plant (VPP) service, a service in balancing the demand and supply in the power grid through money incentive mechanism, is moving their steps from the large power plants or large energy consumers to the small scale energy users like residential house and buildings. The small-scale customers can earn profits by cutting or increasing their energy consumptions in certain periods through the VPP service. However, the main barrier for bringing the VPP service to the residential side is coordinating and controlling the large number of loads in different houses and buildings. With the emergence of smart home and building solutions, the ICT infrastructure of the EMS for smart homes and buildings enables the centralised monitoring, coordinating and controlling the devices in the distribution network. Therefore, the research in embedding the VPP function in the existing smart home and building EMSs and the related control approach can give a clear road map in promoting the VPP service in the distribution network and also create a brand new value stream for smart home and building users.

List of Publications

Journal Papers

Zhou, S., Wu, Z., Li, J., & Zhang, X. P. (2014). Real-time energy control approach for smart home energy management system. *Electric Power Components and Systems*, *42*(3-4), 315-326.

Wu, Z., **Zhou, S**., Li, J., & Zhang, X. P. (2014). Real-Time Scheduling of Residential Appliances via Conditional Risk-at-Value. *Smart Grid, IEEE Transactions on*, *5*(3), 1282-1291.

Yang, X., Zhang, X. P., & **Zhou, S**. (2012). Coordinated algorithms for distributed state estimation with synchronized phasor measurements. *Applied Energy*, *96*, 253-260.

Wu. Z., Zhang, X.P., Brandt, J and **Zhou, S**., "Three Control Approaches for Optimized Energy Flow with Home Energy Management System," *IEEE Power and Energy Technology Systems Journal* 2015.

Conference Papers

Zhou, S., Zhang, X. P., & Yang, X. (2012, October). Design of demand management system for household heating & cooling. In Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on (pp. 1-6). IEEE.

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