Department of Electrical and Computer Engineering

Demand Dispatch Control for Balancing Load with Generation

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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ABSTRACT

Power grid contains a large number of distributed generators, power storages, and loads. Maintaining the supply and demand balance instantaneously has always been a crucial issue especially in recent years due to the high rate of peak load growth. In the traditional way of demand-supply match, generation conforms to loads consumptions but this method is not always applicable and cost effective. In this research, an innovative method for "Demand Dispatch (DD)" has been proposed for smart grid applications.

It has been assumed that different types of aggregated loads are distributed all over the grid, which can act as spinning reserve for the network. Therefore, in time of DD event, the power consumption of these aggregated loads alter to match generation with demand.

There are different methods to implement demand management. In this thesis, a Demand Side Frequency Droop (DSFD) is proposed to calculate the require power reduction. Moreover, this method provides ancillary service to the grid and maintains the frequency of the power system when the generation system is not capable of following the demand.

At the time of a frequency fall/rise, BA (Balancing Authority) can detect aggregated load or group of aggregated loads that have power consumption above or below their standard maximum/minimum consumption levels. Then, the BA issues droop-based signal to the relevant aggregators. Afterwards, the DSFD will be

implemented by an aggregator or a group of aggregators to specify the required power consumption amount for bringing the frequency back to its rated level. Subsequently, this signal will be sent to the Appliance Management Unit (AMU) at each participating house. The AMU sends the signal in the form of deferral or interruptible commands to the appliances depending on the priority, availability and the specification of the appliances. It has been demonstrated that the proposed DSFD control maintains the frequency of the power system within a specified range.

The advancement in the battery systems makes the application of the battery storage more affordable. Moreover, the high penetration of the PV systems in residential levels has raised the necessity to use the PV-Battery system to prevent the deterioration of the power quality of the grid. Thus, to improve the operation of DD schedule, the renewable resources and the storage devices are integrated to the DD.

DD are capable of providing the spinning reserve. Usually a group of fossil fuel generators are responsible for providing this spinning reserve service during occurrence of the peak loads. However, the cost of procurement, maintenance, and control of the extra generators is not always rational as the peak loads happen in a few days a year. In this thesis, the capability of the proposed DD in providing the spinning reserve has been discussed. In addition, the estimated cost of running a fossil fuel generator to provide spinning reserve has been compared to the cost of the exploiting of DD as a quick spinning reserve.

The proposed methods in this thesis have been validated through PSCAD software simulation and MATLAB.

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KEYWORDS

Demand Side Management, Demand Dispatch, Controllable appliance, Frequency Droop, Deferrable Appliances, Interruptible Appliances, Spinning Reserve, Appliances Management Unit, Balancing Authority, Demand Side Frequency Droop, Clod Load Pick Up, Customers Satisfaction, Load Factor.

ABBREVIATIONS

AC: Air Conditioner

AGC: Automatic Generation Control

CW: Cloth Washer

DD: Demand Dispatch

DSFD: Demand Side Frequency Droop

DSM: Demand Side Management

DRY: Dryer

DW: Dishwasher

EV: Electrical Vehicle

FCAS: Frequency Control Ancillary Services

FR: Fridge

LF: Load Factor

NEM: National Electricity Market

OCS: Overall Customers' Satisfaction

PHEV: Plug-in Hybrid Electric Vehicle

PP: Pool Pump

PV: Photo Voltaic

SCADA: Supervisory Control And Data Acquisition

SoC: State of Charge

WH: Water Heater

CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

For the safe operation of a power system, the generation and demand (including losses) must be balanced instantaneously. For example, if the demand is more than generation capacity, load shedding has to be implemented to maintain this balance. Form the customers' point of view, loss of supply causes discomfort and/or financial loss. On the other hand, from the utility point of view, the loss of balance of generation and demand can severely affect system stability [1-6]. In the conventional operation of power system, the generation side has been responsible for maintaining the power balance. However, the recent years have seen unprecedented load increase resulting from population growth and the continuous improvement in the standard of living. This needs an expansion in all the three facets of power infrastructure. With the current concern about climate change, an increasing number of renewable energy sources such as wind and solar are being integrated with power systems. This has resulted in the phasing out of older generation units. Unfortunately however, the sun does only shines during the daytimes and the wind does not blow always. To complicate the problem even further, the energy harvested from these sources can drop suddenly. For example, a passing cloud can have a shadow effect on PV cells. Therefore, these renewables sources are generally termed as "intermittent," even though this is a misnomer.

The installation of extra fossil fuel generators to cater to increased power need is expensive and these generators have deleterious effect on the environment [1, 7]. Demand side management (DSM) can resolve load unbalance in transmission and distribution networks and reduce the expense of transmission assets [8-14]. Moreover, changing a load in intelligent way is more cost-effective than constructing a new power plant [5, 6, 8, 10, 15-19].

In the recent years, a remarkable progress in research has been made in the area of DSM. However, implementation of DSM in residential level has been neglected due to the diversity of electrical appliances, their relatively low power consumption, and the complexity of residential load profiles. Moreover, it is expected that in the near future, high penetration of Electrical Vehicles (EV) will drastically change the residential load profile [3] [20]. At the same time, smart appliances equipped with built-in communication systems are on the horizon, which will enhance the role of residential DSM [5] [21]. At the same time, the advancement in load modelling and load prediction methods can alleviate the residential load profile complexity [12] [22-25].

There are different load management methods, which have been reported in the literature as listed below [26-32]:

- Permanent changes of appliances: For example, replacing an inefficient ventilation system with a more energy efficient one or changing the insulation of buildings. This method results in an immediate and permanent energy savings, albeit expensive [6, 33, 34].
- Energy storage system: In [15] and [1, 16] authors propose using energy storage to alleviate the peak demand. This method can be an expensive solution and cause extra cost for householders [34].

- Real-time pricing: References [35-37] propose real time pricing and reward-based schedule to shift the peak demand time. Moreover, this method considers customer's priority and flexibility, which can also be cost effective for customers. Smart meters are required to be installed at houses to provide required data for secondary controller which are placed at the transformers [34].

- Load transfer scheme: Transferring load from one phase to another is implemented in [38] based on the commands which are dispatched from a central controller by means of static transfer switch [34].

- Multi objective decision for load control: In [39] such scheme is proposed to choose the loads to be controlled with the help of two-way communication. The goal of this approach is to control peak load by considering customer's satisfaction [34].

- Electrical spring: This approach involves active and reactive power compensations for different types of loads, which has been introduced in [16]. This smart control strategy stabilizes a power grid through controlling the demand [16, 19, 34].

- Transactive energy: By using economic signals or incentive, the end users are encouraged to participate in demand side management by means of all intelligent devices in the power grid [34, 40, 41].

All of the above-mentioned methods contribute in balancing loads and generations. Because of diversity in load management methods, it is hard to categorise them into specific groups. However, load management in residential level can be categorised into two main methods: Direct Load Control, in which the network operators control the appliances in each house directly and Indirect Load Control, which aims to motivate the consumers to reduce their power consumption based on the incentives such as different electricity prices for different time intervals [42]. As shown in Fig. 1.1, these two methods of load control can be obtained through different schemes. These two methods are briefly described as follow:

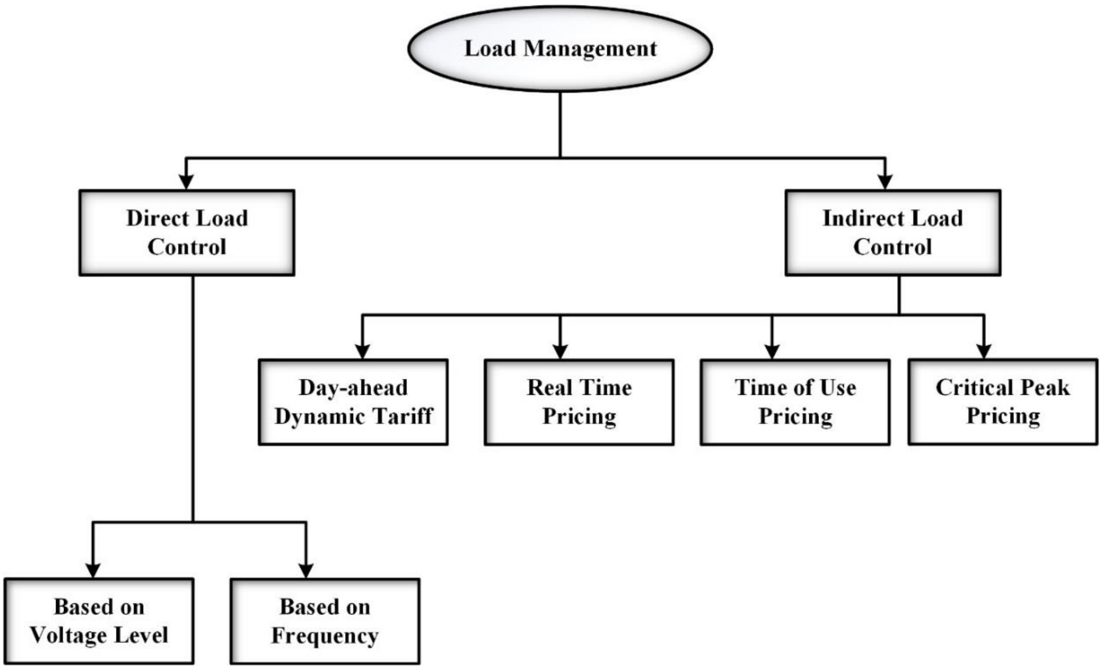

Fig. 1.1. Load management categories.

1) Direct Load Control:

In this method, based on contractual agreement between the end user consumers and the utility operator, the utility operator is allowed to control the appliances of a house directly during peak demand time [42, 43]. The goal of this method is to shave the peak demand and reshape the load profile. The trigger for direct load control can be based on frequency of the system [21, 32]. For example, DSM can perform load shedding to maintain the frequency of the power system in a relatively more cost effective way. Cost-based incentives such as interruption compensation and/or upfront payment can be offered to customers to encourage them to participate in demand management programs [29] [30] [31]. On the other hand, DSM has this potential to act as spinning reserve for the power grid and participate in stabilising the frequency. The frequency control problem is addressed in an isolated power system equipped with a wind turbine in [32]. Another trigger for direct load control is voltage levels at connection points of houses [44].

The main advantage of direct load control method is that the utility operator have almost full control of the load profile. However, violating the customers' privacy and satisfaction can be the main drawback of this method. If these are taken into account during the signing of the agreement and within the load control scheme, this method can bring many benefits to the utility.

2) Indirect Load Control:

Contrary to the Direct Load Control, the utility operators are not allowed to control the load pattern directly. This method reduces the demand indirectly through price-based schemes such as [42]:

- Day-ahead dynamic tariffs:

In this method, day-to-day prices for electricity consumption is introduced to the customers. This method required two-way communication and smart metering technology. The electricity cost depends on both the power consumption level and the time of electricity use. This method can solve the congestion problem for utility. However, the demand prediction can be a challenge for this method [45, 46].

- Time of use pricing:

In this method, customers are charged with different fixed rates depending on the specific time interval of a day – mainly the peak and off peak hours. This method is the simplest among the indirect load control, as it does not need any two-way communications. However, it may cause an increase in the peak demand or lead to another peak [47].

- Critical peak pricing:

In this method, a dramatically higher peak price is applied compared to the normal peak price for a short period. In order to offer the critical peak price to the customers who are willing to participate in this scheme, there are two main constrains for utility operators such as the number of critical peak time calls and the time interval between two critical peak time calls. Moreover, the customers are able to accept or reject these critical peak time calls which makes this method uncertain [48].

- Real time pricing

In this method, consumers receives hourly prices for electricity consumption. The price rates can alter based on factors such as the time of high demand and availability of the renewable energy resources [49]. The uncertainty, which comes from the customers' behaviour is one of the main challenges for the utility. Therefore, this method needs proper forecasting methods and planning schedule to adjust real time prices for real time changes in the load patterns [50].

Aside from the abovementioned methods of load management, DSM can be applied in a centralised way, decentralised way, or the combination of both [51]. In literature, most of the research works are based on the centralized demand control. In [39], a centralised method is introduced to bring the power consumption below the rated level of distribution transformers. However, a purely centralized method is not appropriate when a large number of various loads are in the mix. This is because the detailed control of different levels of aggregated loads will be missed in the central method. Authors in [26] developed a decentralized Home Energy Management (HEM) algorithm by which the consumers can schedule their loads' consumption patterns. A combination of centralized and decentralized load managements which forms a multi-level DSM is proposed in [27]. A DSM is usually applied in the form of load curtailment or load deferral. In [28] an optimised time delay for periodic loads is proposed to prevent peak loading. A load interruption based method is proposed in [52] to shift the demand time and bring the power consumption of a house below the required limit through the HEM system.

In recent years, due to large-scale deployments of electric vehicle, PV, and storage devices in power system, the nature of DD has changed more towards transaction-based energy management [53, 54]. For example, authors of [53] proposed an optimal transaction-based method to reschedule distribution aggregators to maintain power system balance. This method helps resolving the conflict between the transmission and distribution network operators.

1.1.1. DEMAND DISPATCH

In the recent years, communication technology has prospered and more electrical loads are expected to be equipped with communication and control systems. Moreover, the emergence of smart meters in residential level has had a significant effect on contribution of DSM in power system balancing [1, 5, 6, 9, 11, 20-25, 34, 55-62]. These trends have introduced a new form of DSM for grid management, which is called DD, which aggregates and dispatches individual dispatchable loads in real time. DD can be considered as an effective solution to balance generation with demand

[5, 10, 16]. Moreover, dispatchable loads can respond to DD command as quickly as an energy storage system. The advantage of deploying dispatchable loads over energy storage system is that dispatchable loads do not incur any additional losses as opposed to energy storage, since they are connected through dc-ac converters.

1.1.2. DD REQUIREMENTS

The first requirement for implementation of DD is to aggregate loads in order to provide aggregated dispatchable loads for the grid. Assembling a large number of dispatchable loads requires some information about loads such as the power draw capability limitations, energy draw capability limitations, and the number of on and off cycle limitations. An aggregator acts as mediator between utility and load and assembles this information from loads [5, 10, 52].

As mentioned above, the aggregators require some information about dispatchable loads such as the power draw capability limitations, energy draw capability limitations, and the number of on and off cycle limitations. Moreover, some critical electrical parameters such as the instantaneous value of current, voltage, and frequency are needed to be measured and monitored. Thus, each house must be equipped with smart meters [63]. Note that, it is essential to monitor loads in each house continuously at all time. Therefore, Appliances Management (AMU) is required at each house which can received the external signals that contain commands for demand curtailment from aggregators.

Another requirement for DD is a low-latency, moderate band-width wireless communication path to electrical appliance. Many electrical appliances that will be equipped with two-way communication are on the horizon [5].

1.1.3. SELECTING PROPER LOADS FOR DD AND THEIR MODELS

So far, the studies done regarding modelling of residential loads were mostly on heating and cooling appliances such as air conditioning unit and water heater [22, 64], while the diversity and state of art of today's residential loads led to increase in their controllability. For example, in [65], a thermal dynamic model of an individual AC was proposed and then an aggregated model of the AC systems within a simple control scheme was tested.

In [66], authors focused on stochastic model of EVs and its effect on DSM. However, as mentioned before, today's households contain more controllable appliances than before. In [67], a bottom up approach for load modeling of different types of residential buildings in Singapore was proposed. However, the controllability of the individual appliances was not taken into account.

Authors of [68] provided the dynamic model of AC, WH, DRY, and EV in details. However, today's appliances such as CW, PP, DW, and defrost cycle of FR are highly capable of participating in DSM.

Loads that can be considered as good candidates for DD must have the following features:

1) The time of turning the load on must not be critical for consumers. In other words, the only issue which matters that the load is drawing a specific energy during a specific time.

2) There must be a slack time for loads. It means there must be a course of time between the latest possible time for completion of tasks and the earliest possible time of completion of the load's task.

According to the above mentioned features, the following loads are good candidates for DD [69]:

- Dishwashers: which can work at any time overnight, provided that they finish their tasks before morning.

- Clothes dryers: they consist of a motor part, which consumes approximately a few hundred watts (around 300 W) and heating coils consume several kilowatts (around 4 kW). Thus, in time of DD command the heating part can be turned off while the rotating part keeps working.

- PHEV, the charging process of PHEV can be postponed as long as it is fully charged by mornings.

- Electric water heater, when a hot water temperature reaches the desire set point, water heater heating coils can be turned off.

- Air conditioning system.

- Refrigerator with defrost cycle.

To investigate the accurate behavior of a typical residential load profile, the models of a wide range of controllable appliances are necessary. Moreover, the dynamic models of the controllable appliances are required to illustrate the functionality of the proposed DD methods.

In this thesis, the wide range of models of appliances have been considered and the controllability of the appliances has been integrated to the dynamic models of the appliances. Many factors such as the ambient temperature, soil temperature, room temperature, house size, and water usage pattern have been considered in the appliances models.

To make a comprehensive study, the residential loads have been categorized into two groups – controllable and non-controllable. Pool Pump (PP), Water Heater (WH), Air Conditioning unit (AC), Fridge (FR), Dish Washer (DW), Dryer (DRY), Clothes Washer (CW), and Electrical Vehicle (EV) are considered as controllable appliances, while Hair Dryer, Toaster, Lightings, stove and oven and so on have been considered as non-controllable ones. Controllable appliances, in turn, have been divided into to two categories; deferrable and interruptible appliances. DW, DRY, CW, and PP have been categorized as deferrable appliances. Note that, these appliances consist of electrical motors, which have large inrush starting current that can cause a current dip in the cold load pick up condition in aggregated scale after resuming their tasks. So, their tasks are postponed instead of being interrupted. Therefore, they have been categorized as deferrable appliances. On the other hands, DRY's heating part, defrost cycle of FR, EV, WH are interruptible loads as they do not cause inrush currents and they can be switched on remotely without the needs for human interference.

1.2. OBJECTIVES OF THE THESIS

As mentioned in the previous section, different DSM strategies have different shortcomings. For example, utility is not allowed to control the customers' load directly in all of the indirect load management methods such as day-ahead dynamic tariffs, time of use pricing, critical peak pricing, and real time pricing. Therefore, the uncertainty that comes from the customers' behaviour is one of the main challenges for the utility. In this research, the direct load management approach has been considered.

A purely centralized demand management is not an effective approach for controlling a large number of various loads. This is because the detailed control of different levels of aggregated loads will be missed in a purely central method. In this research, a hierarchy centralized demand management method is considered to overcome the shortcomings of the purely centralized method.

Most of the research in the field of load management has been done on industrial and commercial load and the residential loads have been neglected, although implementation of DD schedule in residential level can have significant effects on the power system. The DD schedule is a cost effective and environmental friendly method to balance the demand and supply. This thesis focuses on DD schedule in residential loads. A frequency droop based demand dispatch to lower the power consumption of the residential aggregated loads has been proposed. Moreover, the effect of integration of renewable resources and storage device to the DD schedule has been investigated which has been neglected in most of the previous load management schedule. In addition, the cost of implementing DD to provide spinning reserve have been estimated and compared with the estimated cost of providing the same spinning reserve through fossil fuel generators.

Based on the above discussions, the objectives of this thesis are developed. The main aim of this thesis is to develop an innovative method for DD schedule to balance supply with demand through a wide variety of residential loads. In order to achieve the main goal, the following sub-goals are set:

- Implementation of DD from Balancing Authority (BA) point of view to prevent frequency deviation due to the lack of demand-supply match.
- Development of a proper algorithm for AMU to keep the power consumption of a house below the power limit which has been issued from BA to each house, considering the availability and limitation of appliances and customers' satisfactions.
- Development of Droop Based DD to control the frequency of the system within an acceptable range.
- Integration of the storage device and renewable resources to the DD schedule and investigate their effects on the customers' satisfaction and Cold Load Pick Up (CLPU) and Load Factor.
- Investigate the cost effectiveness of implementation of DD in comparison with the conventional power generation to provide spinning reserve for the network.

1.3. THE MAIN CONTRIBUTION OF THE RESEARCH

The main contributions of this thesis are stated as follow:

1) A new control strategy based on droop control is proposed to keep the frequency stable by altering the power set points of dispatchable loads according to the generation's variations.

A conference paper is published based on the content of this chapter [34].

2) A control algorithm has been proposed for an AMU of a house with a wide variety of deferrable and interruptible appliances considering consumers priority and satisfaction. The results show the proposed AMU algorithm is capable of maintaining the total power consumption of a house during DD events below the requested demand limit, while preserving consumer satisfaction.

   A conference paper is published based on the content of this chapter [70].

3) The Demand Side Frequency Droop (DSFD) has been proposed to improve maintaining the frequency of the power system within the acceptable range.

   A journal paper is published based on the content of this chapter [71]

4) Integration of the renewable energy and storage system to the DD schedule and investigation of their impacts on the DD function.

5) Investigate the estimation cost of implementing DD to provide spinning reserve and compare it with spinning reserve provided by fossil fuel generators.

1.4. STRUCTURE OF THE THESIS

This thesis is organised in seven chapters. The current chapter presents a brief literature review to provide a general understanding of DD program, its requirements and, its effect on maintaining the frequency of the power system. Moreover, the objectives and significance of this thesis have been presented.

Chapter 2 presents a control strategy to maintain the frequency of the power system by categorising the residential loads into dispatchable and non-dispatchable load clusters. Non-dispatchable load cluster cannot participate in load management and must be supplied continuously. On the other hand, dispatchable loads can be altered according to the power difference between the source and the demand at any time. These have been further categorised into discrete and continuous load clusters. Discrete load power absorption is limited between two adjacent limits and cannot be altered continuously in contrary to the continuous load. The proposed method has been evaluated via PSCAD simulation studies for various combinations of load clusters under different scenarios. The results show that the DD control strategy can tune the mismatch between aggregated demand and supply. Consequently, it keeps the frequency stable by changing the power set points of dispatchable loads according to the generation changes by implementing the droop control schedule on the demand side. Besides, it is investigated that the aggregated loads are able to track the set points accurately.

In **Chapter 3**, a house with a wide range of controllable and non-controllable appliances has been considered. It has been assumed that the power consumption of an entire house and appliances are measured and monitored every 30 sec. Moreover, the controllable appliance models are explained in details. It has been assumed that this house does not have any renewable energy source or storage device, and hence it is called a semi-smart house. A DD algorithm for this semi-smart house has been proposed which enables the AMU of the to bring its power consumption below the limit issued from a balancing authority (BA). This algorithm has considered the customers priority and satisfaction in choosing controllable appliances to be switched off or postponed. Moreover, the availability and limitations of the controllable appliances have been taken into account. During DD events, the proposed AMU algorithm keeps the total household power consumption below the required limit. In addition, the load rebound possibility of the semi-smart house is investigated in this chapter. At the end of this chapter, the necessity of integration of renewable energy resources and battery storage system to the DD schedule to prevent load rebound is highlighted.

In **Chapter 4**, a Demand Side Frequency Droop (DSFD) control in aggregators' level has been presented to provide ancillary service to the grid by maintaining the frequency of the power system when the generation system cannot follow the demand. According to the DSFD method, the frequency deviation is considered as a trip signal to trigger the DD schedule. In time of frequency deviations, the BA recognises the aggregated loads with the power consumption above/below the permitted level and issues droop-based regulation signals to the aggregators to nominate them to participate in DD program. Afterwards, the feasibility of the issued command will be investigated by the aggregators considering the droop characteristic of the aggregated loads. Then, the droop-based demand dispatch commands are sent to the AMU in a form of interpretable/deferrable signals until the next command from the BA. These commands are issued based on the time of the day, the priority of the consumers, the features of appliances and the overall characteristic of the aggregated loads.

In **Chapter 5**, the renewable resource and storage device have been integrated to the DD plan to improve the functionality of the DD. Three different scenarios have been proposed for integrating the PV-battery system to the DD schedule. Also, they have been compared to the DD schedule without any renewable resource and storage device. These three scenarios have been compared considering factors such as Cold Load Pick Up (CLPU), Load Factor (LF), and Overall Customers' Satisfactions (OCS). According to the results, by replacing the battery for the appliances with the highest priorities, the proposed DD reaches the best results. This leads to a 100% CLPU factor. Also, as this group of controllable appliances were among the both combination of interruptible and deferrable appliances, the battery has been utilised in the best possible way.

In **Chapter 6**, the capability of the proposed DD in providing the spinning reserve has been investigated. The estimated cost of running a fossil fuel generator that provides spinning reserve, has been compared to the cost of providing the same service by DD as a readily available spinning reserve. According to the results, compared to the conventional fossil fuel based spinning reserve generation, the implementation of the DD method is much more economical. The cost of the spinning reserve provided by the DD mainly consists of some upfront equipment and software expenses. However, the ongoing costs are very low compared to the traditional spinning reserve sources. Moreover, the DD method has the advantage of being environment friendly as its carbon emission is zero.

Chapter 7 presented the overall conclusion along with the scopes of future research.

CHAPTER 2

DROOP-BASED DEMAND DISPATCH SCHEDULE IN SMART GRID

Due to the remarkably fast rate of rise in the electricity consumption, keeping the demand and supply balance instantaneously has become a major concern for utilities all over the world [1, 72]. Without a proper demand response, both power system stability and customers' satisfaction can be affected, albeit in different ways [2, 3]. Thus, it has always been a challenge for the utility industries to balance the generation with demand by making the generation comply with demand. Much of the research has been focused to achieve this balance [4-6]. Construction of new power plants is a lengthy and costly process. For example, it takes 5-10 years to build a nuclear power plants or almost 6 years and 3 years to construct a coal plant and a natural gas combined cycle power plant respectively. Aside from the time requirements and the cost, environmental and human health concerns have forced the utilities to employ renewable energy [1, 73]. The most common form of renewable energy generators that has been widely used in recent years is the non-dispatchable type such as PV and wind turbine. They operate in maximum power point tracking (MPPT) mode in which their maximum available power is extracted. This implies that a system containing only non-dispatchable sources cannot always match the power generation with demand without any back up dispatchable sources [7].

Also, the penetration of non-dispatchable renewable energy resources decreases the reliability of the power system since there are unpredictable and intermittent. To come up with solution to the problems of unpredictability and intermittency of these resources, Demand Side Management (DSM) has been introduced to the power system applications [5, 10, 16, 19]. Moreover, the advancement in communication systems and advent of the smart electrical loads equipped with communication and control, have paved the way for effective implementation of DSM [74].

In Chapter 1, seven different ways of load management are briefly discussed. In all these, the objective is make the loads follow the generation. In this chapter, a new concept in which the demand follows the generation is discussed. This way, the frequency can be stabilized following any drop or rise in the renewable generations. This is called the paradigm of “demand dispatch” [5] and this is exactly opposite to the conventional method of demand response. The proposed method has been evaluated via PSCAD simulation studies for various combinations of load clusters under different scenarios.

It should be noted that the content of this chapter has been mainly extracted from [34].

2.1. DEMAND DISPATCH

In a demand dispatch regime, the error between the load demand and supply is reduced continually until it reaches nearly zero such that the frequency is maintained close to its rated value. In the procedure discussed in this chapter, the demand dispatch is implemented from balancing authority point of view. In chapter 4, a control strategy will be formulated such that the aggregators can select which of the loads need to participate in demand dispatch program. Moreover, it has been assumed that the loads are aggregated on distribution transformers nodes.

2.2. DISPATCHABLE/ NON-DISPATCHABLE AGGREGATED LOADS

In the algorithm presented here, the distributed aggregated loads are considered to be controllable and are divided into two categories: dispatchable and non-dispatchable. Non-dispatchable loads are not capable of participating in load management schedule and must be supplied under any conditions, while dispatchable loads can be altered according to the power difference between the source and the demand at any time. The dispatchable loads can respond to DD commands quickly and thereby act as virtual spinning reserves in the grid. Since the active power influences the system frequency, the power difference between the generation and demand has been used in a droop control amongst the loads.

Dispatchable loads can respond to DD command as quickly as an energy storage system. The advantage of deploying dispatchable loads over energy storage system is that dispatchable loads do not incur any additional losses as opposed to energy storage.

It has been assumed that different types of aggregated loads are distributed all over the grid, and cumulatively, they can act as the spinning reserve for the network. These aggregated loads in distribution grid can participate in grid stabilization based on whether they are categorized as dispatchable or non-dispatchable loads.

Air conditioner, dryer, Electrical Vehicle, clothes washer, dish washer, pool pump, and water heater can be considered as dispatchable loads according to the preference and satisfaction of the costumers.

2.3. THE SMART GRID STRUCTURE

The smart grid which is considered in this here is equipped with two way communication and smart devices. Smart meters are installed at each house to collect its power consumption data and the status of appliances. Also, each appliance in a house is equipped with a smart unit, which can collect data such as mix/min power draw, on/off cycle of the appliance and transmit them via WiFi or ZigBee to the Appliances Management Unit (AMU). Then, this information is assembled through aggregators from each AMU. Aggregators act as mediator between utility and individual loads.

The grid consists of generators and different types of loads as shown in Fig. 2.1. All the loads are considered to be aggregated. In Fig. 2.1, P_G, Q_G, P_{L1}, Q_{L1}, P_{L2}, Q_{L2} and P_{L3}, Q_{L3} denote the real and reactive powers which are produced/absorbed by the generator and loads. Z_1, Z_2, and Z_3 are the line impedances. Circuit breakers C_{B1}, C_{B2}, and C_{B3} can isolate loads from grid in case any need arises.

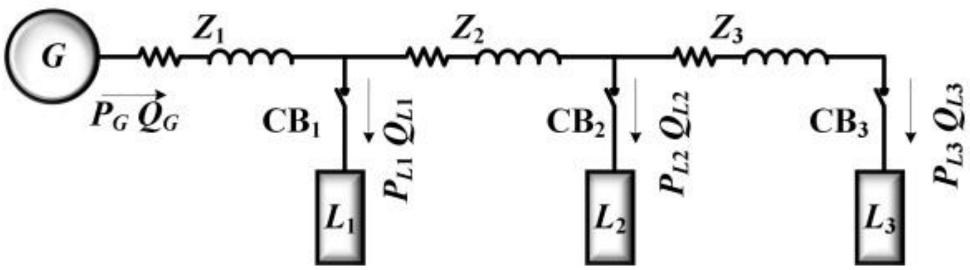

Fig. 2.1. Grid structure.

2.4. TRADITIONAL FREQUENCY DROOP IN GENERATION SIDE

The frequency in a power system is dependent on the active power. It is a means of controlling the power generated when several generators supply loads. When the demand changes a mismatch between mechanical and electrical torque causes the frequency/speed deviation from its rated value. Therefore, to compensate the power shortage, generators need to increase their output power based on frequency deviations.

However, the generation side is not always capable of compensating this mismatch. Therefore, the bigger sized generators are needed for peak shaving. Sometimes spinning reserves are needed to alleviate this problem. Usually the maximum peaks occur for a limited number of days in a year. Thus, from economic and environmental point of view, it is better to control the load demand, which can be effectively utilized to maintain the frequency of the power system. Therefore, demand management, when successfully implemented, can be considered as having a spinning reserve [75].

2.5. PROPOSED FREQUENCY DROOP FOR DEMAND DISPATCH

In this thesis, frequency droop has been employed for demand control. When the generation is not capable of following the demand, the frequency will drop below its synchronous (rated) level. In order to bring the frequency back close to the rated level, the load consumption needs to be decreased to compensate the power shortfall. To this end, some loads can be curtailed based on the frequency signal. On the other hand, when the demand is less than the generation, the frequency will rise. Thus, to bring the frequency back to its rated value, demand must go up. Therefore, some loads can be switched on in order to consume more power.

The frequency droop employed in this study is given by

$$\omega = \omega_s + m \times (P^* - P) = \omega_s + m \times \Delta P \tag{2.1}$$

where ω and ω_s are the instantaneous and rated frequency respectively and m is the droop coefficient. P and P^* are the instantaneous and rated power respectively. The droop control for consumption side is shown in Fig. 2.2, in which the power consumption is placed on the left half of the x-axis in order to differentiate it from power generation.

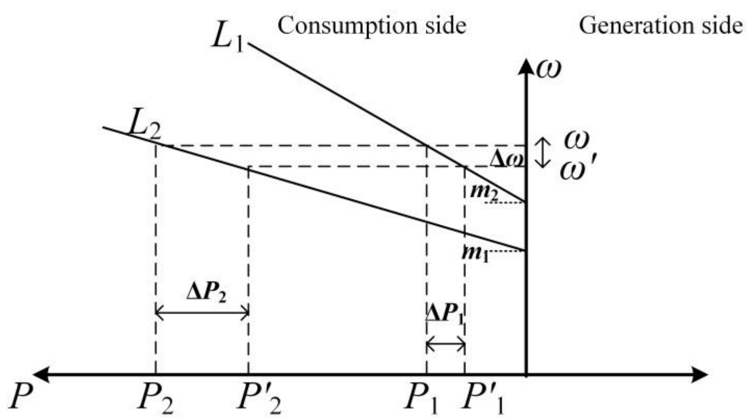

Fig. 2.2. Frequency droop for two loads.

In Fig. 2.2, the frequency droop lines for two loads are shown. L_1 and L_2 consume P_1 and P_2 respectively at an angular frequency of ω. When the frequency decreases to ω', decreased power consumption is required from both loads to bring the frequency back to its rated level. The loads L_1 and L_2 need to decrease their power consumption by ΔP_1 and ΔP_2 respectively, as shown in the figure. The new load levels are P'_1 and P'_2.

2.6. DEMAND SHARING AMONG THE AGGREGATED LOADS

The load demand can be shared assuming that they are continuously variable. However, this is not very practical, even assuming the loads are aggregated. A more realistic approach is to consider them to be a combination of both continuously variable and discretely variable loads. These two approaches are discussed below.

2.6.1. DEMAND SHARING AMONG LOAD CLUSTERS CONSIDERING AS CONTINUOUS LOADS

The demand sharing in this case is implemented based on the following equations assuming that there is a total n number of loads consuming power P_1, P_2, …, P_n respectively.

$$\Delta P_i = \Delta P \times \frac{P_i}{P_1 + P_2 + \cdots + P_n} \tag{2.2}$$

$$P_{i\_new} = P_i + \Delta P \frac{P_i}{P_1 + P_2 + \cdots + P_n} \tag{2.3}$$

where ΔP is the power difference between the amount of demand and supply, ΔP_i is the amount of power which i^{th} load needs to increase/decrease from its current consumption level and P_{i_new} is the new set point for the i^{th} load.

For the system shown in Fig. 2.2, Fig. 2.3 shows the implementation of frequency droop control for L_1. The frequency difference at a load bus is passed through a PI controller to obtain ΔP. Equation (2.3) is then employed to find the new set point. Similar control scheme is also employed for all the other loads.

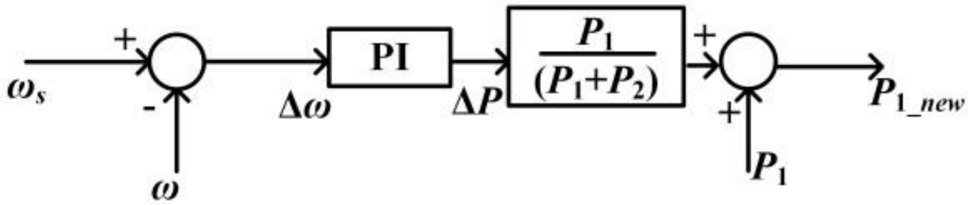

Fig. 2.3. Implementation of frequency droop and demand sharing scheme.

2.6.2. DEMAND SHARING AMONG LOAD CLUSTERS CONSIDERING AS THE COMBINATION OF CONTINUOUS AND DISCRETE LOADS

In the previous sub-section, all the aggregated loads are assumed to be continuously variable. This is not really realistic. For example, a certain variation can be made in passive loads by changing the applied voltage across them. However since the voltage variation must remain within ± 0.5 per unit, the load variation that can be achieved is limited. However from an aggregator point of view, the loads are a combination of some continuously variable and some discretely variable loads, which can be brought in or out depending on the frequency changes. A strategy is proposed in this sub-section for the control of combined continuously variable and discretely variable loads. How this combination responds to the frequency droop is discussed below.

A system with n discrete and m continuous loads is considered. Each discrete load has its own maximum and minimum power drawing limits. Between these two limits, there are several discrete steps in which the load can belong, but not in between any two adjacent steps. For example, if the j^{th} discrete load is between two discrete intervals a_{k-1} and a_k, then it is rounded down to the lower interval, i.e.,

$$If \quad a_{k-1} \le P_{Dj\_new} < a_k \quad then \quad P_{Dj\_new} = a_{k-1}\,,\ j = 1, 2, \ldots, n \tag{2.4}$$

Continuous loads draw the remaining power, which discrete loads are not able to consume. This power remainder will again be dispatched amongst the continuous loads through equations (2.2) and (2.3). The load dispatch process is given by the following equations

$$\Delta P_{new} = \left(P_{D1\_new} + P_{D2\_new} + \ldots + P_{Dn\_new}\right) - \left(P_{D1\_final} + P_{D2\_final} + \ldots + P_{Dn\_final}\right)$$

(2.5)

$$\Delta P_{C_{i\_new}} = \Delta P_{new} \frac{P_{C_i}}{P_{C_1} + P_{C_2} + \cdots + P_{C_m}} \tag{2.6}$$

$$P_{C_{i\_final}} = P_{C_{i\_new}} + \Delta P_{C_{i\_new}} \frac{P_{C_i}}{P_{C_1} + P_{C_2} + \cdots + P_{C_m}} \tag{2.7}$$

where ΔP_{new} is the amount of power which the discrete loads are not able to consume, ΔP_{Ci_new} is the amount of power which i^{th} continuous load needs to consume. P_{Dj_new} and P_{Dj_final} respectively are the power set points for j^{th} discrete load before and after applying power interval limitation. Also, P_{Ci_new} and P_{Ci_final} are the power set points for i^{th} continuous load before and after applying power interval limitation.

2.7. SIMULATION STUDIES

Four study cases have been considered to validate the proposed DD algorithm. These are:

Case-1: A frequency drop without DD has been considered.

Case-2: This shows that the continuous loads are capable of tracking the changes in generation.

Case-3: To demonstrate the implementation of DD in a load cluster.

Case-4: To show DD in a system consisting of both dispatchable and non-dispatchable loads.

The data used for these tests are given in Tables 2.1 to 2.3.

Table 2.1: Grid's Components Quantities.

System Data	**Value**
Discrete Dispatchable Aggregated Load ($L1$)	PL_1= 0.4 MW QL_1=0.1 MVar PF_1= 0.97
Discrete Dispatchable Aggregated Load ($L2$)	PL_2= 0.6 MW QL_2= 0.15 MVar PF_2= 0.97
Continuous Dispatchable Aggregated Load ($L3$)	PL_3= 0.45 MW QL_3= 0.11 MVar PF_3= 0.97

Non-dispatchable Aggregated Load (*L*4) in Case 4	PL_4= 0.45 MW QL_4= 0.11 MVar PF_4= 0.97
L1 Feeder Impedance	Z_1=R_1+jX_1= 0.05 +j0.01 Ω (L_1= 32 mH)
L2 Feeder Impedance	Z_2= R_2+jX_2 =0.1 +j0.02 Ω (L_2= 64 mH)
L3 Feeder Impedance	Z_3= R_3+jX_3=0.05 +j0.05 Ω (L_3= 160 mH)

Table 2.2: Discrete Loads Power Limitations.

Discrete Load	**Power Interval Limitations**
Controllable Aggregated Load (L1)	a_1= 0.15 MW a_2= 0.25 MW a_3=0.35 MW a_4= 0.45 MW a_5= 0.55 MW a_6= 0.65 MW
Controllable Aggregated Load (L2)	b_1= 0.15 MW b_2= 0.25 MW

	b_3= 0.35 MW b_4= 0.45 MW b_5= 0.55 MW b_6= 0.65 MW b_7= 0.75 MW b_8= 0.85 MW

Table 2.3: Generation Ramped Down and Up Values.

Generation	**Power Changes**
Generation Ramped Down	From 1.4 MW at time t = 1 s to 1 MW at time t = 6 s
Generation Ramped Up	From 1.55 MW at time t= 1 s to 1 .95 MW at time t = 6 s

2.7.1. CASE 1: DEMONSTRATION OF FREQUENCY DROP WITHOUT DEMAND DISPATCH

Consider a grid consisting of generators and three aggregated loads. When the generators are able to supply the power demand of 1.4 MW, the grid works in the rated frequency of 50 Hz. At time t = 2 s, the generation drops by 200 kW. This causes a drop in the frequency, as shown in Fig. 2.4. The purpose of DD is to bring the frequency back to 50 Hz by load control. However since DD has not been employed here, the frequency cannot be restored.

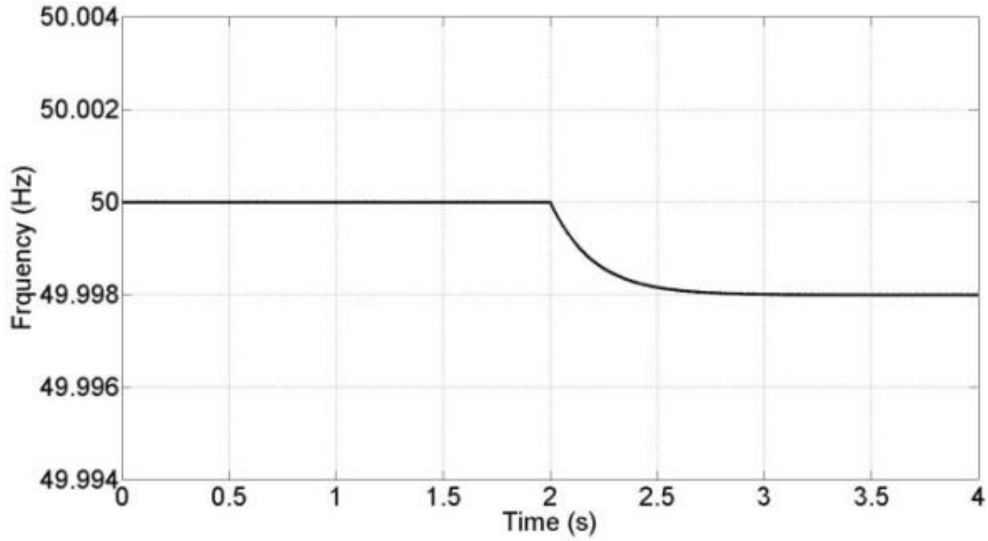

Fig. 2.4. Drop in frequency with generation shortfall.

2.7.2. CASE 2: CAPABILITY OF CONTINUOUS LOADS TO TRACK CHANGES TO GENERATION

To show how accurately demand can track generation in the presence of continuous loads, a decrease in generation occurs at 1 s and a ramp down in generation occurs from 4 s to 9 s. When generation starts dropping, frequency will drop. The proposed control strategy senses this drop and calculates ΔP from (2.1). Accordingly ΔP_i for each load is calculated using (2.2), as shown in Fig. 2.5. Thereafter, the new set points for aggregated loads are calculated using (2.3) and the frequency restored to 50 Hz. The changes in consumption pattern (solid lines) and the changes in their set points (red dashed lines) for the three loads are shown in Fig. 2.6. It can be seen that all the loads drop to accommodate the drop in system frequency.

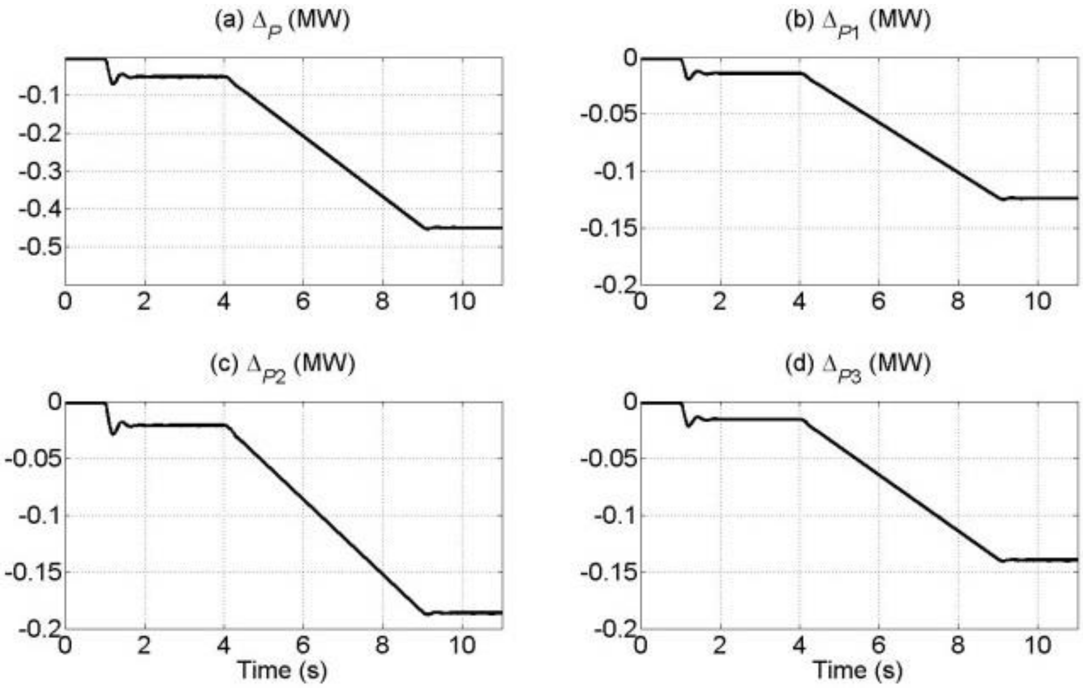

Fig. 2.5. Changes in ΔP with changes in frequency.

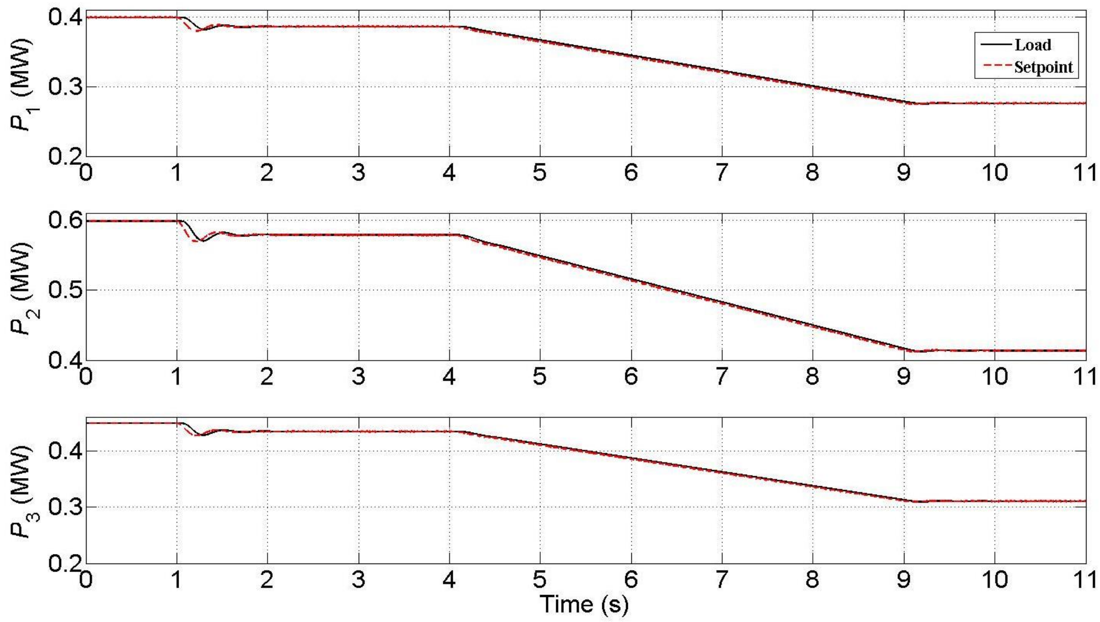

Fig. 2.6. Demand dispatch illustration with continuous loads.

2.7.3. CASE 3: IMPLEMENTATION OF DD FOR A LOAD CLUSTER

In this case, a single load cluster, containing both continuous and discrete loads, is considered. Loads 1 and 2 are assumed to be discrete, while load 3 is continuous. The system generation is ramped down from 1 to 6 s. The results are shown in Fig. 2.7. As can be seen, the frequency is held constant at 50 Hz. It can also be seen that the continuous load changes frequently in order to keep the frequency constant. The discrete loads change according to the condition stated in (2.4). It can be surmised that the continuous load varies its power absorption since the discrete load power absorption is limited between two adjacent limits.

As shown in Fig. 2.7, at time t=1 s when the generation starts dropping, the power consumption of continuous load begins to decrease according to the issued set points from the proposed controller. However the power consumptions of the discrete loads do not change since their boundaries have not been reached. At around t=2 s, the power consumption by discrete load 2 drops to the next discrete level. This causes the continuous load to increase. In a similar way, the continuous load again increases when discrete load 1 drops its power consumption at around 3 s. This process continues till the generation ramping down stops. It is to be noted that the rapid change in the continuous load can be minimized by reducing the heights of the discrete load changes, i.e., by choosing lower values than 0.1 MW chosen in this example.

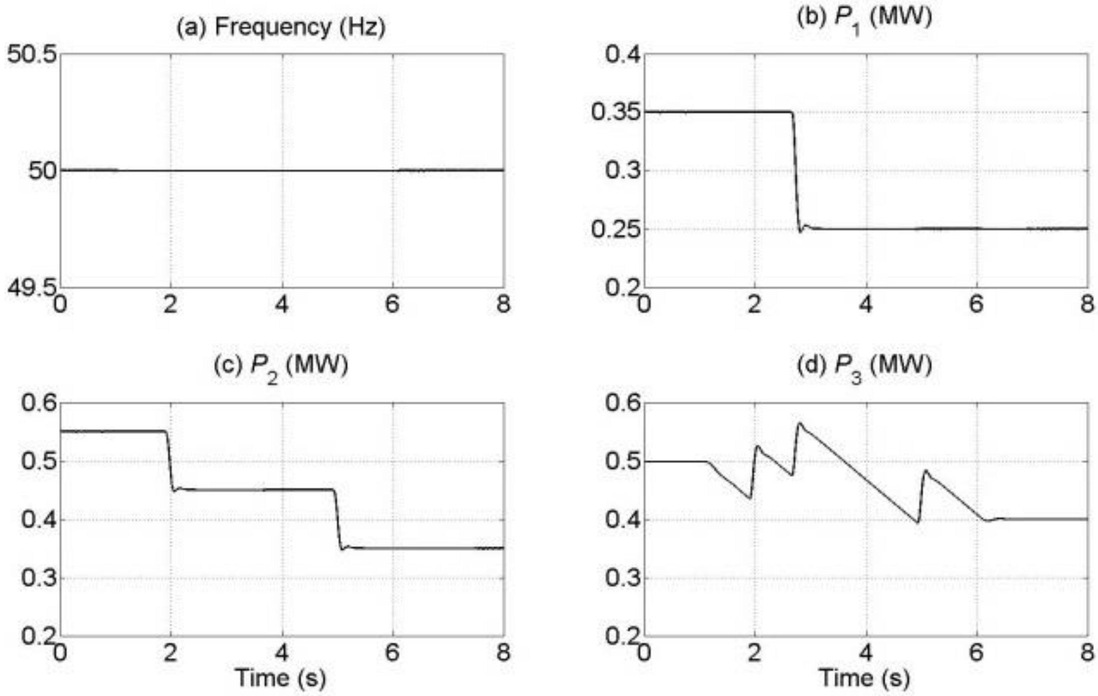

Fig. 2.7. System response in Case 3 for generation shortfall.

To investigate the response of DD to a rise in generation, the power generated is ramped up between 1 to 6 s. The results are plotted in Fig. 2.8. It can again be seen that the continuous load 3 changes frequently to hold the frequency constant, while the discrete loads change in steps. Contrary to the case in which power generation ramped down, when a rise in generation occurs, power consumptions of loads need to increase according to the power difference between the amount of demand and supply.

In Fig. 2.8, as the generation starts rising at *t*=1 s, the continuous load power begins to increase according to the set points from the controller. The power drawn by the discrete loads does not change because the issued set points from controller are not in the proper range. Therefore, whenever the new set points are within the proper power interval of discrete loads, their power consumption increase and accordingly the power consumption of continuous load decreases. This procedure continues until the rise in generation stops.

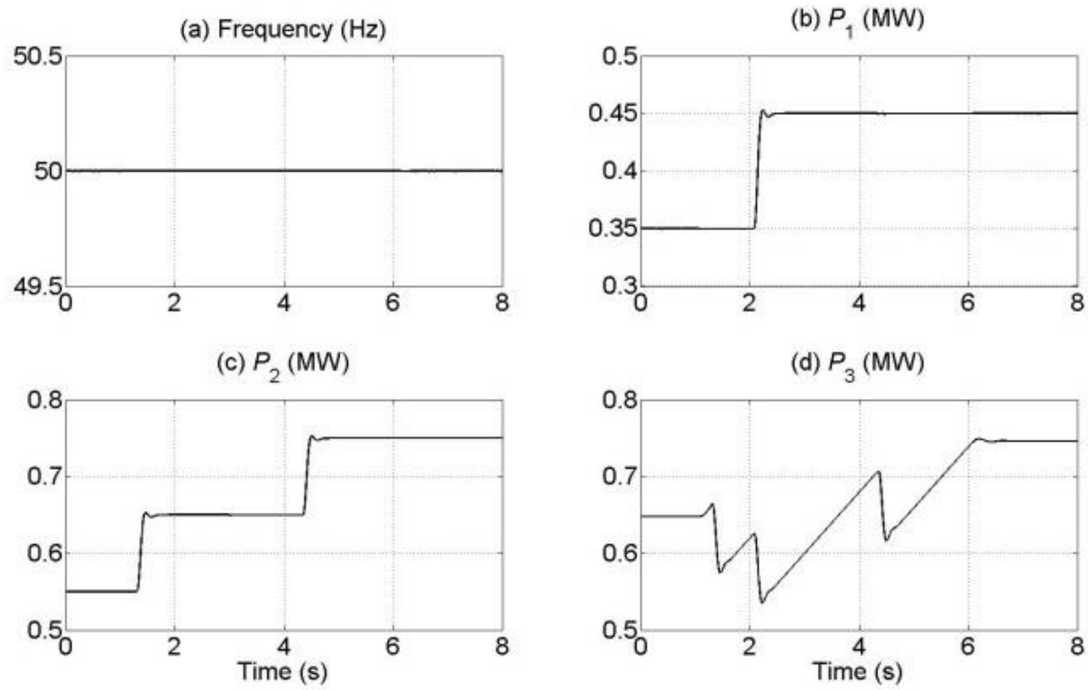

Fig. 2.8. System response in Case 3 for a rise in generation.

2.7.4. CASE 4: IMPLEMENTATION OF DD FOR A SYSTEM CONTAINING BOTH DISPATCHABLE AND NON-DISPATCHABLE LOADS

In this case, four different load clusters are considered, in which loads 1, 2 and 3 are considered dispatchable, while load 4 is considered as non-dispatchable (constant). Moreover, like in Case-3, the first two loads are considered discrete, while load 3 is considered as continuous. The objective of this study is to keep the consumption of load 4 constant and eliminate any frequency deviation.

In the first study, the generation is ramped down between 1 to 6 s. The results are shown in Fig. 2.9. It can be seen that load 4 remains constant, and variations in the other three loads are similar in nature to those shown in Fig. 2.7. However, both the time and quantity of load changes are different in this case.

In the next study, the generation is ramped up between 1 to 6 s. The results are shown in Fig. 2.10. It can be seen that load 4 remains constant, while the other three loads participate in DD. The frequencies for these two cases are shown in Fig. 2.11. It can be seen that the frequency remains constant all throughout the changes. This proves the efficacy of the proposed DD approach.

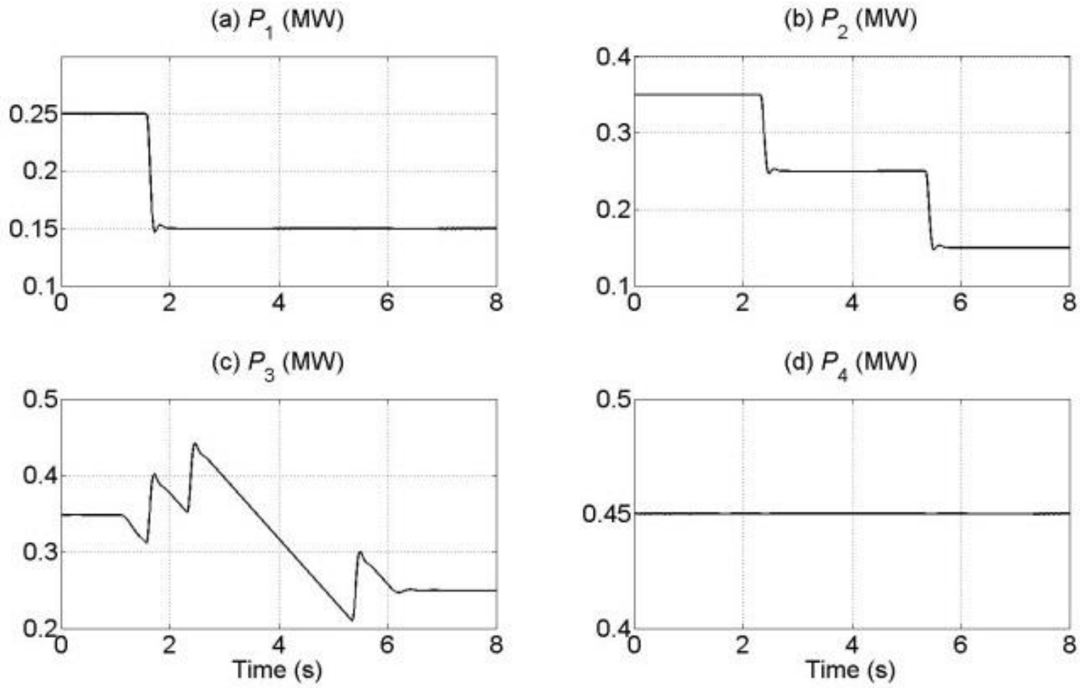

Fig. 2.9. System response in Case 4 for generation shortfall.

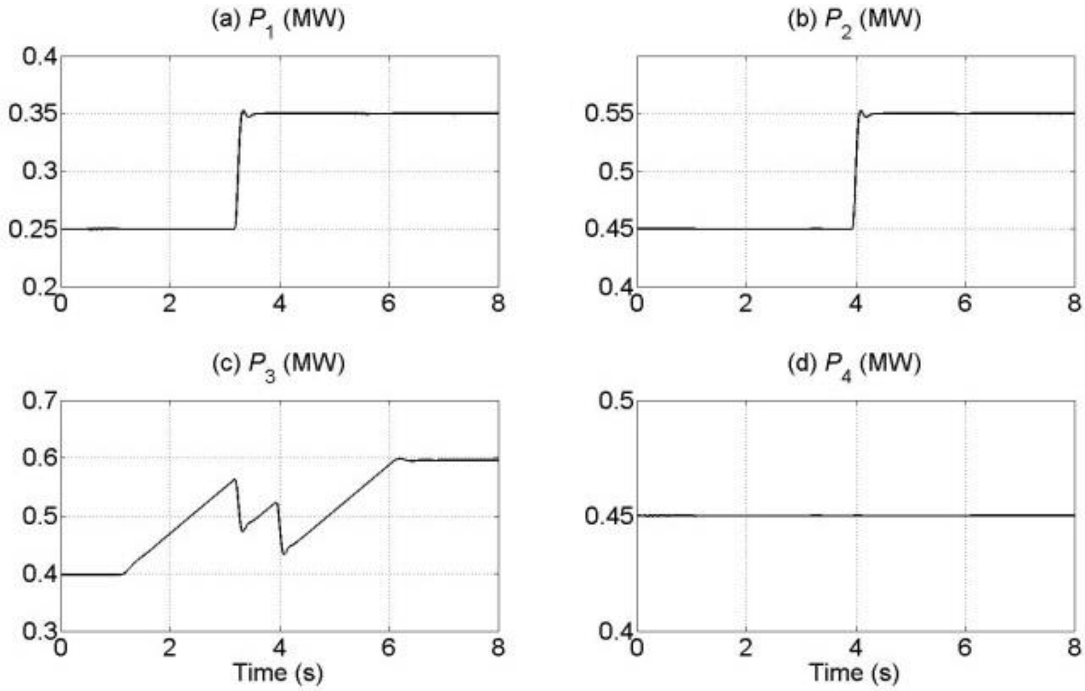

Fig. 2.10. System response in Case 4 for a rise in generation.

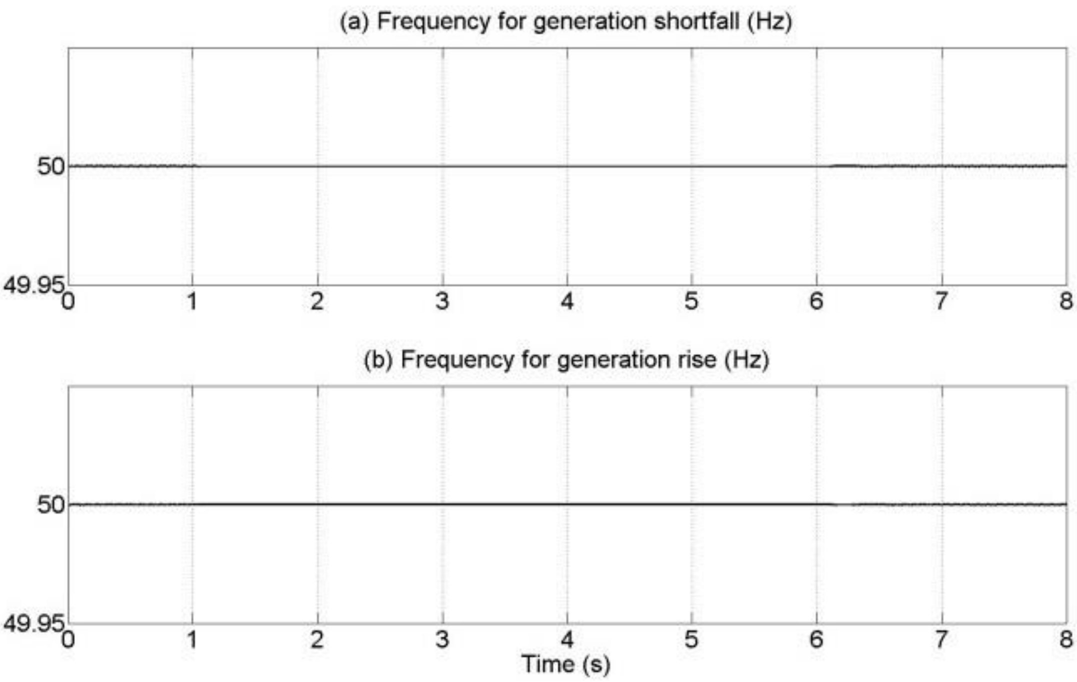

Fig. 2.11. System frequency for both the tests of Case 4.

2.8. CONCLUSIONS

In this chapter, an innovative method for "Demand Dispatch" is developed. According to demand dispatch, loads follow generation, in lieu of load-following generation, to keep the demand and supply balance and therefore system stability is maintained. To this end, the dispatchable and non-dispatchable aggregated loads have been considered.

The proposed method is validated through PSCAD simulation studies. The results show that the control strategy for DD is able to tune aggregated demand-supply mismatch. Accordingly, it keeps the frequency stable by altering the power set points of dispatchable loads according to the generation's variations based on the droop control implementation on the consumption side. Besides, it is investigated that the aggregated loads are able to track the set points accurately. Also, different types of dispatchable loads, both continuous and discrete loads, participate in the proposed DD to keep the frequency constant, while non-dispatchable loads are supplied continuously. The impact of load reduction/increase on frequency of system has been investigated. In the subsequent chapters, this method will be integrated with detailed features of various appliances.

CHAPTER 3

DEMAND DISPATCH THROUGH APPLIANCE MANAGEMENT UNIT IN A SEMI-SMART HOME

In recent years, due to a considerable rise in the electrical power consumption in residential level, the impact of Demand Side Management (DSM) on power system balancing has gained a special interest among researchers in the field of power system [1, 34, 58, 59]. Moreover, emergence of the smart meters in residential level has had a significant effect on the contribution of DSM in power system balancing [5, 6, 9, 11, 55-57]. Also, the advancement in communication technology and its application to power systems have introduced a new era in power system scheduling. Demand Side Management (DSM) is one of the main outcomes of this combination.

In this chapter, a droop-based hierarchical control strategy has been proposed to execute automatic Demand Dispatch (DD). When the frequency of the system falls/rises below/above rated level, Balancing Authority (BA) issues droop-based signals to the aggregators to check the feasibility and availability of DD according to the capability of aggregated loads. Then, these signals are sent to the Appliance Management Unit (AMU). According to the availability, priority, and features of the appliances, the AMU sends these commands in the form of deferral or interruptible signals to the appliances. At the time of DD events, the proposed AMU algorithm keeps the total household power consumption within the required limit to maintain the system frequency at the nominal level.

A wide variety of residential loads has been considered in the DD applications. It will be demonstrated that the proposed AMU algorithm is capable of maintaining the total demand of a house below the limit determined by the BA.

In the last section of this chapter, the necessity of renewable energy resources and battery storage system to prevent load rebound is highlighted. In the next section, the appliance models which have been used in this thesis are explained in detail.

It should be noted that the content of this chapter has been mainly extracted from [70]

3.1. APPLIANCES MODELS

Because of the increase in diversity and complexity of the residential appliances, the capability of the residential appliances to participate in DD has been risen in recent years. To evaluate capability of the residential loads to take part in DD, a typical residential load is required [60-62].

To investigate the accurate behavior of a typical residential load profile, the wide range of controllable appliance models is necessary. Moreover, the dynamic models of the controllable appliances are required to illustrate the functionality of the proposed methods.

In this study, the dynamic models for different appliance are integrated with their controllable features. Several factors such as the ambient temperature, soil temperature, room temperature, house size, and water usage pattern have been considered in the proposed models.

The residential loads have been categorized into two groups of controllable and non-controllable. In this study, Pool Pump (PP), Water Heater (WH), Air Conditioning unit (AC), Fridge (FR), Dish Washer (DW), Dryer (DRY), Clothes Washer (CW), and Electrical Vehicle (EV) are considered as controllable appliances, while Hair Dryer, Toaster, Lightings, Stoves and Ovens have been considered as non-controllable ones. Controllable appliances, in turn, have been divided into to two categories; deferrable and interruptible controllable appliances, where DW, DRY, CW, and PP have been categorized as deferrable appliances. These appliances consist of electrical motors and motors have high starting current which can cause a cold load pick up in aggregated scale after resuming their tasks. On the other hands, DRY's heating part, defrost cycle of FR, EV, WH are interruptible loads as they do not cause inrush currents and they can be switched on remotely without the need for human presence.

It should be noted that the load profile which has been yielded is a typical load pattern of an individual house consist of four people (parent and two children who go to school during weekdays). The aggregated model of the load model can be generated through stochastics models. The load profile of the house has been considered for a summer day.

3.1.1. CONTROLLABLE APPLIANCES MODELS

As mentioned before, WH, AC, FR, DRY, DW, CW, EV and PP are controllable appliances. Their models, rating and, the integration of control signals to their models are described in part *(1)-(8)*.

1) Water Heater (WH) Model

The WH model is derived for each time interval t_i, which has been chosen as half a minute[68]:

$$P_{wh,t_i} = P_{wh} \times S_{wh,t_i} \times C_{wh,t_i} \tag{3.1}$$

where, $P_{wh,ti}$ is WH power consumption in time interval t_i (W), P_{wh} is rated power consumption of WH (W), $S_{wh,ti}$ is switching status of WH in time interval t_i (0 or 1), and $C_{wh,ti}$ is DSM control signal in time interval t_i (0 or 1). Note that switching status "0" mean OFF, while "1" mean ON. The DSM control signal is issued based on the DSM algorithm.

The switching status of WH depends on the hot water temperature set points, the instantaneous temperature of the hot water [68].

$$S_{wh,ti} = \begin{cases} 0. & \text{if } T_{wh,ti} \geq T_{s,wh} \\ 1, & \text{if } T_{wh,ti} < T_{s,wh} - \Delta T_{wh} \\ S_{wh,ti-1}, & \text{if } T_{s,wh} - \Delta T_{wh} \leq T_{wh,ti} < T_{s,wh} \end{cases} \tag{3.2}$$

where, $T_{wh,ti}$ is the instantaneous temperature of the hot water in time interval t_i (^{o}C), ΔT_{wh} (^{o}C) is the lower limit deviation of hot water, and $T_{s,wh}$ is the hot water temperature set point (^{o}C). The water heater maintains the hot water temperature within ($T_{s,wh} - \Delta T_{wh}$) and $T_{s,wh}$ by switching the water heater on or off as per (3.2) [68].

The instantaneous temperature of the hot water in time interval t_i depends on different factors as shown in (3.3)[68]:

$$T_{wh,ti} = \frac{T_{wh,ti-1}(V_t - FR_{i-1}.\Delta t)}{V_t} + \frac{T_{in,ti-1}.FR_{ti-1}.\Delta t}{V_t} + \left[p_{wh,ti-1} - \frac{A_t(T_{wh,i-1} - T_a)}{R_t} \right] . \frac{\Delta t}{60} . \frac{1}{V_t} \tag{3.3}$$

where, $T_{in,ti-1}$ is the temperature of the water that flows into the tank of WH in time interval t_{i-1} (^oC), T_a is the room temperature equal to thermostat set point of AC (^oC), FR_{ti-1} is the hot water flow rate in time interval t_{i-1} (litre/m), A_t is the surface area of the water tank (m^2), V_t is volume of the water tank (litre), R_t is the heat resistance of the water tank ($^oC.m^2/w$), and Δt is duration of time interval in (min) which is chosen as half a minute in this work [68].

The hot water flow rate is obtained through equations (3.4)-(3.6) as[68]:

$$FR_{ti} = \frac{LPH}{WH - du_m} \tag{3.4}$$

$$LPH = LPD \times SCH_m \tag{3.5}$$

$$LPD = 81\,(litre/day) + 0.56 \times CFA \tag{3.6}$$

where, LPH is litre per hour of the water consumption, LPD is litre per day of the water consumption, CFA is conditioned floor area of the house (m^2), SCH_m is hot water usage hourly fraction in hour m during 24 hours (m=1, 2,…, 24), and WH_du_m is hot water usage duration in hour m during 24 hours (m=1, 2,…, 24).

The parameter used for $T_{in,ti}$, SCH_m, and WH_du_m (minute) in this paper are listed in Table 3.1. In Table 3.2, the WH parameters have been illustrated [68, 76, 77].

Table 3.1: $T_{in,ti}$, SCH_m, and WH_du_m amounts [68, 76, 77].

***m*(1-12)**	$T_{in,ti}$	***SCH***	WH_du_m	***m*(13-24)**	$T_{in,ti}$	***SCH***	WH_du_m
1	30.24	0	0	13	40.32	0	0
2	29.68	0	0	14	43.12	0	0
3	29.12	0	0	15	42	0	0
4	28.56	0	0	16	39.2	0	0
5	28.56	0	0	17	37.52	0	0
6	28.56	0	0	18	35.84	0	0
7	28	0.29	30	19	34.16	0	0
8	28	0	0	20	33.04	0	0
9	28.56	0	0	21	32.48	0	0
10	29.68	0.01	10	22	31.92	0.61	45
11	32.48	0	0	23	31.36	0.008	10
12	36.40	0	0	24	30.8	0.008	10

Table 3.2: WH Parameters [76, 77].

Parameter	**Value**
ΔT_w	3(°C)
T_{wh_s}	54(°C)
T_a	25 (°C)

P_{wh}	4500 (w)
A_t	2.5 (m^2)
V_t	190 (liter)
R_t	3.5 ($^oC.m^2/w$)
CFA	240 (m^2)

The power consumption of WH and hot water temperature have been shown in Fig. 3.1 over a period of 24 hours. As shown in this figure, the hot water temperature is maintained within the desired temperature interval of (51°-54°).

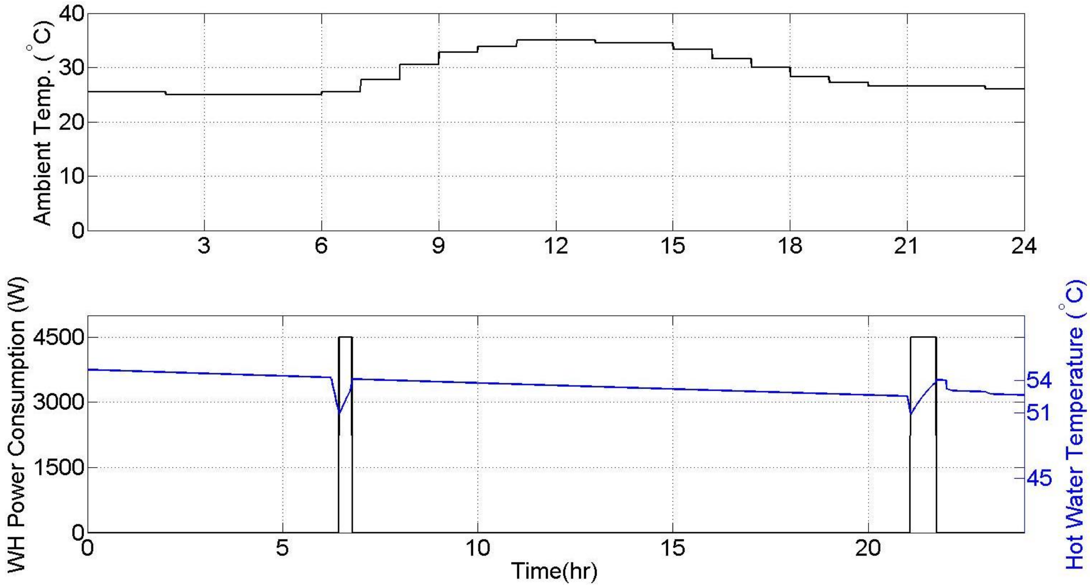

Fig. 3.1. Power consumption of WH and hot water temperature.

2) Air Conditioning Unit (AC) Model

The model of an AC unit is described in this section. The AC system is considered to be a reverse cycle type that is capable of either cooling or heating the house depending on season.

In each time interval of t_i, the power consumption of the AC system is equal to[68]:

$$P_{AC,t_i} = P_{AC} \times S_{AC,t_i} \tag{3.7}$$

where, $P_{AC,ti}$ is the instantaneous power consumption of the AC at t_i (W), P_{AC} is rated power of the AC unit (W), and $S_{AC,ti}$ is the switching status of the AC system at t_i (0 or 1).

The switching status of the AC system depends on the several factors, such as the set point temperature, room temperature, outdoor temperature, house size, and so on. Equation (3.8) and (3.9) show how switching status of AC related to the room temperature and the temperature set point in cooling and heating mode respectively [68]:

$$S_{AC,ti} = \begin{cases} 0 & \text{,if } T_{room,ti} < \left(T_{s,AC} + C_{AC,ti}\right) - \Delta T_{AC} \\ 1 & \text{,if } T_{room,ti} > \left(T_{s,AC} + C_{AC,ti}\right) + \Delta T_{AC} \\ S_{AC,ti-1} & \text{,if } \left(T_{s,AC} - \Delta T_{AC}\right) \le \left(T_{room,ti} - C_{AC,ti}\right) \le \left(T_{s,AC} + \Delta T_{AC}\right) \end{cases} \tag{3.8}$$

$$S_{AC,ti} = \begin{cases} 0 & \text{,if } T_{room,ti} > \left(T_{s,AC} + C_{AC,ti}\right) - \Delta T_{AC} \\ 1 & \text{,if } T_{room,ti} < \left(T_{s,AC} + C_{AC,ti}\right) + \Delta T_{AC} \\ S_{AC,ti-1} & \text{,if } \left(T_{s,AC} - \Delta T_{AC}\right) \le \left(T_{room,ti} - C_{AC,ti}\right) \le \left(T_{s,AC} + \Delta T_{AC}\right) \end{cases} \tag{3.9}$$

where, $T_{s,AC}$ is the set point temperature of AC (°C), $T_{room,ti}$ is the room temperature at t_i (°C), $C_{AC,ti}$ is the DSM control signal, ΔT_{AC} is allowed temperature deviation around the temperature set point ($T_{s,AC}$) (°C) [68].

The DSM control signal, $C_{AC,ti}$, is assumed to be ± 4 °C or 0°C. This means that $C_{AC,ti}$ is + 4°C for the cooling mode and – 4°C for the heating mode. It is 0°C when neither cooling nor heating is required. In the following, only the cooling mode is considered as focus here is a typical summer day in Western Australia.

The instantaneous room temperature depends on the room temperature in the previous time slot, as given by[68]:

$$T_{room,ti} = T_{room,ti-1} + \frac{\Delta t/60}{\Delta C} \cdot \left(G_{ti-1} + C_{HVAC} \cdot S_{AC,ti-1}\right) \tag{3.10}$$

where, Δt is the length of time interval in (min) which is assumed to be half a minute, ΔC is the energy require to increase/decrease the temperature by 1(°C) in (J/°C), C_{HVAC} is the capacity of the AC.in (W), $G_{ti\text{-}1}$ is heat gain rate of the house at $t_{i\text{-}1}$ (°C) in (W). ΔC is equal to[68]:

$$\Delta C = C_a \times V_H \tag{3.11}$$

where, V_H is the volume of the house in (m^3) and C_a is heat capacity of the rooms. G_{ti} can be obtained through equation (3.12)[68]:

$$\begin{aligned} G_{ti} &= \left(T_{amb,ti} - T_{room,ti}\right) \times \left(\frac{A_w}{R_w} + \frac{A_c}{R_c} + \frac{A_{wd}}{R_{wd}} + 220 \times V_H\right) \\ &\quad + \left(SHGC \times A_{wd\_sth} \times H_{so}\right) + H_p \end{aligned} \tag{3.12}$$

where, $T_{amb,ti}$ is the outdoor ambient temperature (°C), A_w, A_c, A_{wd} are the area of the wall, ceiling, and windows of the house in (m^2) respectively, R_w, R_c, and R_{wd} are the heat resistance wall, ceiling and the window of the house in (°C.m^2/W), *SHGH* is the solar gain of the windows, H_{so} is the solar radiation in (W/m^2), A_{wd_sth} is the area of windows toward south in (m^2)and H_p is people's heat gain in (W). *SHGH* and is yielded via equation (3.13) [68]:

$$SHGH = SC \times 0.87 \tag{3.13}$$

where, *SC* is shading coefficient.

Table 3.3 shows the specification of parameters used in this study[68]. Fig. 3.2 shows the solar radiation and the outdoor ambient temperature.

Table 3.3: AC Parameters [68].

Parameter	**Value**	**Parameter**	**Value**
$T_{s,AC}$	21	A_{wd}	20
ΔT_{AC}	1	R_w	2.5
$C_{AC,ti}$	0 or 4	R_c,	9
C_{HVAC}	-4700	R_{wd}	0.17
V_H	720	SC	0.3448
C_a	0.3633	A_{wd_sth}	0.65
A_w	200	H_p	102
A_c	240	P_{ac}	1500

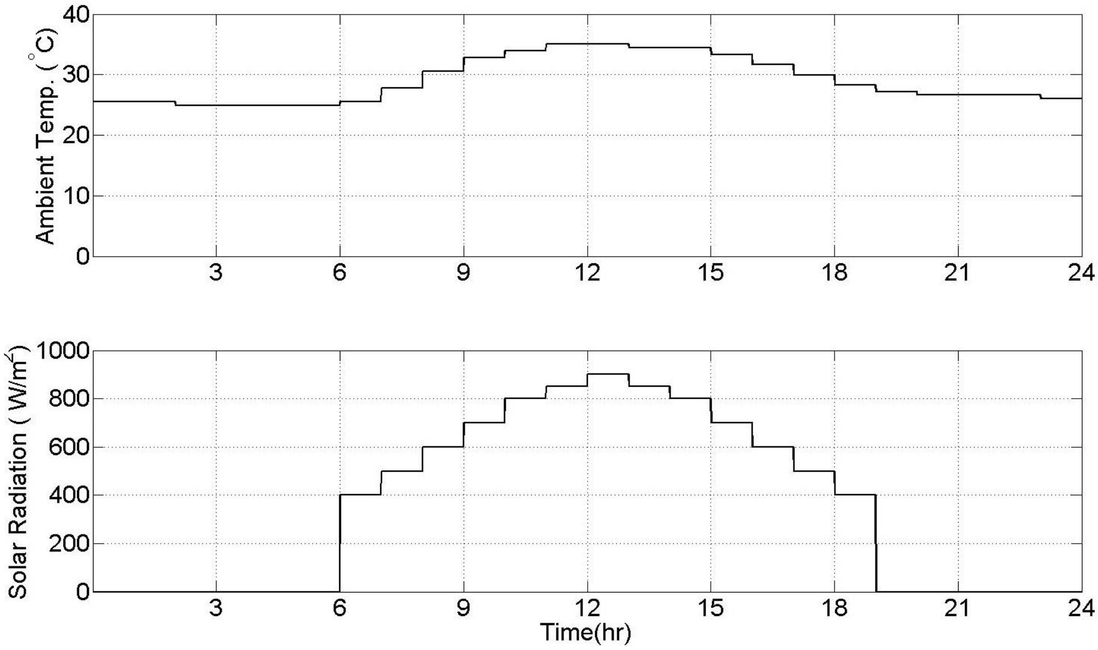

Fig. 3.2. The solar radiation and the outdoor ambient temperature.

The power consumption and the room temperature have been shown in Fig. 3.3. The AC system keeps the room temperature within the acceptable range.

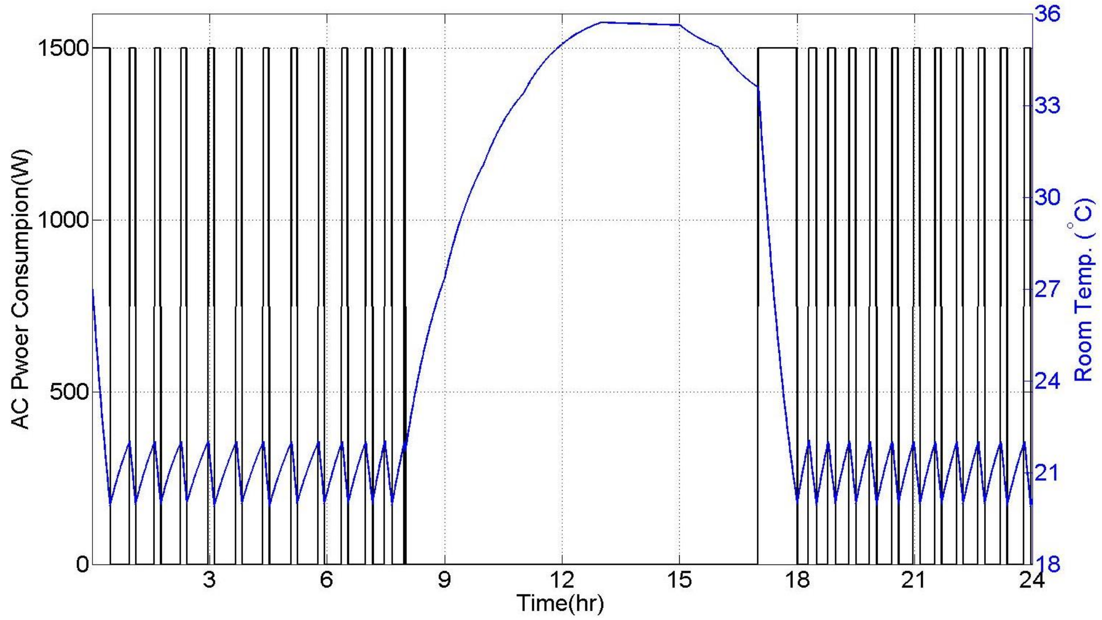

Fig. 3.3. The power consumption and the room temperature.

3) Fridge (FR) Model

In this section, the electrical model of a FR is described, in which the model has been divided into two parts: compressor and defrost cycle. As the compressor part is a motor load, just defrost cycle participates in DSM.

The instantaneous power consumption of a FR is obtained through equation (3.14):

$$P_{FR,ti} = P_{FR,def} \times C_{FR,ti} \times S_{FR,def,ti} + P_{FR,comp} \times S_{FR,comp,ti} \tag{3.14}$$

where, $P_{FR,ti}$ is the instantaneous power consumption of the FR in time interval of t_i in (W), $C_{FR,ti}$ is the DSM control signal for the FR (0 or 1), $P_{FR,def}$ is the rated power of defrost cycle of the FR in (W), $P_{FR,comp}$ is the rated power of the compressor part in (W), $S_{FR,def,ti}$ is the switching status of the FR's defrost cycle (0 or 1). $S_{FR,comp,ti}$ is the switching status of the FR's compressor (0 or 1).

It should be noted that the DSM control signal of the FR is zero in the time of DSM and is one in operating normal conditions. The switching status of the FR compressor depends on the FR temperature and its set points. Equation (3.15) illustrates this relationship:

$$S_{FR,comp,ti} = \begin{cases} 0 & ,\text{if } T_{FR,ti} < \left(T_{s,FR} - \Delta T_{FR}\right) \\ 1 & ,\text{if } T_{FR,ti} > \left(T_{s,FR} + \Delta T_{FR}\right) \\ S_{FR,comp,ti-1} & ,\text{if } \left(T_{s,FR} - \Delta T_{FR}\right) \le T_{FR,ti} \le \left(T_{s,FR} + \Delta T_{FR}\right) \end{cases} \tag{3.15}$$

where, $T_{s,FR}$ is the set point temperature of FR (^{o}C), $T_{FR,ti}$ is the instantaneous temperature inside FR at t_i in (^{o}C), and ΔT_{FR} is allowed temperature deviation around the temperature set point ($T_{s,FR}$) (^{o}C).

The instantaneous FR temperature depends on the FR temperature in the previous time slot as shown in Equation (3.16) [25, 78, 79]:

$$\begin{aligned} T_{FR,ti} &= e^{\left(\frac{-\Delta t.A}{60m}\right)} \times \left(T_{FR,ti-1} - T_{room,ti-1}\right) + T_{room,ti-1} \\ &\quad - \eta \cdot \frac{P_{FR,comp}}{A} \times \left(1 - e^{\left(\frac{-\Delta t.A}{60m}\right)}\right) \times S_{FR,comp,ti-1} \end{aligned} \tag{3.16}$$

where $T_{room,ti\text{-}1}$ is the room temperature (ambient temperature of the FR) at $t_{i\text{-}1}$ in (°C) which is the output temperature of the AC, Δt is the length of time interval in (min), A is thermal conductivity in (kW/°C), m is thermal mass in (kWh/°C), $T_{FR,ti\text{-}1}$ is the temperature inside the FR at $t_{i\text{-}1}$ in (°C), η is cooling efficiency, $P_{FR,comp}$ is the rated power of the compressor part of the FR in (w), and $S_{FR,comp,ti\text{-}1}$ is switching status of the compressor at $t_{i\text{-}1}$ [25, 78, 79].

Table 3.4 shows the FR parameters which have been used in this chapter. Fig.3.4 shows the power consumption of the FR's compressor, the FR's defrost cycle and the overall power consumption of the FR [25, 78, 79].

Table 3.4: FR Parameters.

Parameter	**Value**
$P_{FR,def}$	400
$P_{FR,comp}$	150
$T_{s,FR}$	4
ΔT_{FR}	2
A	3.21

m	15
η	4

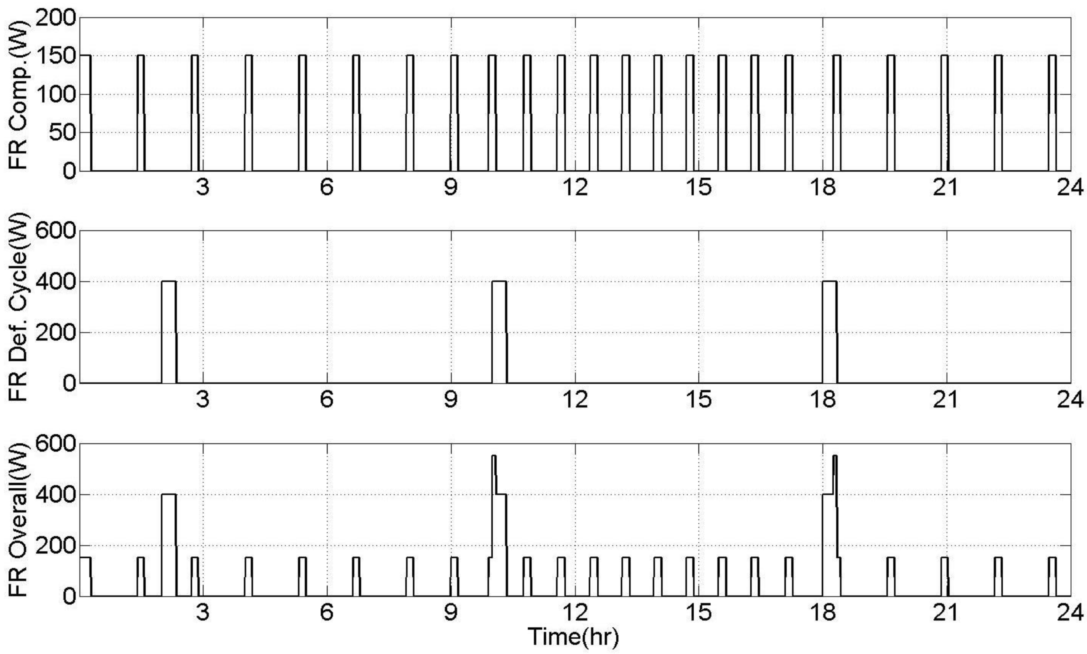

Fig. 3.4. The power consumption of FR.

4) Dryer (DRY) Model

The electrical model of a DRY is explained in this section. The DRY model has been divided into two parts: Heating Part (HP) and Rotating Part (RP). As mentioned before, because the rotating part consists of an electrical motor and it is not desirable that this component should participate in DD. So, in this study, just the heating part is considered as a controllable load.

The instantaneous power consumption of a DRY is given by equation (3.17) [68]:

$$P_{DRY,ti} = P_{DRY,HP} \times C_{DRY,\text{int},ti} \times S_{DRY,ti} + P_{DRY,RP} \times S_{DRY,ti} \tag{3-17}$$

where $P_{DRY,ti}$ is the instantaneous power consumption of DRY in (w), $C_{DRY,int,ti}$ is the DSM control signal to interrupt the operation of heating part of DRY while the rotating part may still operate , $P_{DRY,RP}$ is the rated power of the rotating part in (W), $P_{DRY,HP}$ is the rated power of the heating part in (w), $S_{DRY,ti}$ is the switching status of the DRY (0 or 1). $S_{DRY,ti}$ is considered as 1 when the householder switched the DRY on and 0 when it is switched off provided that the deferrable control signal is 0 [68].

In this study, DRY considered to be both deferrable and interruptible appliances. There are three scenarios which can happen regarding the controllability of DRY:

A- This DRY is used after CW. If during DD schedule CW, which has been considered as deferrable appliance, is postponed then DRY's operation must be delayed depending on the starting time and the satisfying finishing time of the DRY. So, in this case the DRY has been considered as a deferrable load.

B- The DRY is switched on and in the middle of the operation the DD schedule is issued. So, at this time DRY acts as an interruptible appliance and the heating part will be switched off.

C- The CW finished its task. Then, the DD signal has been issued before the DRY starts its operation. In this case, DRY is considered to be deferrable appliance.

Thus, the DSM control signal of DRY, $C_{DRY,int,ti}$ is set to one in normal operation and zero in time of interruption. In case of deferring, there is another DD control signal, $C_{DRY,def,ti}$ which affects switching status of the DRY. In scenarios a and c, this signal will be activated. This signal affects the starting time of the DRY. The instantaneous and rated power consumption of the DRY has been shown in Fig.3.5 and Table 3.5 respectively.

5) *Dish Washer (DW) Model*

In this study, DW considered to be a deferrable appliance. In time of DD signal, the DW starting time will be postponed according to the customer's desired finishing time. The DW's average power consumption has been considered for different modes of operations.

The model is given by:

$$P_{DW,ti} = P_{DW} \times S_{DW,ti} \tag{3.18}$$

where $P_{DW,ti}$ is the instantaneous power consumption of DW in (W), P_{DW} is the rated power of DW in (W), $S_{DW,ti}$ is the switching status of DW. The instantaneous and rated power consumption of the DW has been shown in Fig. 3.5 and Table 3.5 respectively.

6) *Clothes Washer (CW) Model*

Similar to DW, clothed washer has been categorized as deferrable appliance. In time of DD schedule, the starting time of the appliance will be postponed according to the household's priorities and satisfaction. The CW's average power consumption has been considered for different modes of operations as follow:

$$P_{CW,ti} = P_{CW} \times S_{CW,ti} \tag{3.19}$$

where $P_{CW,ti}$ is the instantaneous power consumption of CW in (W), P_{CW} is the rated power of CW in (W), $S_{CW,ti}$ is the switching status of CW.

The instantaneous and rated power consumption of the CW has been shown in Fig.3.5 and Table 3.5 respectively.

Table 3.5: DRY, DW, and CW Parameters.

Parameter	**Value**
P_{DRY}	3800 (W)
P_{DW}	1500 (W)
P_{CW}	600 (W)

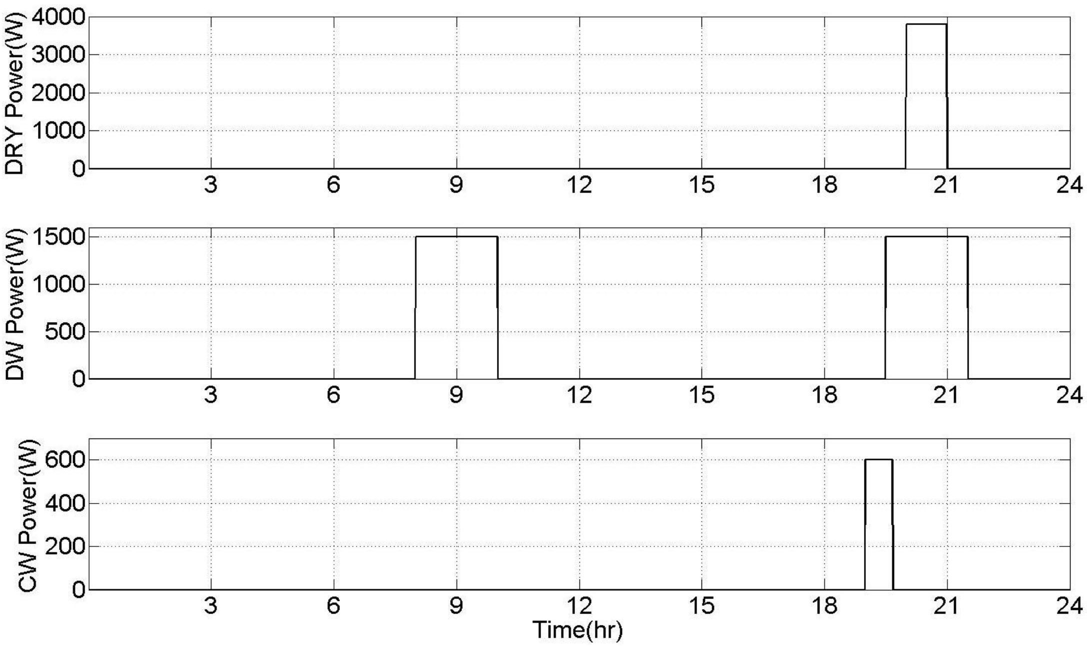

Fig. 3.5. The power consumption of DRY, DW, and CW.

7) Electric Vehicle (EV) Model

In this study, EV considered to be an interruptible appliance. It acts as just an electrical load. The model given by equation (3.20), provided that the EV is plugged in [68].

$$P_{EV,ti} = P_{EV} \times S_{EV,ti} \tag{3.20}$$

where $P_{EV,ti}$ is the instantaneous power consumption of EV in (W), P_{EV} is the rated power of EV in (W), $S_{EV,ti}$ is the switching status of the EV, considering the EV is plugged in. The switching status of the EV depends on the SoC of the EV's battery and $C_{EV,ti}$ which is the DD signal as given in equation (3.21)[68]

$$S_{EV,ti} = \begin{cases} 0 & ,\text{if } \left(SoC_{EV,ti} \geq 1 \quad \& \quad C_{EV,ti} \neq 1\right) \quad OR \quad C_{EV,ti} = 1 \\ 1 & ,\text{if } SoC_{EV,ti} < 1 \quad \& \quad C_{EV,ti} \neq 1 \end{cases} \tag{3.21}$$

where $SoC_{EV,ti}$ is the SoC of the EV in time interval t_i. The SoC of the EV is as follow[68]:

$$SoC_{EV,ti} = \begin{cases} SoC_{EV,ti-1} + P_{EV} \times \dfrac{\Delta t}{60 \times Cap_{EV}} & ,\text{if } C_{EV,ti} \neq 1 \\ SoC_{EV,ti-1} & ,\text{if } C_{EV,ti} = 1 \end{cases} \tag{3.22}$$

where Cap_{EV} is the rated capacity of the EV's battery in (Wh). SoC_{arr} which is the SoC of the EV's battery in time of arrival at home can be yielded as[68]:

$$SoC_{arr} = 1 - \frac{E_{dri}}{Cap_{EV}} \tag{3.23}$$

where Cap_{EV} which is the rated capacity of the EV's battery in (Wh), E_{dri} is the used total driving energy in (Wh).

The instantaneous power consumption of the EV and the SoC of the EV's battery when there is not any interruption have been shown in Fig. 3.6. Also, the EV's parameters are listed in Table 3.6 [68].

Table 3.6: EV's Parameters.

Parameter	**Value**
P_{EV}	3300 (W)
Cap_{EV}	16000 (Wh)
E_{dri}	8000 (Wh)

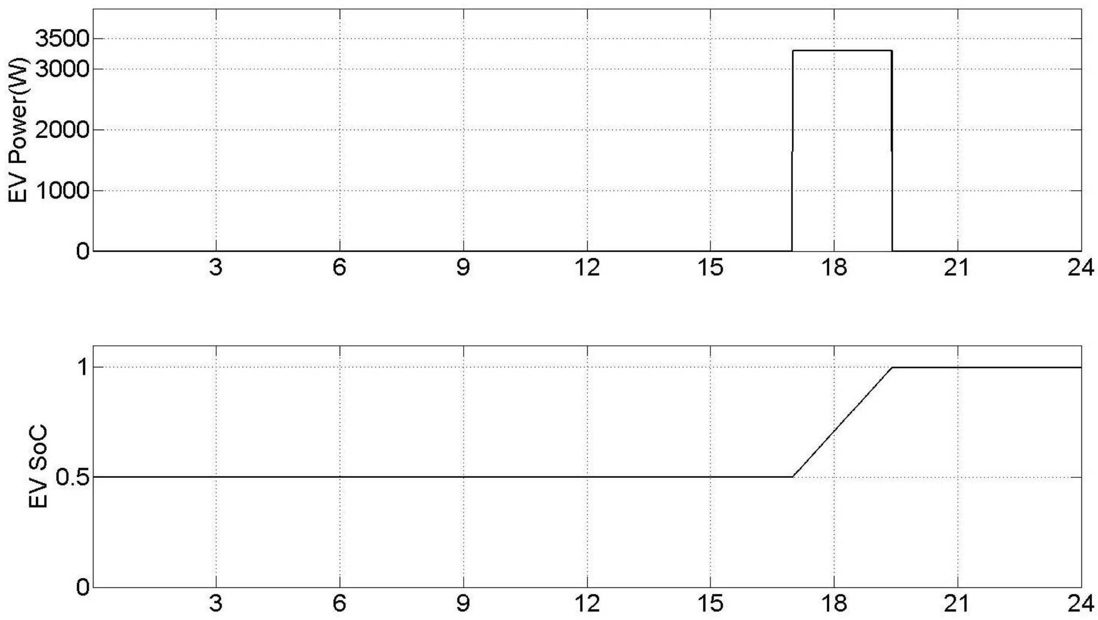

Fig. 3.6. SoC of EV's battery and the power consumption of the EV.

8) Pool Pump (PP) Model

Pool pump's operation can be postponed, provided that the PP has worked for a specific duration in 24 hours. The average power consumption of PP is

$$P_{PP,ti} = P_{PP} \times S_{PP,ti} \tag{3.24}$$

where $P_{PP,ti}$ is the instantaneous power consumption of PP in (W), P_{PP} is the rated power of PP in (W), $S_{PP,ti}$ is the switching status of the PP. The household prefer to split the operation of the PP into two different time periods; once in the morning and the other time in the afternoon. The rated power consumption of the PP is 1500 (W). The instantaneous power consumption of the PP has been shown in Fig.3.7.

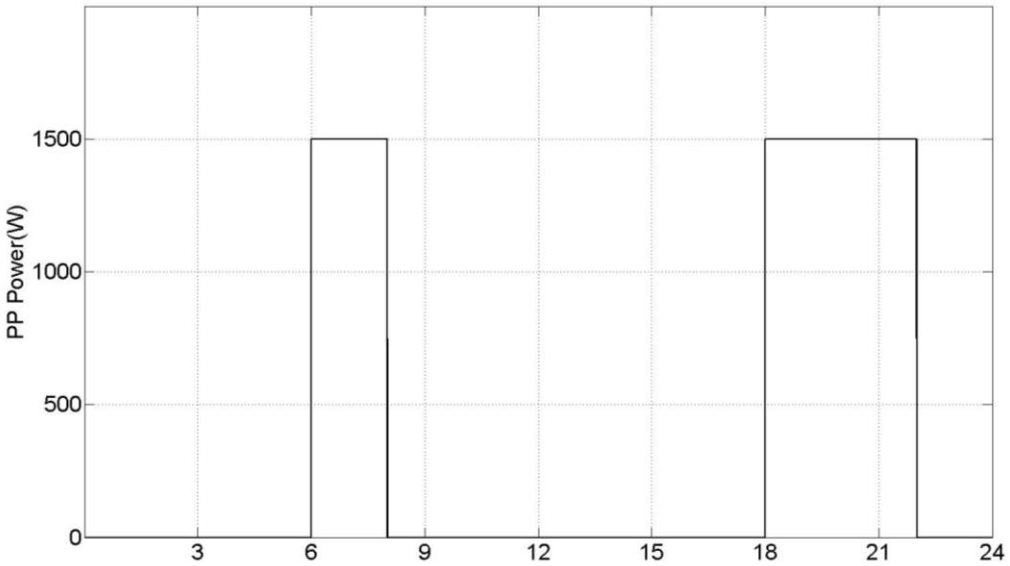

Fig. 3.7. The power consumption of the PP.

3.1.2. NON-CONTROLLABLE APPLIANCES SPECIFICATIONS

Non-controllable appliances are not capable of participating in DSM. Table 3.7 lists the non-controllable appliances and their ratings. The overall power consumption of non-controllable appliances has been shown in Fig. 3.8.

Table 3.7: Non-controllable Appliances Specifications.

Non-controllable Appliance	**Rated power (W)**	**Start time (hr)**	**Duration (min)**
KT (Kettle)	1500	7.5	10
		18.4	10
HD (Hair dryer)	1500	7	15
		22	15
LI (Lighting)	Vary (50-300)	Vary	Vary
OV (Oven)	2000	18.5	90
MW (Microwave)	1100	7	5
		18.5	10
CM (Coffee Machine)	1000	7.4	10
TO (Toaster)	1000	7.5	5
		18	20
TV (Television)	250	7.5	30
		20	120
MS (Miscellaneous Appliances such as iron, computers, chargers…)	Vary (1500-3000)	Vary	Vary

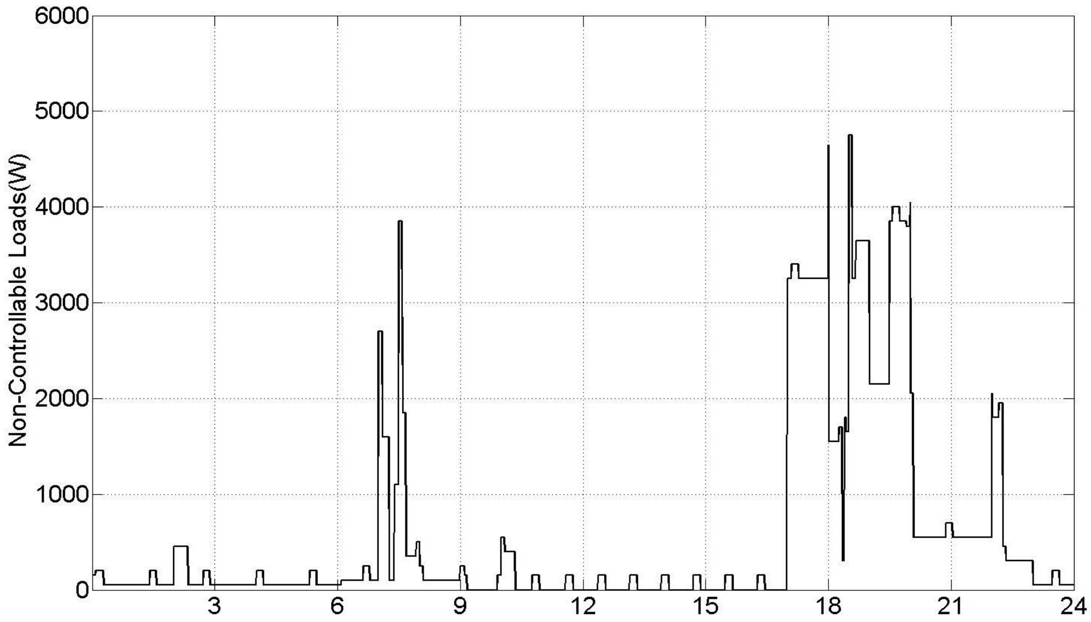

Fig. 3.8. The overall power consumption of non-controllable appliances.

3.2. PROPOSED CONTROL STRATEGY

In this study, it is assumed balancing authority (BA) issues external signals to the aggregators and then to the AMU system based on droop characteristic. When frequency of the system drops (rises) below (above) the synchronous level, BA issues load reduction (increase) commands to the aggregators. Afterwards, aggregators investigate the feasibility of implementation of these commands and will send them to AMUs to bring the frequency back to the rated value. Then, the AMU applies these commands, which are in the forms of deferral or interruption requests (during frequency drop), to appliances until the next frequency command from BA. These commands are released according to the time of the day, the priority of the consumers, and the features of appliances (for example, the max/min limitation for power draw/consumption). During DD events, the proposed AMU algorithm keeps the total household power consumption below the required limit to maintain the system's frequency within specific limit.

It has been assumed that the power consumption of an entire house and appliances are measured and monitored every 30 sec. Therefore, DD can be implemented at appliance level with the help of the AMU, which is installed in each house. DD is capable of controlling the individual loads on command. The hierarchical DD control structure is shown in Fig. 3.9.

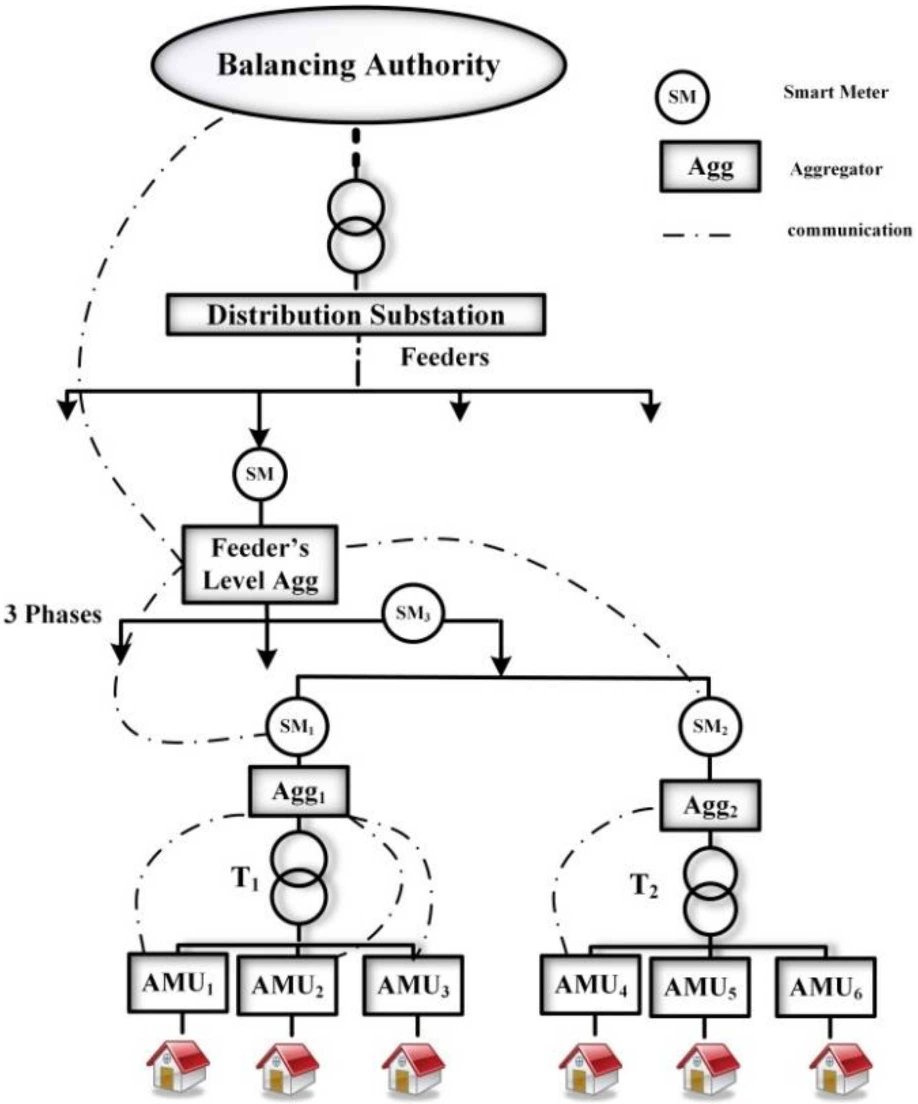

Fig. 3.9. Hierarchical control for decentralised droop-based demand dispatch.

It should be noted that the smart house is equipped with communication interface and different sensors and measurement devices, which enable the AMU system to gather data about room temperature, water temperature, power consumption, status of appliances, load priority, costumer's preference, State of Charge (SoC) of EV batteries etc.

An AMU system has a significant role in performing an automated DD within residential properties and ideally should have the least intrusive effects on consumers. In this study, BA issues external signals to the AMU system via the aggregators. When the frequency of the system drops below the synchronous level, BA issues load reduction commands to the aggregators to check the feasibility and availability of implementation of DD. Then, these commands will be sent to the AMU to bring the frequency back to the rated value. On the other hand, when frequency rises above the synchronous level, a load increase command will be issued. This load-based droop characteristic, which has been shown in Fig. 3.10, can improve the balancing process. The frequency droop employed in this study is given by [34]

$$\omega = \omega_s + m \times (P^* - P) = \omega_s + m \times \Delta P \tag{3.25}$$

where ω and ω_s are the instantaneous and rated frequency respectively and m is the droop coefficient; P and P^* are the instantaneous and rated power, respectively. Implementation of frequency droop on load side is shown in Fig. 3.11. To obtain ΔP, the frequency difference, $\Delta\omega$, has passed through a PI controller. Thereafter, these commands will be applied to appliances through the AMU until the issuance of next command from BA to halt or change load decrease or increase.

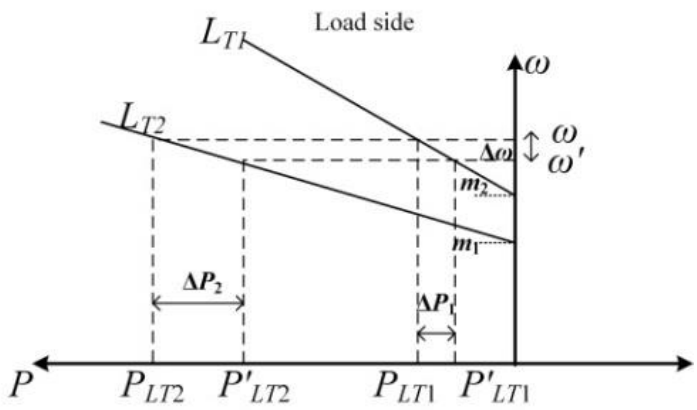

Fig. 3.10. Frequency droop for the loads of two distribution transformers.

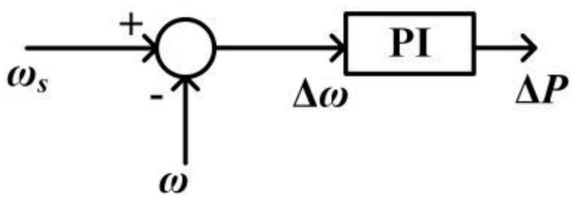

Fig. 3.11. Implementation of frequency droop on load side.

Considering the system in Fig. 3.9, if a frequency deviation happens in this system, the BA calculates the amount and the duration of required regulation through demand-side droop control and sends the information to feeder level aggregator. So, if the frequency signal needs any modification, it will be done by the feeder level aggregator and will be issued back to the BA, and accordingly, to the AMU systems.

In order to encourage householders to participate in DD, utility considers some benefits for householders such as low tariff rates for the time they participate in load reducing/increasing schemes. Then, BA dispatches the required power curtailment/increase according to the factors such as Volt/Var control, line losses considerations, and max/min power consumption limits for each householder.

Fig. 3.12. The AMU system for a typical house.

Accordingly, the signals issued from the AMU to appliances are in a form of a deferral or interruption requests when the frequency of the system drops or it can be a request to switch the loads on in time of frequency rise. The AMU releases these commands according to the time of the day, the priority of the consumers, and the features of appliances. A typical AMU application is shown in Fig. 3.12. Table 3.7 lists the appliances' types and specifications. As mentioned before, to prevent customers' preference violation, loads priority and customers' preferred conditions are described in Table 3.8. This information can be received from consumers in time of signing the DD contract.

To investigate the possibility of performing demand dispatch at appliance level, we focus on a proper algorithm for the AMU to reduce the household power consumption according to external signals, which are issued from BA. The proposed

AMU algorithm is illustrated in the form of a flowchart shown in Fig.3.13. This algorithm is focused on load reduction during the peak times.

Table 3.8: Appliances Specifications.

Appliance		**Type of the Appliance:** A) Non-controllable B) Controllable a) deferrable b) interruptible	**Rated power (W)**
DRY (Dryer)	Rotating Tumble (RT)	non-controllable	300
	Heating Coil (HC)	controllable/interruptible & deferrable	3500
FR (Fridge)	Defrost Cycle	controllable/ deferrable	400
	Fridge Compressor	non-controllable	150
WH (Water Heater)		controllable/interruptible	4500
AC (Air Conditioner)		controllable/interruptible	1500
EV (Electrical Vehicle)		controllable/interruptible & deferrable	3300
PP (Pool Pump)		controllable/ deferrable	1500
CW(Clothes Washer)		controllable/ deferrable	600
DW(Dishwashers)		controllable/ deferrable	1500
KT (Kettle)		non-controllable	1500
HD (Hair dryer)		non-controllable	1500

LI (Lighting)	non-controllable	Vary (50-300)
OV (Oven)	non-controllable	2000
MW (Microwave)	non-controllable	1100
CM (Coffee Machine)	non-controllable	1000
TO (Toaster)	non-controllable	1000
TV	non-controllable	250
MS (Miscellaneous Appliances such as iron, computers, chargers…)	non-controllable	Vary (1500-3000)

Table 3.9: Customer's Satisfaction and Priority.

Appliance	Priority	Preference
DRY	4	Finish the tasks before 23:00. Max 30 min off time in time of interruption.
FR	7	Defrost cycle can be delayed for up to several hours. In this chapter, delay time is 3 hrs.
WH	1	Water temperature must be within 51-54˚C.
AC	2	Room temperature must be within 20-22˚C. During DD, 4˚C increase is acceptable. Also, Max 5 times being interrupted.

EV	5	SoC_{min}= %50, SoC_{max}= %100 Fully charged by 8am. Max 3 times being switched off during interruption.
PP	6	Run at least 6 hours in 24 hours.
CW	3	Must finish the task before starting time of DRY. Finish the task before 23:00.
DW	3	Finish the task before 23:00.

According to this algorithm, once the frequency signal has been received by the AMU, it acquires information such as

- Appliances power consumption (Papp,j)
- Total load power consumption of home (PTL)
- Status of appliances (Sapp,j)
- Room temperature (Tr)
- Hot water temperature (THW)
- Demand limit power (PDL)
- Demand limit duration (tDL)
- Priority and satisfaction of consumers.

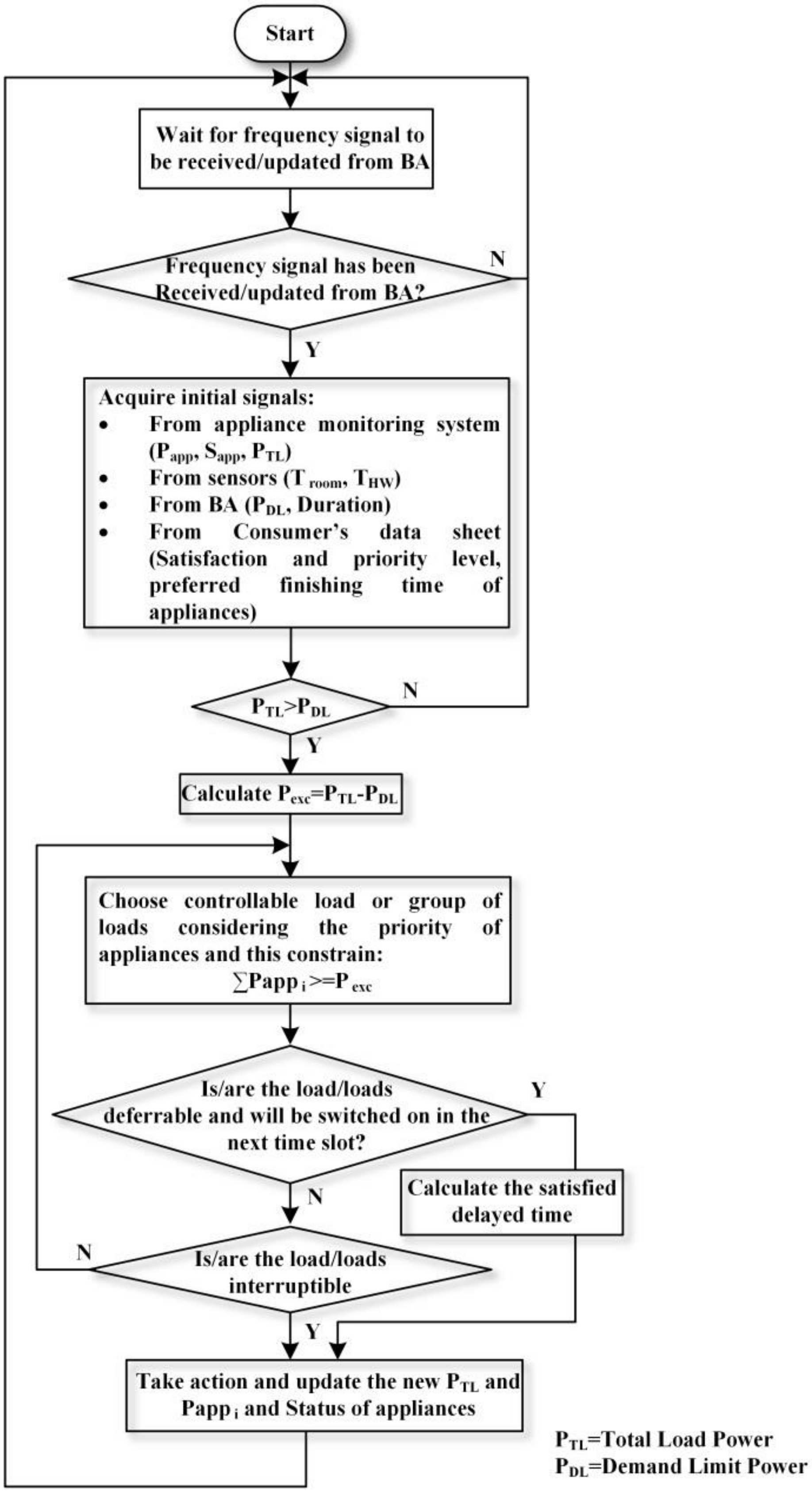

Fig. 3.13. The Proposed AMU load reduction algorithm.

If the total load power consumption of the house is bigger than demand limit power, then the excess power (P_{exc}) will be calculated according to

$$If\ P_{TL} \leq P_{DL} \quad then \quad P_{exc} = P_{TL} - P_{DL} \tag{3.26}$$

Afterwards, a load or a group of loads will be selected according to the priority and consumer satisfaction levels, which have been mentioned in Table 3.8, as well as the following constraints:

- *Controllable Appliances:*

$$\sum_{j=1}^{n} P_{app,j} \geq P_{exc} \tag{3.27}$$

where j is the number of selected controllable loads which are required to be delayed or interrupted and n is the number of controllable appliances. It should be noted that the maximum value for n is 8.

- *Clothes Dryer (DRY):*

$$t_{delay,dr} < 23:00 - t_{cycle,dr} - t_i$$

(3.28)

where $t_{delay,dry}$, $t_{cycle,dry}$, and t_i are DRY delay time duration (hr), DRY cycle time (hr), and current time slot i (hr) respectively. Here, $t_{cycle,dry}$ is chosen as 1 hour.

- *EV:*

$$SoC_{\min} \leq SoC \leq SoC_{\max} \tag{3.29}$$

where SoC_{min} and SoC_{max} are minimum and maximum SoC of EV's battery.

$$t_{off,ev} \leq 30\,\text{min} \tag{3.30}$$

where $t_{off,ev}$ is off time duration of EV (min).

$$N_{S\_sofar,ev} \leq 3 \tag{3.31}$$

where $N_{s\_sofar,ev}$ is the number of signals which EV has received to be switched off so far.

- *Pool Pump (PP):*

$$t_{on\_sofar,pp} \geq 6:00 \tag{3.32}$$

where $t_{on\_sofar,pp}$ is the time which PP has been switched on until the current time (hr).

$$t_{delay,pp} \leq 24:00-(6:00-t_{on\_sofar,pp}) \tag{3.33}$$

where $t_{delay,pp}$ is PP delay time duration (hr).

- *Clothes Washer (CW):*

$$t_{delay,cw}+t_{cycle,cw}<t_{start,dry} \tag{3.34}$$

where $t_{delay,cw}$ and $t_{cycle,cw}$ are CW delay time duration (hr) and CW cycle time (hr) respectively. In this chapter, $t_{cycle,cw}$ is 40 min. $t_{start,dry}$ is starting time of DRY.

$$t_{delay,cw}<23:00-t_{cycle,cw}-t_i \tag{3.35}$$

where $t_{delay,dw}$ and $t_{cycle,dw}$ are delay time duration (hr) and cycle time (hr) of DW respectively.

- *Dish Washer (DW):*

$$t_{delay,dw} < 23:00 - t_{cycle,dw} - t_i \qquad (3.36)$$

where $t_{cycle,dw}$ is 2:00 hr.

- *Water Heater (WH):*

$$Sat_{hw,i} = \begin{cases} 1 & \text{if } T_{hw,i} \geq T_{s,hw} \\ 0 & \text{if } T_{hw,i} < T_{s,hw} - \Delta T_{hw} \\ \dfrac{T_{hw,i} - (T_{s,hw} - \Delta T_{hw})}{\Delta T_{hw}} & \text{if } T_{s,hw} - \Delta T_{hw} \leq T_{hw,i} < T_{s,hw} \end{cases} \qquad (3.37)$$

where, $Sat_{hw,i}$ is weighting of WH's satisfaction in time slot i, $T_{hw,i}$, is the hot water temperature in time slot i, $T_{s,wh}$ is WH's temperature set point which is equal to 51˚C and ΔT_{hw} is the maximum acceptable temperature deviation during DD event which is 2˚ C.

These constraints have been considered according to the consumers' satisfactions explained in Table 3.8. If the selected controllable load is deferrable and will be switched on in the next time slot, then the starting time of the deferrable appliance will be postponed according to the consumer's satisfaction. On the other hand, if the selected load is interruptible then it will be switched off. Then, the initial information will be updated. This procedure will be continued until the new frequency signal is issued from BA.

3.3. CASE STUDIES

To study the effect of the proposed AMU control strategy for demand dispatch, a typical house including four family members has been considered. The family consists of a couple who have fulltime jobs and two school kids. A typical summer weekday has been considered. The family members leave the home at 8:00 hr and arrive back at 17:00 hr. Two different home types are considered:

- Home with no control, which does not have any control on appliances of the home.
- Semi-smart home, which has control on appliances but it does not have any renewable energy resources.

3.3.1. HOME WITH NO CONTROL

In this case, no control over appliances is possible. Fig. 3.14 shows total load of the house without any load control and the power consumptions of the controllable appliances mentioned in the previous section on a summer weekday. As shown in this figure, the PP must remain switched on for at least 6 hours during 24 hours and it is preferred to be switched on for more than two times instead of working 6 hours continuously. The DW is used twice a day – once in the morning and another in the evening. The CW and DRY have been switched on at 19:00 and 20:00 respectively. As shown in Fig. 3.15, EV plugs in as soon as the householders arrive home. AC is on as long as they are at home and as it has been shown in Fig. 3.15 room temperature has been kept within 20-22˚C. However, the AC remains switched off when no one is at home. This will obviously increase the room temperature during those hours. There are two large hot water draws which force the WH to be switched on, once in the morning and the other one in the evening between 21:00-22:00 hrs, and as it has been shown in Fig. 3.15, the hot water temperature has been kept between 51-54˚C. The desire hot water temperature is set to be between 51-54˚C. However, in time of hot water draw, the water temperature is naturally slightly violated.

As shown in Fig. 3.14, there are two peaks in the total load, one in the morning and one in the evening. The evening peak starts around 17:00 hr and ends around 21:00 hr. Aggregation of a large number of residential loads with similar or close consumption patterns can cause tensions on the grid, and these tensions show up as frequency deviations. This chapter focuses on frequency dip. Thus, the goal is to alleviate these peaks, especially the one in the evening. To this end, a semi-smart home has been considered.

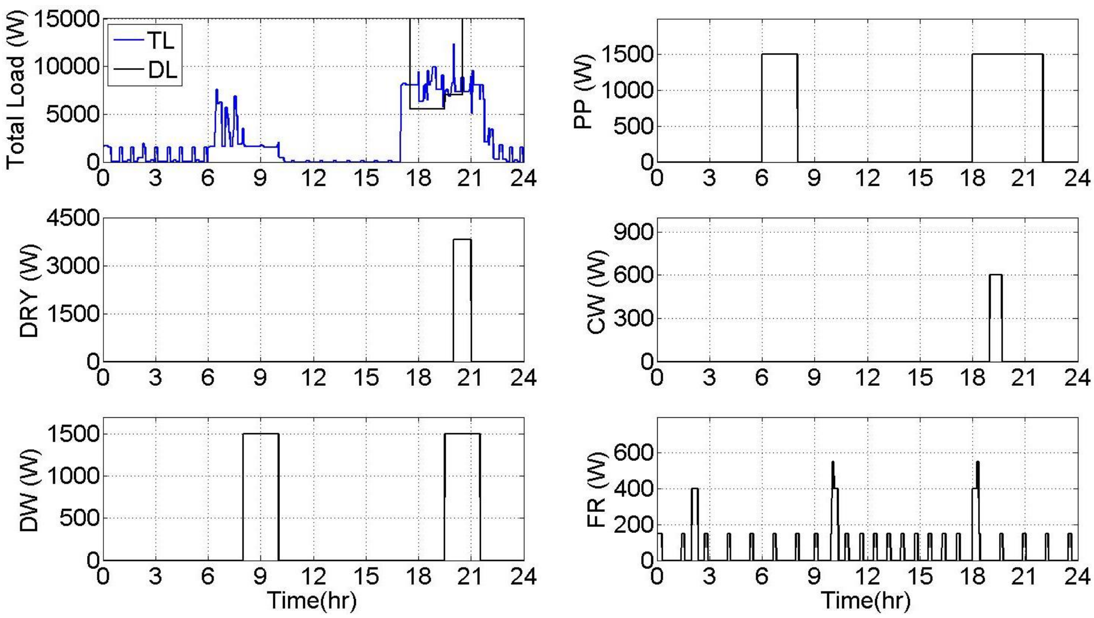

Fig. 3.14. Home with no control consumption pattern.

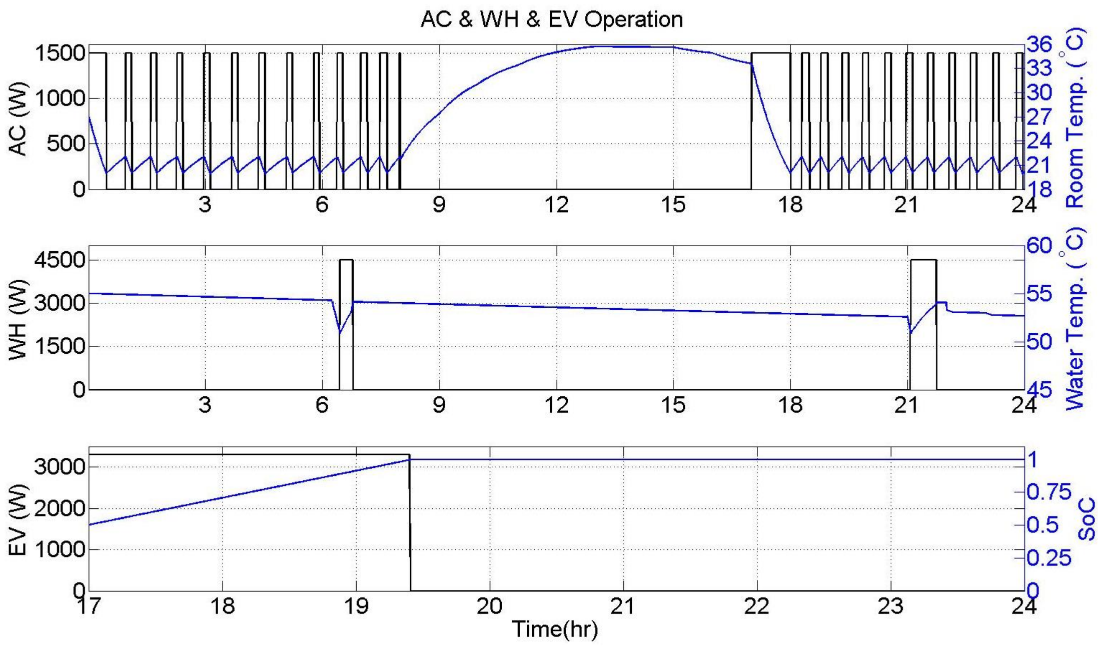

Fig. 3.15. AC, WH, and EV operation in home with no control.

3.3.2. SEMI-SMART HOME

In a semi-smart home, all the controllable appliances are under the control of the AMU. In this part, renewable energy resources and storages such as PV and battery have not been considered and the EV just acts as a load on the system.

Assume at 17:30 hr, the frequency drops due to the peak in the afternoon and demand shedding is required to bring the frequency back to its rated value. Hence, a frequency control signal is issued from BA to the AMU to reduce the overall home load. According to the droop-based DD, the demand limit which has been issued is 5500 W. At this time EV and AC are the only controllable appliances which are switched on but the EV has less priority and according to constraints (3.27), its rated power consumption is more than the amount of P_{exc}. So, the EV will be selected to be turned off and the total load falls down below required demand limit shown in Figs.

3.16 and 3.17. This process will continue until the EV's off-time reaches its maximum which is 30 minutes according to (3.30). Thus, the EV will be forced to be switched on at 18:00. So, the PP and FR's defrost cycle must be delayed for 1.5 hours and 3 hours respectively to meet the constraints mentioned in (3.27), (3.30), and (3.33). This is shown in Fig. 3.16. At around 18:20 hr, the AC is required to increase its temperature set point by 4˚C for 20 min which is the maximum acceptable time for the consumers. As shown in Fig. 3.17, the temperature of the home has increased during this time. Furthermore, the WH does not receive any signal as has the top priority. Again at 18:30 hr, the EV charging process is halted. At 19:00, the CW starting time has been postponed for 1.5 hr and accordingly the DRY's starting time must be delayed by 1.5 hr to meet constraints (3.28), (3.34), and (3.35). Afterwards, the AC's set point has increased at around 19:20 hr for 20 min. Then, at 19:30 hr, the tension on grid reduces. Therefore, demand limit has increased to 7000 W. However the load is still higher than this level and hence, EV's charging has been stopped for 30 min. Finally, at 20:30 hr, demand limit has been removed.

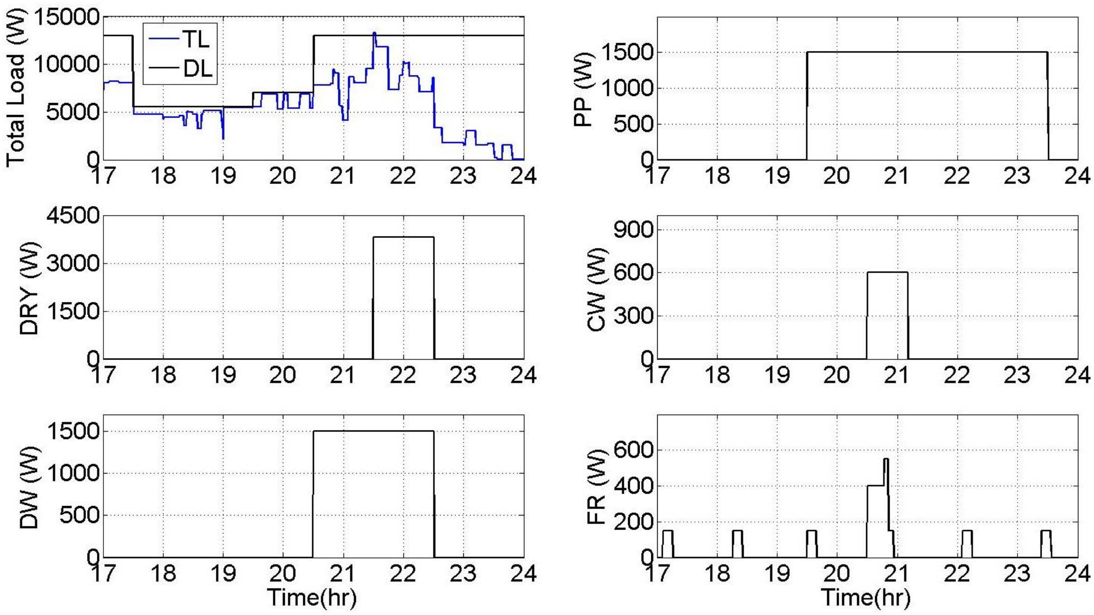

Fig. 3.16. Semi smart home consumption pattern.

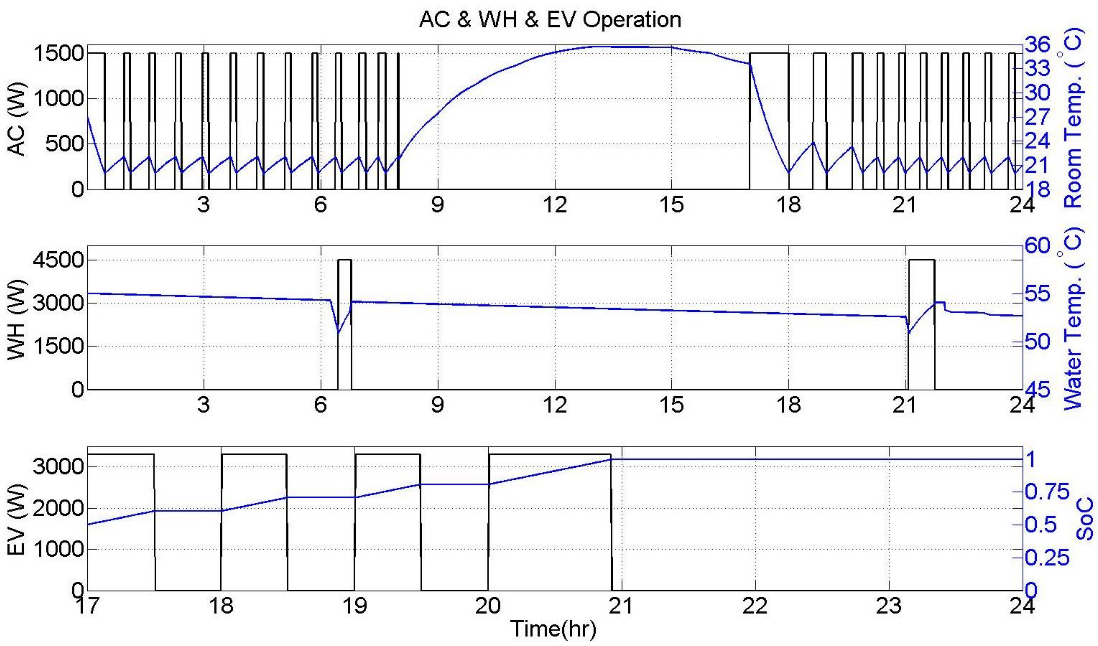

Fig. 3.17. AC, WH, and EV operation in semi smart home.

A. Load Rebound Possibility in Semi-Smart Home

As illustrated in Figs. 3.16 and 3.17, the proposed control algorithm works effectively and brings the total consumption level of the home below the demand limit. However, there is a possibility of load rebound between 21:00 and 22:00 hrs because some deferrable appliances such as the DRY, DW, and PP have been postponed to a later time. Therefore, another frequency signal may be issued from BA between 21:00 and 22:00 hrs. To investigate this case, assume a 7000 W demand limit has been issued at 21:30 hr that lasts for 30 min. The only controllable appliances which are on or are about to be switched on during this time are the WH and DRY. Due to the priority level, first the DRY will be postponed for 30 min to meet the constraint (3.28). However, to meet constraint (3.27), the WH must be turned off as well. As shown in Fig. 3.18, by turning the WH off and postponing the DRY, the total load falls below the required demand limit. This leads to a drop in the WH satisfaction due to the drop in the water temperature. The calculation of the satisfaction of WH is given by (3.37) and plotted in Fig. 3.19.

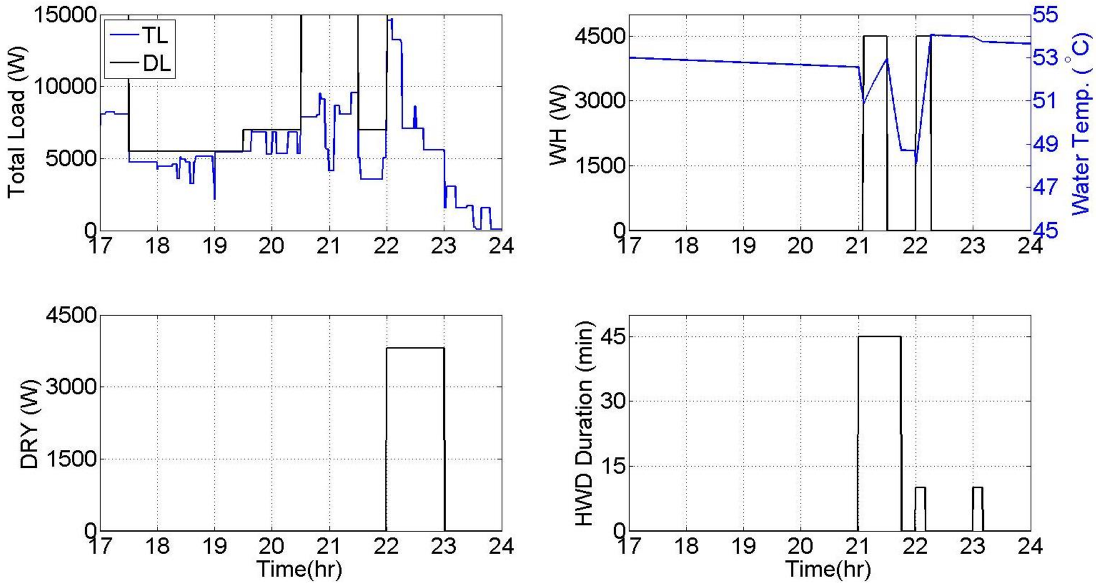

Fig. 3.18. Effect of load rebound on semi smart home.

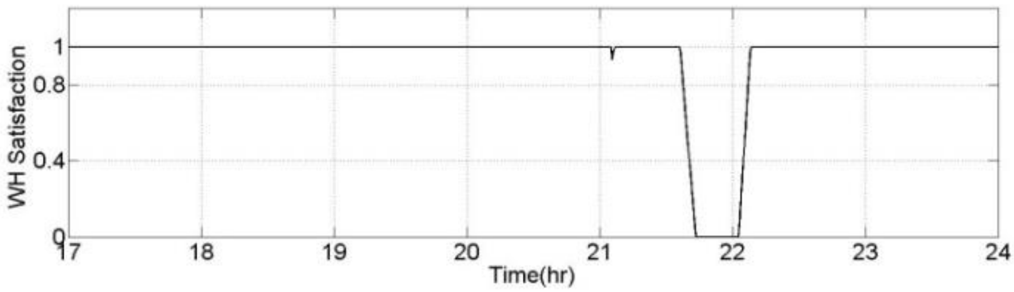

Fig. 3.19. WH satisfaction affected by load rebound in semi smart home.

3.4. CONCLUSION

Demand Side Management (DSM) studies have to be done along with the load studies. As the loads patterns play a significant role on an accurate DSM, the investigation of the behaviour of a typical residential load is necessary. To this end, the detailed appliances models are required. In this study, two types of appliances have been considered; controllable and non-controllable. The dynamic model of the controllable appliances such as; pool pump, water heater, air conditioning unit, fridge, dish washer, dryer, clothes washer, and electrical vehicle are designed in MATLAB environment. Also, Non-controllable loads such as oven, microwave, television, lighting, and so on have been added to controllable appliances to create a more realistic typical residential load profile.

Moreover, a control algorithm has been proposed for an Appliance Management Unit (AMU) that operates under a droop based demand dispatch strategy. A wide variety of deferrable and interruptible appliances participate in the DD considering consumers priority and satisfaction. Also, in the proposed AMU algorithm, the on/off limitations for the appliances have been considered to increase appliances' life spans. The results show the proposed AMU algorithm is capable of maintaining the total power consumption of a house during DD events below the requested demand limit, while preserving consumer satisfaction. However, the availability of renewable energy has not been incorporated in this demand management algorithm. When these are available, the home will be a truly Smart Home. To ensure that the DD remains effective even when renewable energy sources are integrated with a house, a cooperative algorithm needs to be developed in Chapter 5.

CHAPTER 4

DROOP BASED DEMAND DISPATCH FOR RESIDENTIAL LOADS IN SMART GRID APPLICATION

Aggregated loads play a significant role in maintaining the frequency of power system when the generation is not able to follow frequency deviations. An automatic Demand Dispatch (DD) enables the power system to employ the aggregated loads for balancing demand and supply. In this chapter, a Demand Side Frequency Droop (DSFD) has been proposed which provides ancillary service to the grid and maintains the frequency of the power system when the generation system is not capable of following the demand. At the time of a frequency fall/rise, Balancing Authority (BA) can detect aggregated load or group of aggregated loads that have power consumption above or below their standard maximum/minimum consumption levels. Then, the BA issues droop-based signal to the relevant aggregators. Afterwards, the DSFD will be implemented by an aggregator or a group of aggregators to specify the required power consumption amount for bringing the frequency back to its rated level. Subsequently, this signal will be sent to the Appliance Management Unit (AMU) at each participating house. The AMU sends the signal in the form of deferral or interruptible commands to the appliances depending on the priority, availability and the specification of the appliances. It will be demonstrated that the proposed DSFD control maintains the frequency of the power system within a specified range.

It should be noted that the content of this chapter has been mainly extracted from [71].

4.1. PROPOSED DSFD METHOD

The proposed DD method is achieved by employing a Demand Side Frequency Droop (DSFD) in a hierarchical way to implement Demand Dispatch (DD). In a traditional system, the spinning reserve service is the provision of electrical power by a spare generator or a group of spare generators at the time of the generation shortage, with a ramp up time of seconds to 10 minutes [80]. However, when a power system has a high penetration level of intermittent renewable energy sources (e.g. wind or solar), the change in power generation can occur very rapidly. In such events, an ancillary service like spinning reserve through usually old inefficient alternators may not be adequate. To alleviate this problem, in this study a demand dispatch scheme is proposed through which controllable aggregated loads can act as a spinning reserve when there is a generation shortfall.

Usually the loads are quick to respond to external signals and they can be switched on or off almost instantaneously. Therefore, a set of loads can be aggregated and this aggregated load can respond to DD signals faster. Also, due to the enhancement in communication networks, the communication delay of today's communication networks in smart grids have been reduced to milliseconds or less. As a consequence, demand dispatched controllable aggregated loads can provide spinning reserve to a power grid where a rapid change in generation can occur.

In this chapter, the frequency deviation is considered as a trip signal for triggering the DD schedule. When the frequency deviations are sensed in the power system, the BA recognises the aggregated loads with the power consumption above or below the permitted level and issues droop-based regulation signals to the aggregators to nominate them for participating in DD program. Then, the feasibility of the issued command will be investigated by the aggregators considering the droop characteristic of the aggregated loads. Afterwards, the droop based demand dispatch commands will be sent to the AMU in a form of interpretable or deferrable signals until the next command from the BA [70]. These commands are issued based on the time of the day, the priority of the consumers, the features of appliances (for example, the maximum/minimum limitation for power draw/consumption), and the overall characteristic of the aggregated loads.

In power systems, the active power affects the power angle and subsequently the frequency of power system. Similarly, reactive power has significant influence on voltage magnitude [75]. Thus, by controlling active and reactive power in supply side, the frequency and voltage of power system can be adjusted. However, it is not always practical to increase or decrease the power generated by generators as this procedure might be costly and might affect the stability of the power system.

In this study, aggregated residential loads have been considered to be flexible in terms of increasing and decreasing their power consumptions. It has been assumed that each aggregated load has its own characteristics. These characteristics depend on whether the aggregated load is commercial, industrial, or residential. Moreover, the characteristics of the residential loads depend on the type of the residential suburb in which the aggregated load is located. For instance, the households' welfare and wealth level affect the type of the household appliances and the consumption pattern.

It is also assumed that the characteristics of the aggregated loads are obtained by carrying out pre-study demand management research or by means of historical data. These characteristics can define the nominal power of the aggregated load and the power variation limit.

In Fig. 4.1, the hierarchy of the control system and multilevel aggregation of the loads are shown. BA plays the role of a central controller while the feeders level aggregators and the lower level aggregators can act as decentralized controllers. Also, the communication paths have been demonstrated in this figure. Let us assume that a frequency drop occurs and the power generation side is not capable of maintaining the power system frequency. In this case, DD can be applied on the demand side. Through communication and smart metering technology, BA has all the information regarding the aggregated load and is capable of detecting the relevant aggregated load for DD program. According to the specification of each aggregated load, the demand-side droop will be implemented. Each aggregated load has its own specific maximum and minimum power consumptions which represent the flexibility of the aggregated load in changing the demand. They can be obtained through historical data of the power consumption of the aggregated load and the type of appliances which each residential house is equipped with. To employ demand-side droop, droop coefficient of each aggregated load must be calculated which depend on the specification of the aggregated loads. Fig. 4.2 shows the droop characteristic of an aggregated load.

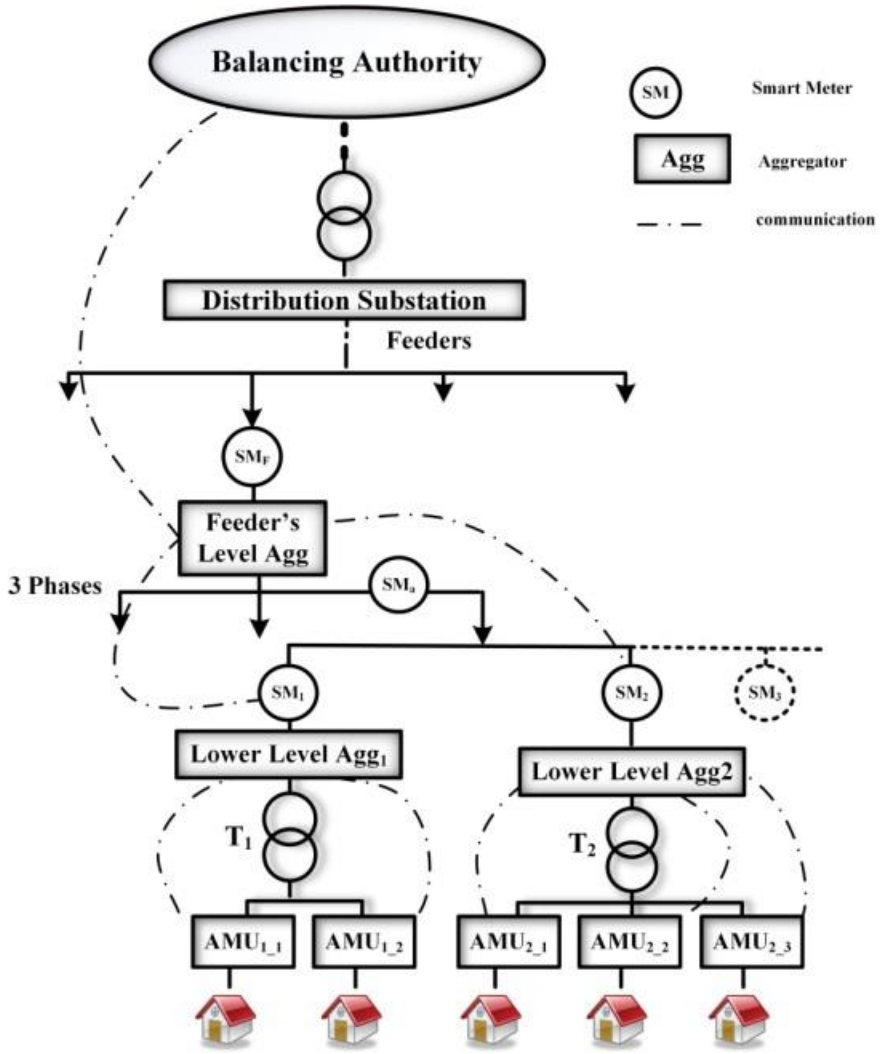

Fig. 4.1. Hierarchical control for droop-based DD.

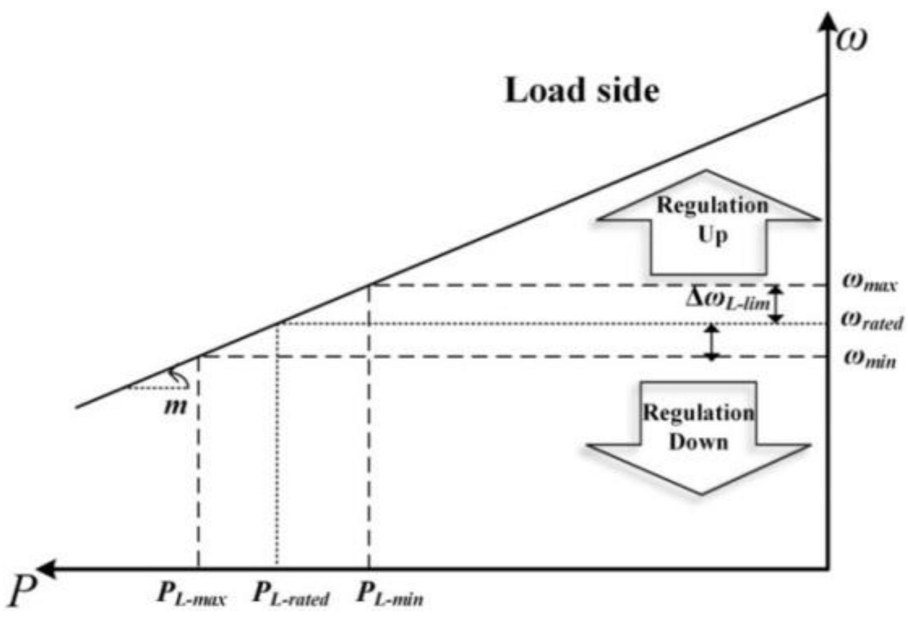

Fig. 4.2. The droop characteristic of an aggregated load.

According to Fig. 4.2, the droop equation can be written as [34]:

$$\omega_{\max} - \omega_{\min} = m_L \cdot \left(P_{L-\max} - P_{L-\min}\right) \tag{4.1}$$

where m_L is droop coefficient of the aggregated load, ω_{max} and ω_{min} are the maximum and minimum angular frequency respectively, P_{L-max} and P_{L-min} are the maximum and minimum power consumption of the aggregated load respectively.

It can be seen from Fig. 4.2 that

$$\omega_{\max} - \omega_{\min} = 2 \times \Delta\omega_{L-\lim} = 4\pi \times \Delta f_{L-\lim} \tag{4.2}$$

where $\Delta\omega_{L-lim}$ is the desired angular frequency limit and Δf_{L-lim} is the desired frequency deviation limit.

Substituting (4.2) in (4.1), we get

$$m_L = \frac{4\pi \times \Delta f_{L-\lim}}{\left(P_{L-\max} - P_{L-\min}\right)}$$

(4.3)

In this study, we have assumed that the rated frequency of 50 Hz occurs when the power consumption is in the midpoint between the minimum and maximum power of the aggregated load, i.e. (see Fig. 4.1),

$$P_{L\text{-}rated} = \frac{\left(P_{L-\max} + P_{L-\min}\right)}{2} \tag{4.4}$$

Here $P_{L\text{-}rated}$ is termed as the rated power consumption of the aggregated load. The frequency deviation is calculated through

$$\Delta f = f_g - f_{rated} \tag{4.5}$$

where Δf is the frequency deviation from f_{rated} and f_g is the grid frequency.

Using the frequency droop, $2\pi.\Delta f = m_L.\Delta P_L$, the feeder level aggregator calculates the amount of power required to be cut off in demand side as:

$$\Delta P_L = \frac{2\pi \times \Delta f}{m_L} \tag{4.6}$$

where ΔP_L is the power consumption which is required to be dropped to bring the frequency back to the rated frequency.

In this chapter, a droop-based hierarchical control strategy has been employed to implement an automatic DD. The required power consumption drop will be calculated through (4.6) in the feeder level aggregator and then will be sent to the lower levels aggregators and eventually to the AMU of the houses which participate in DD. Then, the AMU applies these commands, which are in forms of deferral or interruption requests during frequency drop to the corresponding appliances until the next frequency command from BA.

The calculated ΔP_L will be dispatched among the lower level aggregators according their participation factor which is defined below

$$APF_k = \frac{P_{Agg\_k}}{P_{T\_k}} \tag{4.7}$$

where APF_k is Aggregator Participation Factor of the k^{th} lower level aggregator, P_{Agg_k} is the power consumption of the k^{th} lower level aggregator, and P_{T_k} is the rated power of the distribution transformer which is considered as the aggregated node. It has been assumed that an *APF* higher than 0.8 participate in the DD.

Therefore, the required power to be reduced in the k^{th} lower level aggregator can be calculated as

$$\Delta P_{Agg\_k} = \frac{P_{Agg\_k}}{\sum_{k=1}^{n} P_{Agg\_k}} \times \Delta P_L \tag{4.8}$$

where ΔP_{Agg_k} is the required power consumption curtailment for the k^{th} aggregator and n is the number of the lower level aggregators connected to the feeder level aggregators to participate in DD.

Afterwards, ΔP_{Agg_k} will be shared among the AMUs according to the participation factor of each house:

$$HPF_{kl} = \frac{P_{H\_kl}}{P_{HM\_kl}} \tag{4.9}$$

where HPF_{kl}, P_{H_kl}, and P_{HM_kl} are the Home Participation Factor, the power consumption, and the maximum power consumption threshold of the l^{th} home in the k^{th} lower level aggregator respectively. P_{HM_kl} is defined according to the number of the household members, the size of the property and the type of appliances in the household. Similar to that of the aggregators, the households with *HPF* higher than 0.8 participate in DD.

Therefore, the required power to be curtailed from the l^{th} home in the k^{th} lower level aggregator is

$$\Delta P_{H\_kl} = \frac{P_{H\_kl}}{\sum_{l=1}^{m} P_{H\_kl}} \times \Delta P_{Agg\_k} \tag{4.10}$$

where ΔP_{H_kl} is the required power consumption curtailment for the l^{th} home in the k^{th} lower level aggregator and m is the number of the houses in the k^{th} lower level aggregator which participate in DD.

After calculating the required power reduction, it will be issued to the AMU, which will then either postpone or switch off the loads according to the priority and availability of the appliances. It has been assumed that the power consumption of an entire house and its appliances are measured and monitored every 30 sec. Therefore, DD can be implemented at the appliance level with the help of the AMU, which is required to be installed in each house participating in DD. It should be noted that a smart home is equipped with communication interface and different sensors and measurement devices, which enable the AMU system to gather data about room temperature, water temperature, power consumption, status of appliances, load priority, costumer’s preference, State of Charge (SoC) of EV batteries, etc. An AMU system has a significant role in performing an automated DD within residential properties and ideally should have the least intrusive effects on consumers. The AMU system for a smart house with controllable appliances has been shown in Fig. 3.12 of Chapter 3 [70].

The signals issued from the AMU to appliances are in the form of a deferral or interruption commands when the frequency of the system drops. The AMU releases these commands according to the signals received from the lower level aggregator, the priority of the consumers, and the features of appliances.

The proposed AMU algorithm has been shown in Fig. 3.13 of Chapter 3. The purpose of this algorithm is to reduce the demand during the peak times [70]. When the frequency signal has been issued to the AMU, it gathers information such as, appliances power consumption, overall power consumption of the home, status of appliances, room temperature, hot water temperature, demand limit, duration of demand limit, priority and satisfaction of consumers [70].

If the total load power consumption of the house is more than the demand power limit, then the excess power will be calculated and a load or a group of loads will be selected according to the priority and satisfaction levels, as well as considering constraints mentioned in Chapter 3.

These constraints shall be considered according to the consumers' satisfactions. If the selected controllable load is deferrable, then the starting time of the appliance will be delayed according to the householder's satisfaction. If the load is interruptible then it will be switched off. Then, the information will be updated at the beginning of the next time slot.

4.2. CASE STUDY

To investigate the validity of the proposed DSFD system, the system shown in Fig. 4.1 has been considered. Assume a frequency drop happens at 17:30 hr due to the peak demand in the afternoon and the generation side is not capable of responding to this frequency drop. Thus, demand shedding is required to bring the frequency back to its acceptable range [f_{rated} - $\Delta f_{L\text{-}lim}$, f_{rated} + $\Delta f_{L\text{-}lim}$].

4.2.1. SPECIFICATIONS OF THE SYSTEM UNDER STUDY

The required frequency range and the specifications of the feeder level aggregated load which has been considered in this study case are shown in Table 4.1. Different types of houses have been considered in this study. The specifications of two typical houses with/without EV and their satisfaction have been listed in Table 4.2 and Table 4.3 respectively. The information in Table 4.2 and Table 4.3 can be collected from consumers in time of signing the DD participation contract.

Table 4.1: Specifications of the feeder's level aggregated load.

Parameter	**Value**
f_{rated}	50 Hz
$\Delta f_{L\text{-}lim}$	Hz 0.05
$P_{L\text{-}max}$	KW 630
$P_{L\text{-}min}$	KW 190

Table 4.2: Appliances specifications.

Appliance		**Type of the Appliance:** A) Non-controllable B) Controllable a) deferrable b) interruptible	**Rated power (W)**	
			House 1	House 2
DRY	Rotating Tumble (RT)	non-controllable	300	300

(Dryer)	Heating Coil (HC)	controllable/interruptible & deferrable	3500	3000
FR (Fridge)	Defrost Cycle	controllable/ deferrable	400	400
	Fridge Compressor	non-controllable	150	150
WH (Water Heater)		controllable/interruptible	4500	4000
AC (Air Conditioner)		controllable/interruptible	1500	1400
EV (Electrical Vehicle)		controllable/interruptible & deferrable	3300	N/A
PP (Pool Pump)		controllable/ deferrable	1500	1400
CW(Clothes Washer)		controllable/ deferrable	600	550
DW(Dishwashers)		controllable/ deferrable	1500	1400
KT (Kettle)		non-controllable	1500	1200
HD (Hair dryer)		non-controllable	1500	1300
LI (Lighting)		non-controllable	Vary (50-300)	Vary (40-240)
OV (Oven)		non-controllable	2000	1500
MW (Microwave)		non-controllable	1100	1000
CM (Coffee Machine)		non-controllable	1000	900
TO (Toaster)		non-controllable	1000	800

TV	non-controllable	250	200
MS (Miscellaneous Appliances such as iron, computers, chargers…)	non-controllable	Vary (1500-3000)	Vary (500-1700)

Table 4.3: Customer's satisfaction and Priority.

Appliance	Priority		Preference	
	House 1	House 2	House 1	House 2
DRY	4	4	Finish the tasks before 23:00. Max 30 min off time in time of interruption.	Finish the tasks before 22:30. Max 30 min off time in time of interruption.
FR	7	6	Defrost cycle can be delayed for up to 3 hrs.	Defrost cycle is not allowed to be delayed.
WH	1	1	Water temperature must be within 51-54˚C.	Water temperature must be within 51-55˚C.
AC	2	2	Room temperature must be within 20-22˚C. During DD,	Room temperature must be within 22-24˚C.During DD, 2˚C increase is acceptable.

			3˚C increase is acceptable.	
EV	5	N/A	SoC_{min}= %50, SoC_{max}= %100 Fully charged by 8am. Max 3 times being switched off during interruption.	N/A
PP	6	5	Run at least 6 hours in 24 hours.	Run at least 6 hours in 24 hours.
CW	3	4	Must finish the task before starting time of DRY. Finish the task before 23:00.	Must finish the task before starting time of DRY. Finish the task before 22:30.
DW	3	3	Finish the task before 23:00.	Finish the task before 22:30.

4.2.2. FREQUENCY DROP DETECTION IN FEEDERS LEVEL AGGREGATOR

After sensing the frequency drop in the system, BA detects the feeder level aggregator with the power consumption beyond the limit. It has been considered 100 different houses are connected to this feeder. The objective of this study is to bring the frequency of the system back to the acceptable range with the help of the proposed DSFD and AMU algorithm.

After detecting the problematic feeder, DSFD will be implemented in the corresponding aggregator and the amount of required power curtailment will be calculated using (4.6). Then, the lower level aggregators which must participate in DD will be selected by the feeder level aggregator and the amount of power which is required to be shed will be calculated and issued to them. Then the relevant AMU systems will apply the required changes to the consumption of the relevant loads.

Fig. 4.3 shows aggregator power consumption profile without DSFD, which is not within the acceptable range. On the other hand, Fig. 4.4 shows the results of the DSFD on the feeder’s level aggregator power consumption profile with DSFD. In Fig. 4.3, the power consumption of the feeder level aggregated load rises above the maximum power consumption limit shown in Table 4.1 and this leads to a frequency drop as shown in Fig. 4.5. On the contrary, as shown in Fig. 4.6, the proposed DSFD method is capable of maintaining the frequency within [49.95, 50.05] Hz by reducing the power consumption in the downstream aggregators.

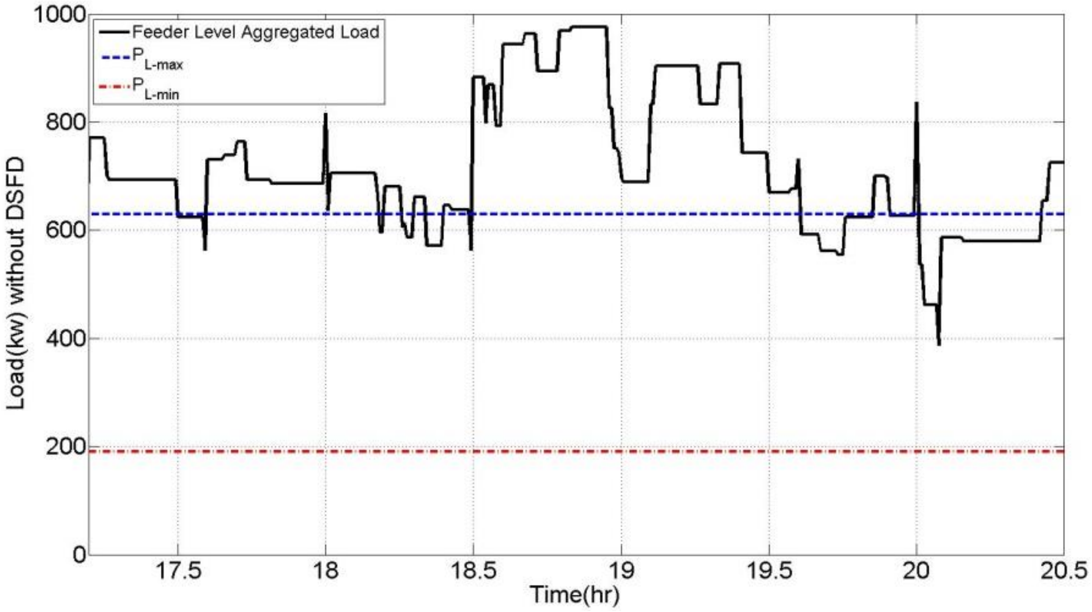

Fig. 4.3. The feeder level aggregated load power consumption profile without DSFD.

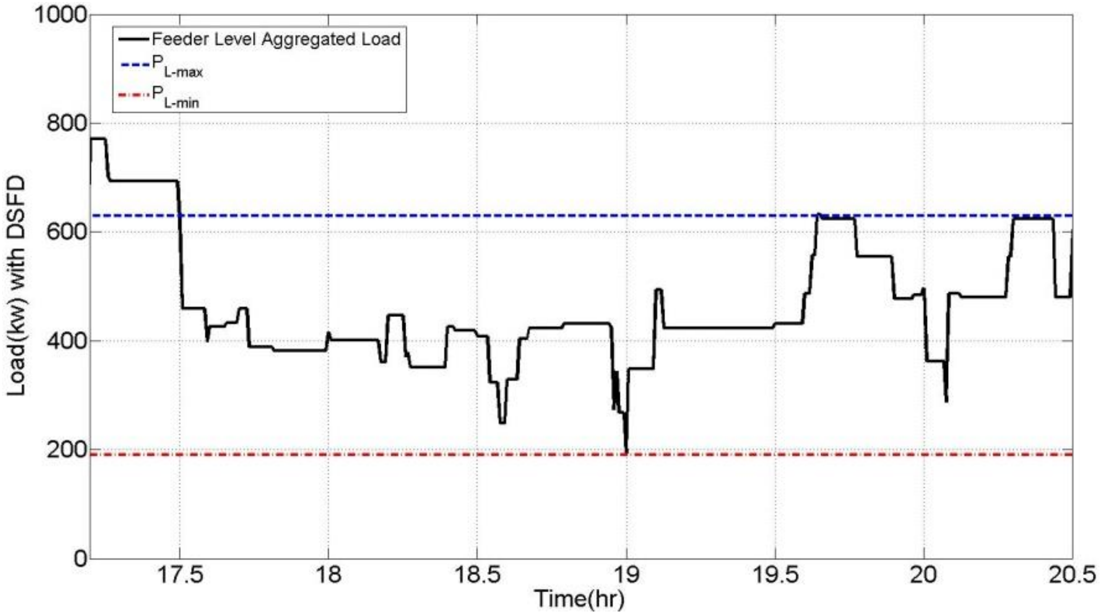

Fig. 4.4. The feeder level aggregated load power consumption profile with DSFD.

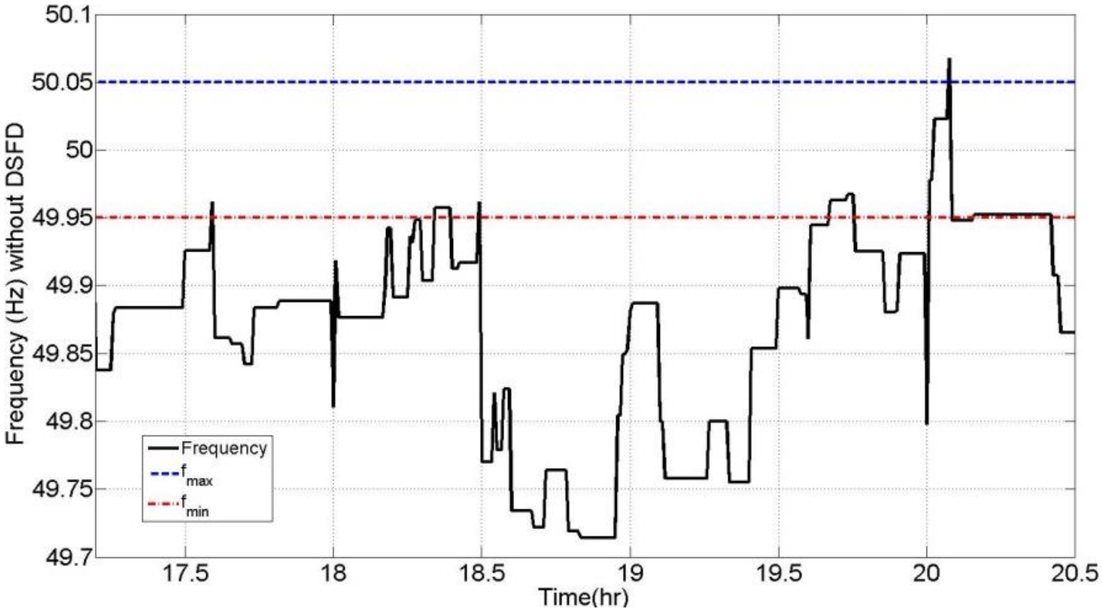

Fig. 4.5. The frequency of the power system without DSFD.

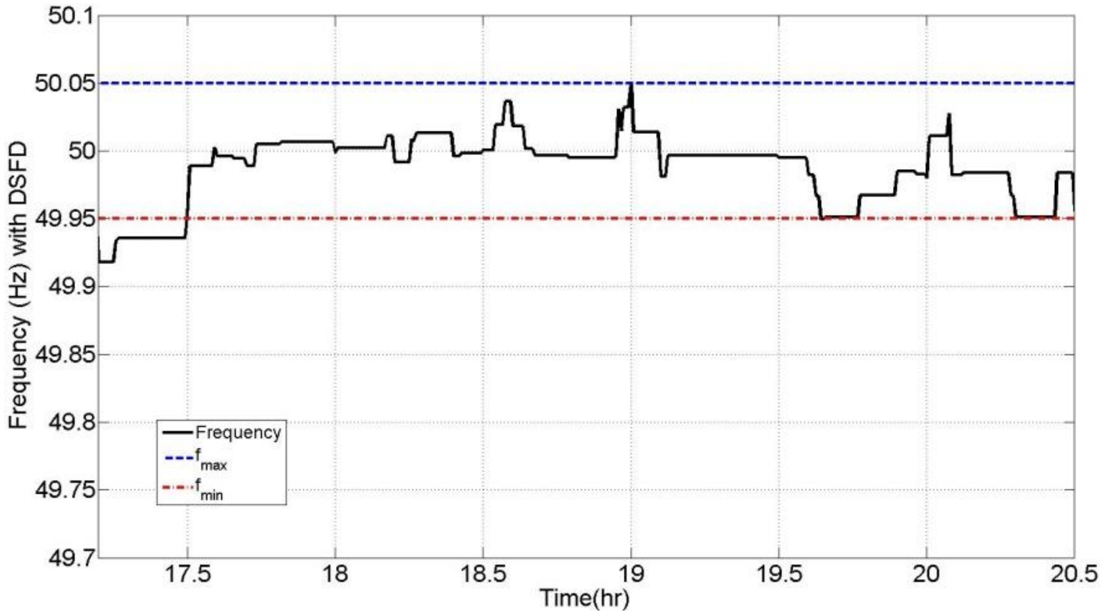

Fig. 4.6. The frequency of the power system with DSFD.

4.2.3. AMU ALGORITHM ALONG WITH THE DSFD

Bringing the frequency of the system within the acceptable range is not achievable without the AMU algorithm. After the required power consumption drop has been assigned to each participating house, the AMU algorithm is responsible for reducing the house power consumption. Two different houses, as described below, have been selected to reflect the effect of the DSFD on the households. House 1 has been considered to have an EV and the householders are not at home between 8:00 and 17:00 hrs. The EV is plugged in as soon as the householders arrive home. House 2 does not have any EV and the householders are at home during the day.

After the AMUs in the selected houses receive the relevant signals, they postpone or interrupt the operation of the appliances according to the AMU algorithm. Figs.4.7 to Fig.4.10 illustrate the load profile of the two houses with/without DSFD. As shown in Fig. 4.8 and Fig. 4.10, the power limit issued from the aggregators to house 1 and 2 has been changed at 19:30 hrs because the tension on frequency of the system has been alleviated. Finally, at 20:30 hrs, the DSFD signals have been removed as the peak period finished. As shown in Figs.4.7 to Fig.4.10, the proposed DSFD method with the help of the AMU algorithm is capable of maintaining the power consumption of the houses below the required power limit.

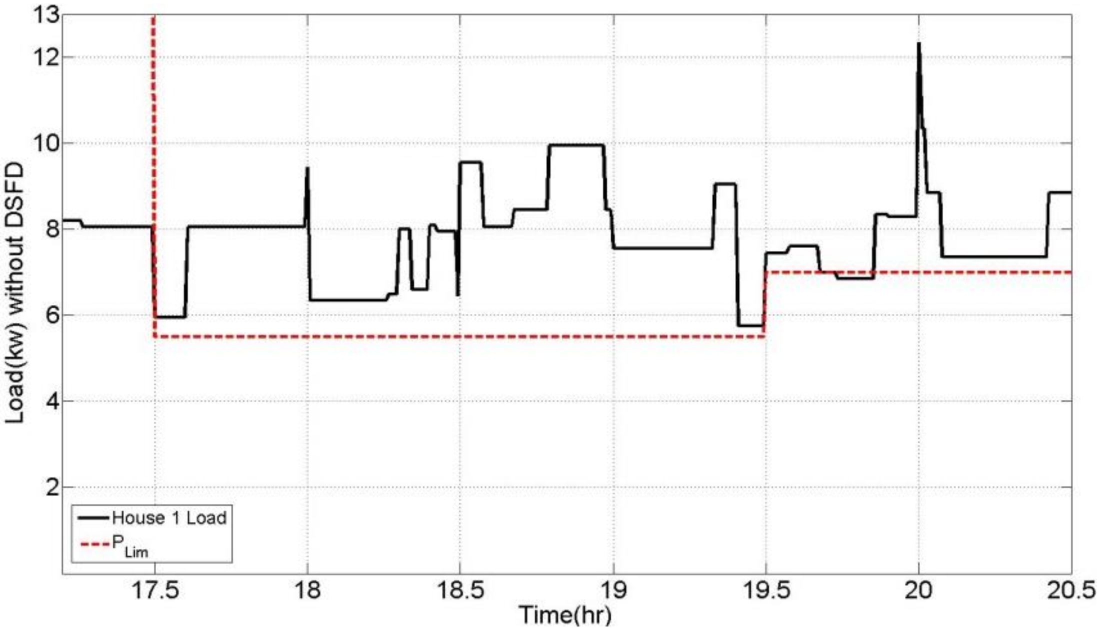

Fig. 4.7. House 1 power consumption without DSFD.

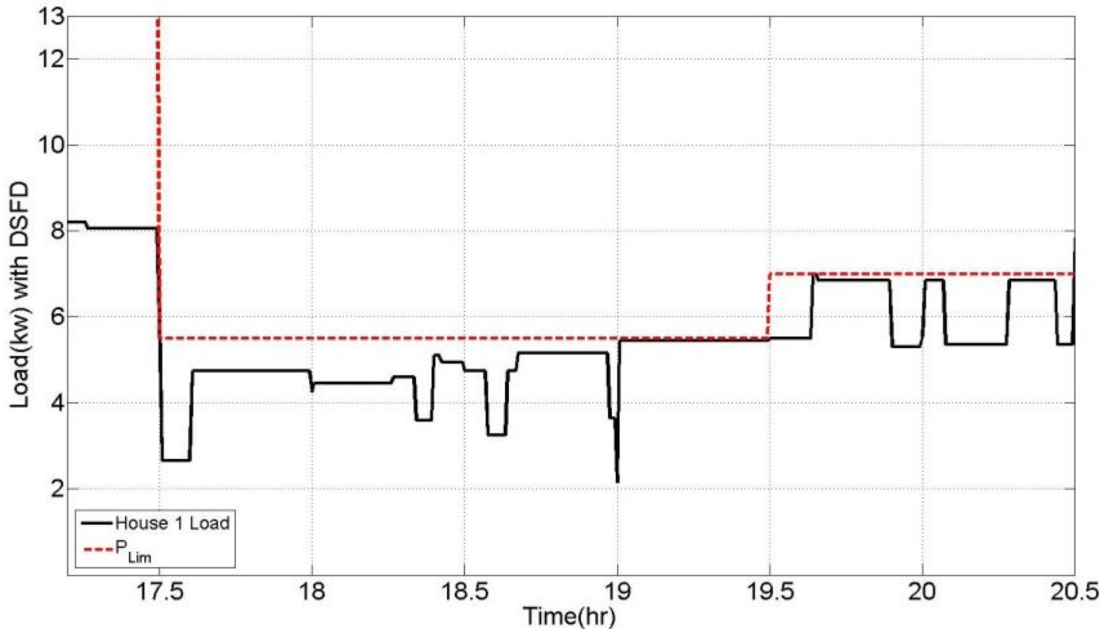

Fig. 4.8. House 1 power consumption with DSFD.

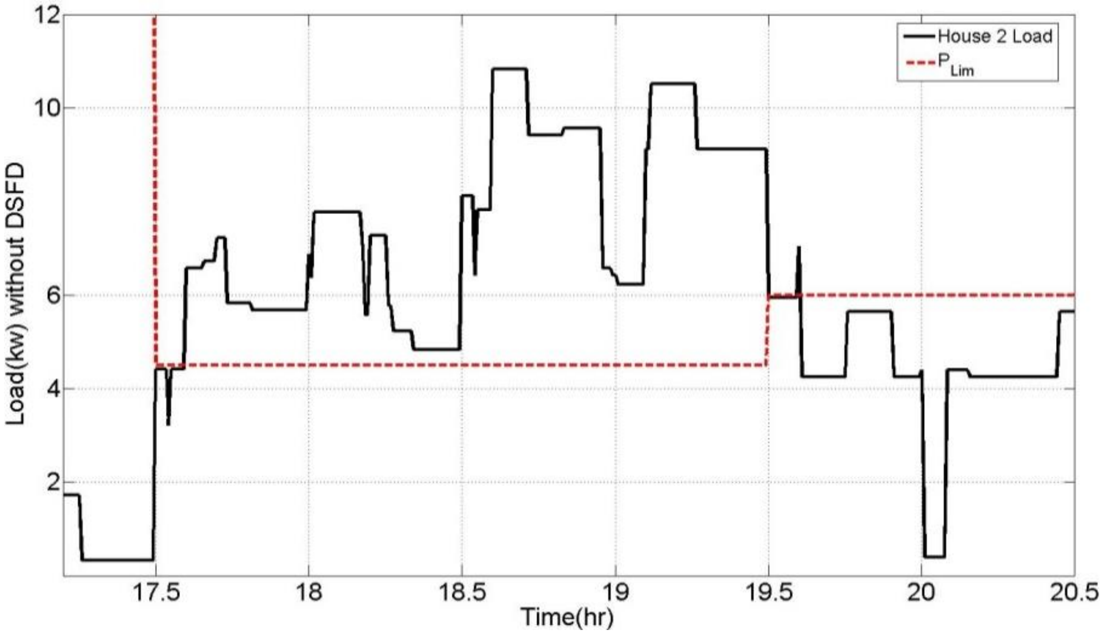

Fig. 4.9. House 2 power consumption without DSFD.

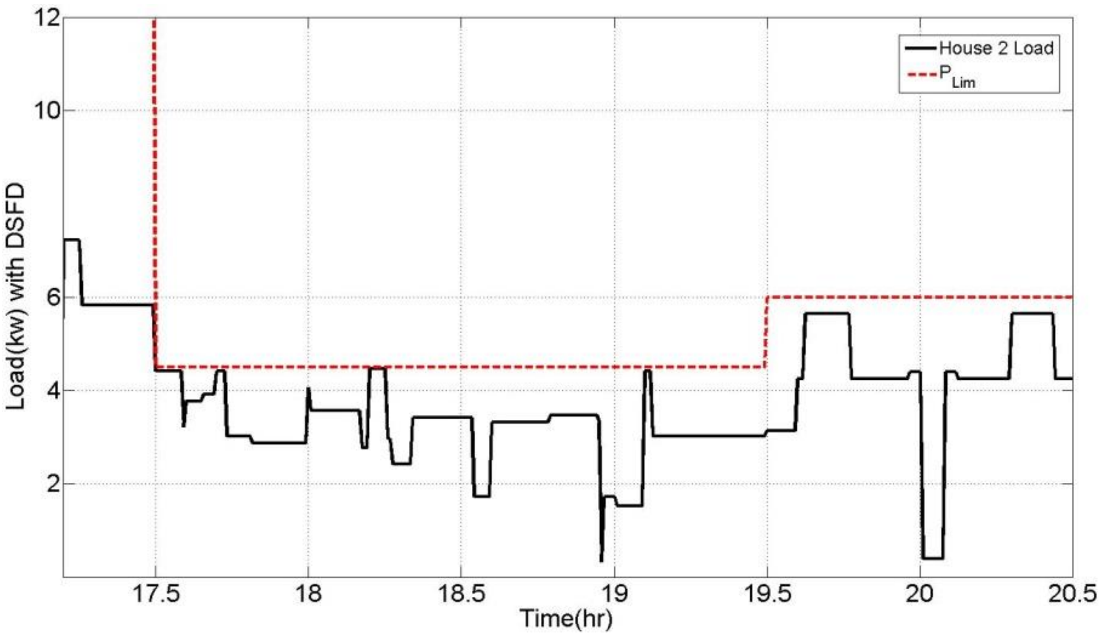

Fig. 4.10. House 2 power consumption with DSFD.

Fig. 4.11 shows the normal operation of the controllable appliances in house 1 before participating in the DD program. Fig. 4.12 shows the detailed operation of the same controllable appliances in house 1 after participating in DD. WH load profile has not been shown as it has not been selected by AMU to participate in DD due to its high priority. As shown in Fig. 4.12, the power consumptions of controllable appliances were altered according to AMU algorithm and DSFD. For example, the operation of CW is delayed for 1.5 hours. The other example of this alteration is AC's temperature and power consumption profile shown in Fig. 4.10. During the DD event, AC is allowed to increase the room temperature by 3˚C according to costumer's satisfaction given in Table 4.3. The operation of other controllable appliances such as DRY, PP, DW, FR defrost cycle, and EV which participate in DD are also shown in Fig. 4.12.

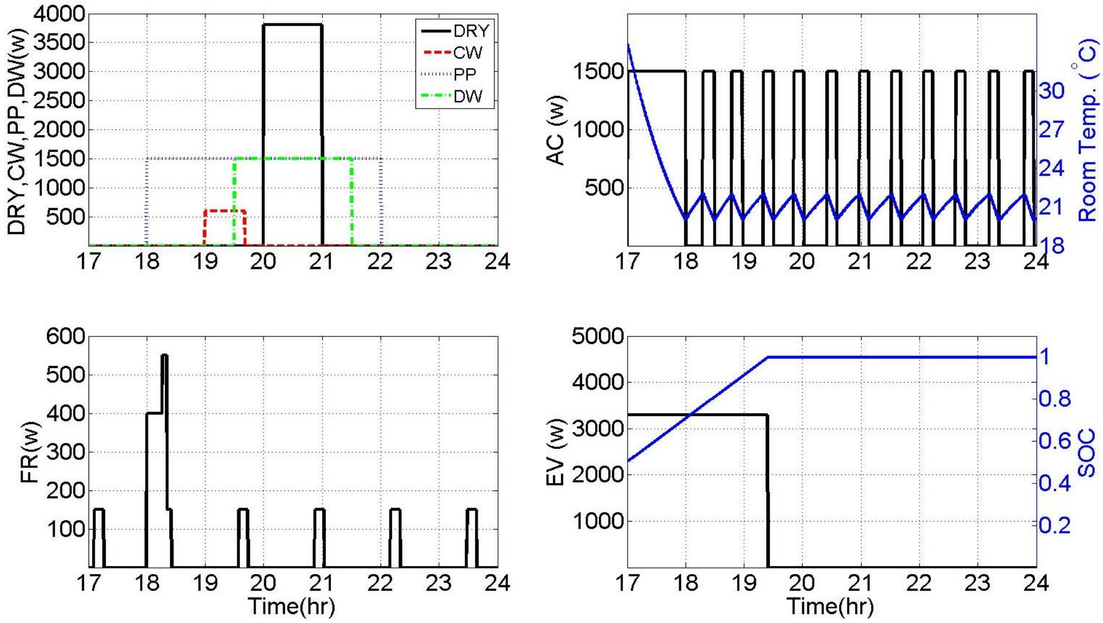

Fig. 4.11. DRY, FR, DW, CW, PP, AC, and EV operation in house 1 without DSFD.

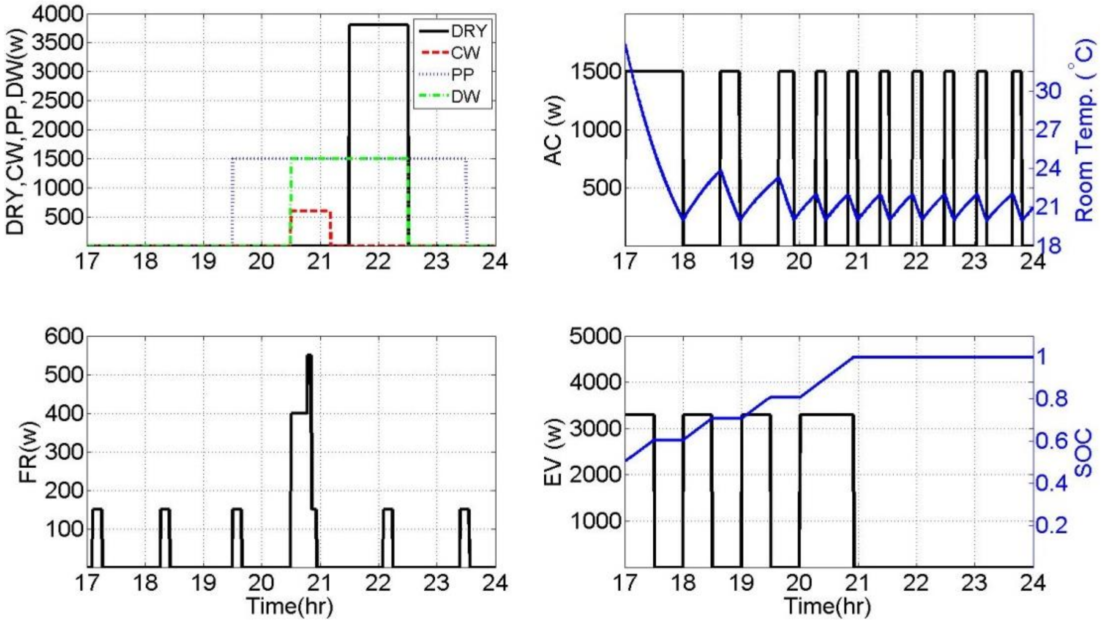

Fig. 4.12. DRY, FR, DW, CW, PP, AC, and EV operation in house 1 with DSFD.

The operation of the controllable appliances in house 2, which have participated in the DD event are shown in Fig. 4.13. As mentioned before, there is no EV in house 2. The detailed operation of AC, DRY, DW, and PP before receiving DD signals have been shown in Fig 4.13. WH and FR and CW load profiles have not been shown as they did not participate in DD due to the priority of the householders. The altered power consumption of AC, DRY, DW, and PP after receiving DD signals have been shown in Fig 4.14. For example, AC's temperature is allowed to rise up to 2˚C according to the satisfaction level of the householders of house 2 as mentioned in Table 4.3.

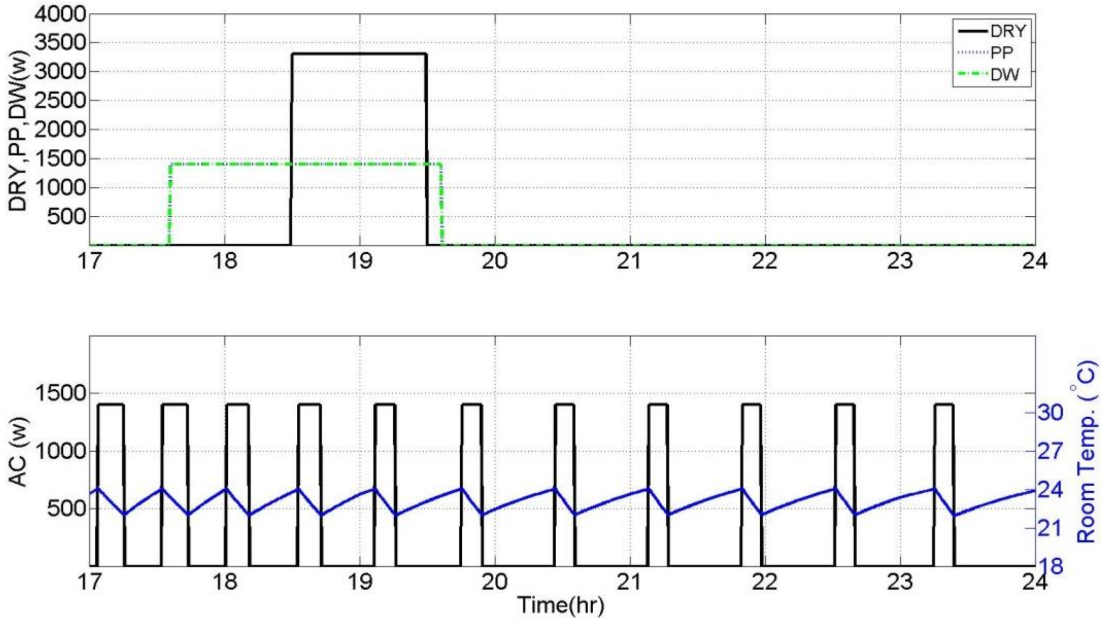

Fig. 4.13. DRY, DW, PP, and AC operation in house 2 without DSFD.

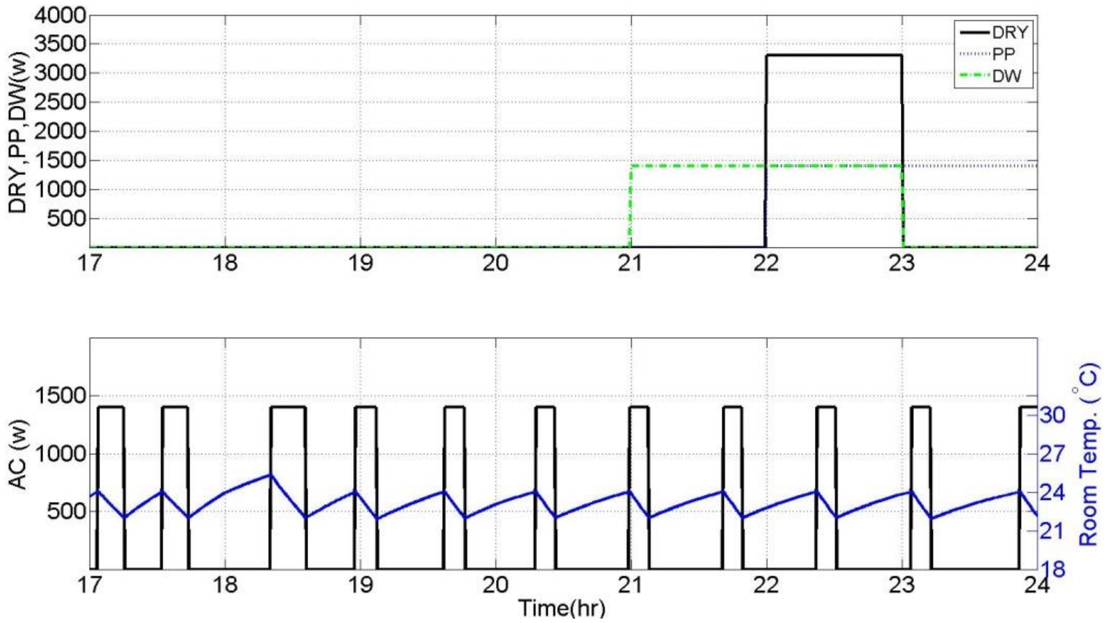

Fig. 4.14. DRY, DW, PP, and AC operation in house 2 with DSFD.

Figs. 4.3 to 4.14 clearly illustrate the cooperative operation of the DSFD and AMU system. DSFD released the frequency signal to the relevant aggregators after sensing the frequency drop in the power system. Afterwards, the required power consumption curtailments were dispatched to the participating AMUs in each house via lower level aggregator to bring the frequency back to the acceptable limits. AMU reduced the required power by postponing or curtailing the power consumptions of the appliances according to their characteristic and householders satisfactions.

4.3. CONCLUSION

The proposed DSFD has offered significant improvements on maintaining the frequency of the power system. This study demonstrated how this method can maintain the frequency of the system within the acceptable range. The BA is capable of detecting the relevant aggregators to participate in DD program. Afterwards, by implementing DSFD in aggregators' level, the required power consumption level which the aggregated loads must consume to bring the frequency back within the rated range will be calculated. This limited amount of power consumption will be issued to the lower level aggregators and then finally to the AMU system in each house. Afterwards, the AMU algorithm alters the power consumption of the house accordingly by sending the commands in form of deferral or interruptible signals to various appliances. The case study results confirm the suitability of the proposed approach.

CHAPTER 5

INTEGRATION OF RENEWABLE ENERGY RESOURCE AND ENERGY STORAGE DEVICE TO DEMAND DISPATCH IN SMART GRID

As has been proved in the previous chapters, DD plays a significant role in balancing demand and generation as it acts as a virtual spinning reserve in the power system. In the recent years, the advancement in the battery systems makes the application of the battery storage more affordable. Moreover, the high penetration of the PV systems in residential levels has raised the necessity to use the PV-Battery system to prevent the deterioration power quality of the system. Thus, it seems that the integration of the renewable resources and the storage devices to the DD is inevitable.

In this chapter, the impact of integration of the renewable energy and storage system to the Demand Dispatch schedule are investigated. To this end, three different DD methods have been proposed, which are then compared with the DD method in the semi smart home. The DD methods considered are given below.

- In the DD method one (DD_1), the overall power consumption of the house is controlled through just DD schedule without participation of the PV and battery. The other three DD methods work on how to integrate the PV and battery to the DD schedule.
- In the DD method two (DD_2), during the DD, first the battery system supplies the house loads until it reaches its minimum allowable SOC. Then the actual DD starts.

- In the DD method three (DD_3), the battery discharges instead of deferrable appliances. For example, if according to DD schedule DW's task needs to be postponed then battery will be discharge instead of postponing the DW.
- In the DD method four (DD_4), battery is discharged for the first four most important appliances with high priorities, i.e., WH, AC, DRY, CW and DW until it reaches the minimum SoC.

To compare these four DD methods and find the more efficient one, three factors have been introduced in this chapter as follow:

- Overall Customers' Satisfactions (OCS) factor,
- Load factor (LF), and
- The Cold Load Pick-up (CLPU) factor.

These factors are explained in detail in the next section. Then, the four methods are explained in Section 5.2 to 5.5.

5.1. INTRODUCTION TO CLPU, OCS, AND LF FACTORS

As mentioned before, to compare and investigate the proposed methods of integration of PV-battery system to the DD schedule, some factors need to be introduced. These are discussed below.

5.1.1. OVERALL CUSTOMERS' SATISFACTION FACTOR

As described in Chapter 3, all controllable appliances have their own priorities and satisfactions which have been set according to the customers' desires. To define, OCS factor, the satisfaction of each appliances must be defined.

WH and AC are the appliances with the highest priority. It means the householders would prefer not to interrupt them as much as possible. According to Table 3.8 and (3.37) in Chapter 3, AC's, HW's, and EV's satisfactions are defined by (5.1), (5.2), and (5.3) respectively. The satisfaction factor of AC is given by

$$Sat_{ac,i} = \begin{cases} 0 & \text{if } T_{room,i} \geq T_{room,hs} + 4 \quad and \quad N_{ac,\text{int}} > 5 \\ \dfrac{5 - N_{ac,\text{int},i}}{5} & \text{if } T_{room,i} < T_{room,hs} + 4 \quad and \quad N_{ac,\text{int},i} \leq 5 \end{cases} \tag{5.1}$$

where, $Sat_{ac,i}$ is weighting of AC's satisfaction in time slot i, $T_{room,i}$, is the room temperature in time slot i, $T_{room,hs}$ is the AC's highest temperature set point which is equal to 22˚C, and $N_{ac,int,i}$ is the number of times AC has received the DD signal for interruption until time slot i. It should be noted that, according to the proposed DD schedule the room temperature is always kept under $T_{room,hs}$+4˚C.

The satisfaction with water heater is

$$Sat_{hw,i} = \begin{cases} 1 & \text{if } T_{hw,i} \geq T_{s,hw} \\ 0 & \text{if } T_{hw,i} < T_{s,hw} - \Delta T_{hw} \\ \dfrac{T_{hw,i} - \left(T_{s,hw} - \Delta T_{hw}\right)}{\Delta T_{hw}} & \text{if } T_{s,hw} - \Delta T_{hw} \leq T_{hw,i} < T_{s,hw} \end{cases} \tag{5.2}$$

where, $Sat_{hw,i}$ is weighting of WH's satisfaction in time slot i, $T_{hw,i}$, is the hot water temperature in time slot i, $T_{s,wh}$ is WH's temperature set point which is equal to 51˚C and ΔT_{hw} is the maximum acceptable temperature deviation during DD event which is 2˚ C.

The satisfaction with EV is

$$Sat_{ev,i} = \begin{cases} 1 & \text{if } t_{off,ev} \leq 30\min \quad and \quad N_{S,sofar\_ev} \leq 3 \\ 0 & \text{if } N_{S,sofar\_ev} > 3 \quad or \quad t_{off,ev} \geq 100\min \\ \dfrac{100 - t_{off,ev}}{100 - 30} & \text{if } 30\min < t_{off,ev} < 100\min \\ & \quad and \quad N_{S,sofar\_ev} \leq 3 \end{cases} \tag{5.3}$$

where, $Sat_{ev,i}$ is weighting of EV's satisfaction in time slot i, $t_{off,ev}$ is off time duration of EV (minute), and $N_{s\_sofar,ev,i}$ is the number of signals which EV has received to be switched off so far. Under some conditions, EV may need to remain off for more than 30 min. However, the off time duration cannot be more than 100 min according to the customers' request. It should be noted that, according to the proposed DD schedule $N_{s\_sofar,ev,i}$ never exceeds 3 times.

As other controllable appliances, DRY, CW, DW, FR, and PP are deferrable and required to finish their tasks before a certain time. So, their satisfactions are considered to be one if they finish their task by the required time, otherwise it is zero.

To investigate the OCS of the householders, the overall satisfaction factor has been defined by

$$OCS = \frac{Sat_{wh} \times W_{wh} + Sat_{ac} \times W_{ac} + Sat_{ev} \times W_{ev} + Sat_{dry} \times W_{dry}}{W_{wh} + W_{ac} + W_{ev} + W_{dry} + W_{cw} + W_{dw} + W_{pp} + W_{fr}} + \frac{Sat_{cw} \times W_{cw} + Sat_{dw} \times W_{dw} + Sat_{pp} \times W_{pp} + Sat_{fr} \times W_{fr}}{W_{wh} + W_{ac} + W_{ev} + W_{dry} + W_{cw} + W_{dw} + W_{pp} + W_{fr}} \tag{5.4}$$

where W_{wh}, W_{ac}, W_{ev}, W_{dry}, W_{cw}, W_{dw}, W_{pp}, and W_{fr} are weightings of the participations factors of WH, AC, EV, DRY, CW, DW, PP, and FR which are shown in Table 5.1. The best OCS is equal to one.

Table 5.1: Weightings of the participations factors.

Parameter	**Value**
W_{wh}	0.9
W_{ac}	0.8
W_{ev}	0.7
W_{dry}	0.7
W_{cw}	0.7
W_{dw}	0.7
W_{pp}	0.5
W_{fr}	0.5

5.1.2. COLD LOAD PICK UP

The CLPU concept have been analysed through different studies. However, most of these studies determined CLPU event as an unwanted peak due to the total outage of power. Different formulas have been introduced to calculate the duration and the magnitude of CLPU which are the important factors in CLPU analysis [81, 82].

However, During DD program, there is a possibility of generating another peak in load after removing the demand limit. In some situations, this peak load may be even bigger than the first peak which led to implementing the DD schedule. In this study, CLPU has been defined as an unexpected peak load after removing a DD schedule due to the interruption/ deferment of the controllable appliances.

CLPU factor in this study is obtained by (5.5).

$$CLPU = \frac{P_{\max,ADD}(in\ \Delta t_{CLPU})}{P_{\max,BDD}(in\ \Delta t_{CLPU})} \tag{5.5}$$

where $P_{max,ADD}$ is the max power consumption occurs in the time interval of Δt_{CLPU}, Δt_{CLPU} is the time interval which is prone to the occurrence of CLPU. In this study, Δt_{CLPU} considered to be the time interval between removal of demand limit and 1.5 hrs (90 min) after that. $P_{max,BDD}$ is the max power consumption occurs in the same time interval before applying DD. It is desired to have a CLPU as little as possible. It should be noted that, the CLPU greater than one has been considered as a critical situation which leads to another DD schedule.

5.1.3. LOAD FACTOR

Flattening the residential load profile implies decreasing the power consumption difference between the peak and nadir. Flattening the load profile alleviates the cost of transmission and distribution systems. The purpose of flattening the load profile is to reduce the difference between the average power consumption and the peak. In this study, Load Factor (LF) is used to investigate the flattening the load profile capability of the DD method. LF is defined as the ratio of the average power consumption to the peak power consumption. As this study intends to investigate the effect of DD on the after peak load, the LF is defined as the ratio of average power consumption of the house to the peak load from the time of applying the demand limit until removing the demand limit as given in (5.6)

$$LF = \frac{P_{ave}}{P_{\max}} \tag{5.6}$$

where LF is the Load Factor, P_{ave} and P_{max} are average and max load respectively in W. It is desired to have a LF close to one.

5.2. THE DD METHOD ONE (DD_1)

This method is the same DD method which was explained in Chapter 3 and considered the first and the base case (method). In this method, a semi-smart home without renewable energy and storage system has been considered. In this method, as mentioned in Chapter 3, the proposed DD is capable of bringing the overall power consumption of the house bellow the demand limits. However, due to the lack of integration of the PV and the battery system to the DD, there is a possibility of CLPU occurrence which finally led to a considerable drop in the satisfaction of the WH. Fig. 5.1 and 5.2 show the overall power consumption of the house and the operation of the controllable appliances which contributed in DD.

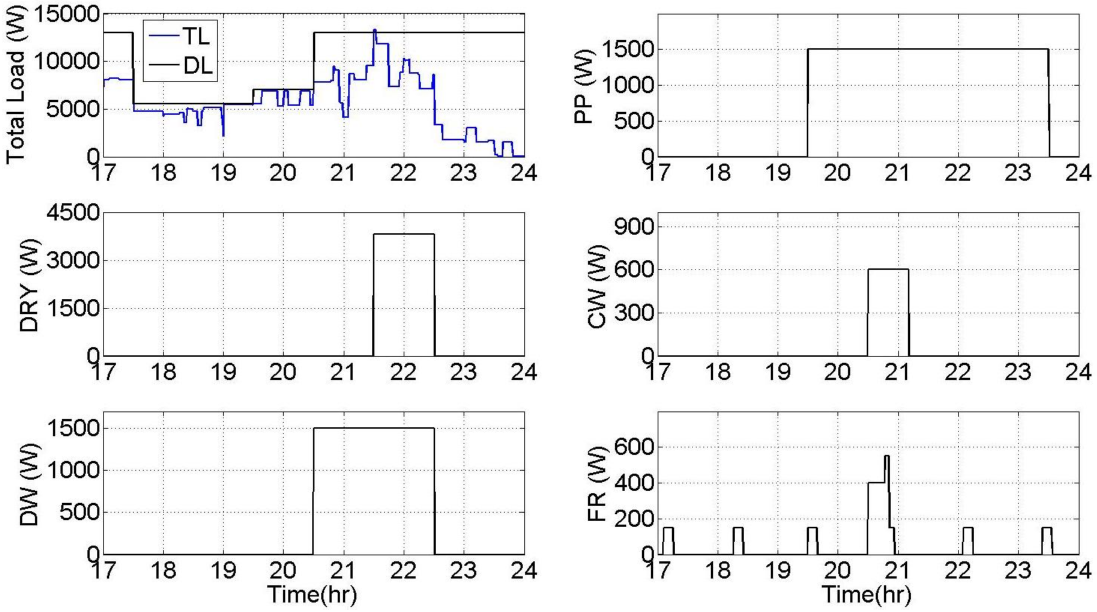

Fig. 5.1. Semi smart home consumption pattern.

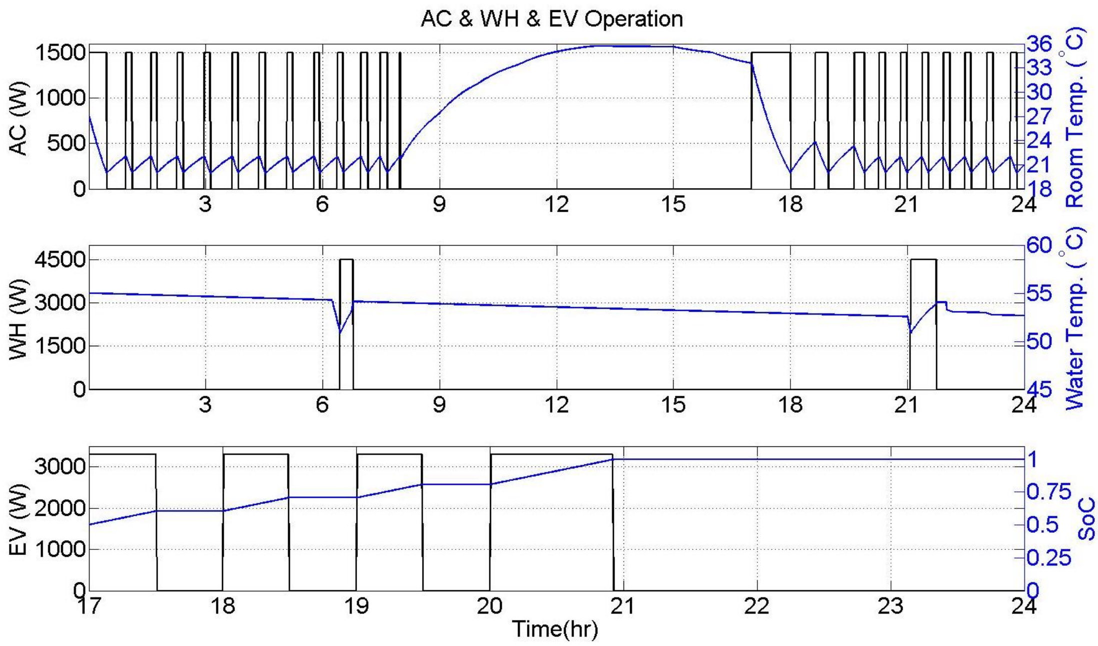

Fig. 5.2. AC, WH, and EV operation in semi smart home.

The OSC factor, CLPU factor, and LF of the semi smart house are shown in Table 5.2.

Table 5.2: The OSC factor, CLPU factor, and LF of the semi smart house.

Parameters	**Value**
OSC Factor	0.9418
CLPU Factor	1.081
LF	0.6922
Number of Appliances participate in DD	7
The Battery's SoC at the end of DD	NA

As shown in Table 5.2, OSC factor is 0.9418 which is quite good. However, as the CLPU is high (greater than one) the second DD will be issued at around 21:30 as explained before in Chapter 3 and bring the WH satisfaction to zero. Thus, the OSC after the second DD is reduced to 0.7781, which is quite low. Moreover, the LF factor is required to be as close as possible to 1.

5.3. THE DD METHOD TWO (DD_2)

In this method, a smart home is considered which has all the capabilities of the semi-smart home such as the smart controllable appliances, the communication system, and the AMU. Moreover, this house is equipped with a PV and a battery system. In this study, battery is charged during the daylight time by the PV and discharged according to the proposed DD schedule. The battery model used in this method has been given by (5.7)-(5-11). The size and the specifications of the PV and the battery system used in the smart home are given in Table 5.3.

Equation (5.7) shows the battery power in time interval *i*.

$$P_{bat,i} = P_{bat,charge,i} + P_{bat,discharge,i} \tag{5.7}$$

where $P_{bat,i}$ is the total instantaneous power of the battery (W) at time interval *i*, $P_{bat,charge,i}$ is the total instantaneous charging power of the battery (W) at time interval *i*, and $P_{bat,discharge,i}$ is the total instantaneous discharging power of the battery (W) at time interval *i*.

Equation (5.8) illustrates the charge power of the battery in time interval *i*.

$$P_{bat,charge,i} = \begin{cases} (P_{pv,i} - P_{TL,i}) & \text{if } (P_{pv,i} - P_{TL,i}) \le P_{bat,\max} \\ & \quad \text{and } SoC_{bat,\min} \le SoC_{bat,i} < SoC_{bat,\max} \\ P_{bat,\max} & \text{if } (P_{pv,i} - P_{TL,i}) > P_{bat,\max} \\ & \quad \text{and } SoC_{bat,\min} \le SoC_{bat,i} < SoC_{bat,\max} \\ 0 & \text{if } SoC_{bat,i} = SoC_{bat,\max} \text{ or } P_{pv,i} \le P_{TL,i} \end{cases} \tag{5.8}$$

where $P_{pv,i}$ is the power which PV generates (W) at time interval *i*, $P_{TL,i}$ is the total load of the house (W) at time interval *i*, $P_{bat,max}$ is the max charging/discharge power of the battery (W) at time interval, $SoC_{bat,i}$ is the SoC of the battery in time interval *i*, $SoC_{bat,min}$ is the minimum SoC of the battery, and $SoC_{bat,max}$ is the maximum SoC of the battery.

Equation (5.9) and (5.10) show the SoC of the battery during the charge and discharge time respectively in time interval *i*.

$$SoC_{bat,charge,i} = \begin{cases} SoC_{bat,i-1} + \dfrac{P_{bat,charge,i} \times dt}{C_{bat} \times 60} & \text{if } SoC_{bat,\min} \le SoC_{bat,i} < SoC_{bat,\max} \\ 0 & \text{if } SoC_{bat,i} = SoC_{bat,\max} \end{cases} \tag{5.9}$$

$$SoC_{bat,discharge,i} = \begin{cases} SoC_{bat,i-1} + \dfrac{P_{bat,discharge,i} \times dt}{C_{bat} \times 60} & \text{if } SoC_{bat,eligible} \leq SoC_{bat,i} < SoC_{bat,\max} \\ 0 & \text{if } SoC_{bat,i} = SoC_{bat,\max} \end{cases}$$

(5.10)

where $SoC_{bat,charge,i-1}$ is the SoC of the battery during charging process in time interval *i-1*, $SoC_{bat,discharge,i-1}$ is the SoC of the battery during discharging process in time interval *i-1*, *dt* is the duration of each time interval in minute and is equal to 0.5 minutes, C_{bat} is the rated capacity of the battery in (Wh), and $SoC_{bat,eligible}$ is the minimum eligible SoC of the battery which is defined base on the householder’s desire.

Table 5.3: The size and the specifications of the PV and battery system used in the smart home

Parameters	**Value**
PV’s size	5000 (W)
Battery’s Capacity	4000 (W.hr)
Battery’s max SOC	%100
Battery’s min SOC	%30
Battery’s eligible SOC	%40
Battery’s max charge/discharge power	3300 (W)

During the daylight hours, depending on the total load of the house, the PV supplies the house and charges the battery and the extra power is fed back to the grid.

In this method, during DD schedule, first battery will be discharged as long as the discharged power is not greater than $P_{bat,max}$ and the SoC of the battery is greater than the minimum acceptable SoC. If the excess power is greater than $P_{bat,max}$, then the status and availability of the controllable appliances must be investigated and the proposed DD schedule introduced in Chapter 3 must be implemented to bring the power consumption of the house bellow the demand limit. Fig. 5.3 illustrates the proposed algorithm in this method.

According to the proposed algorithm, first the battery starts to discharge until it reaches the eligible SOC. The discharge power of the battery is equal to the excess power which is the total power consumption deducted by the demand limit, as long as it is not greater than $P_{bat,max}$ as given in (5.11).

$$P_{bat,discharge,i} = \begin{cases} -(P_{TL,i} - P_{DL,i}) & \text{if } (P_{TL,i} - P_{DL,i}) \le P_{bat,\max} \\ & \quad \text{and } SoC_{bat,eligible} \le SoC_{bat,i} < SoC_{bat,\max} \\ -P_{bat,\max} & \text{if } (P_{TL,i} - P_{DL,i}) > P_{bat,\max} \\ & \quad \text{and } SoC_{bat,eligible} \le SoC_{bat,i} < SoC_{bat,\max} \\ 0 & \text{if } SoC_{bat,i} = SoC_{bat,eligible} \text{ or } P_{TL,i} \le P_{DL,i} \end{cases}$$

(5.11)

where $P_{bat,discharge,i}$ is the discharging power of the battery (W) in time interval i, $P_{DL,i}$ is the demand limit in during DD schedule (W) in time interval i.

Fig. 5.4 shows the overall power consumption of the house and the PV generation. The negative amount of power means the extra power from the PV system is fed back to the grid.

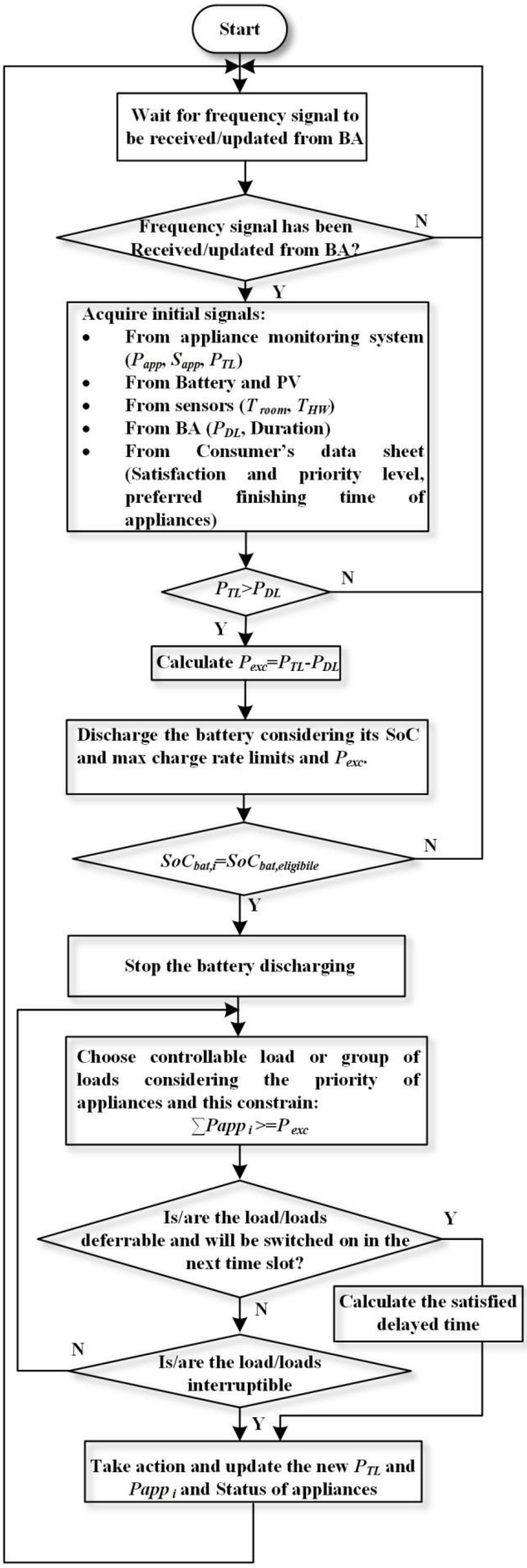

Fig. 5.3. The proposed algorithm in DD2.

Fig. 5.5 illustrates the battery discharge power and the SOC of the battery. Fig. 5.6 shows the power consumption of the EV and the AC. In Fig. 5.7, the power consumption of CW, DW, and DRY are illustrated.

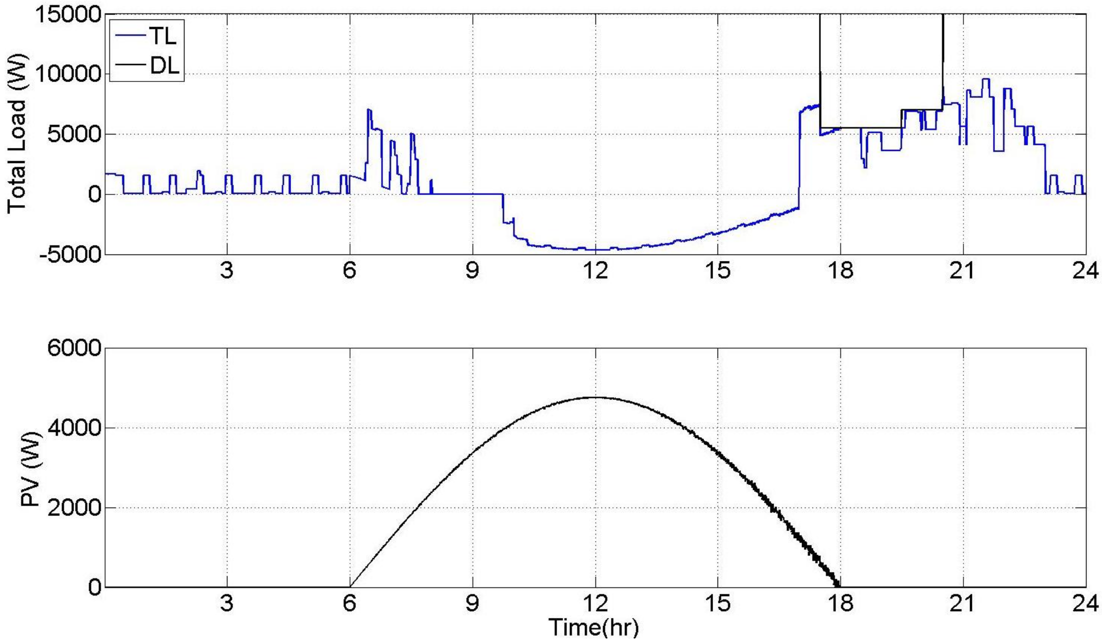

Fig. 5.4. The overall power consumption of the house and the PV generation in DD_2.

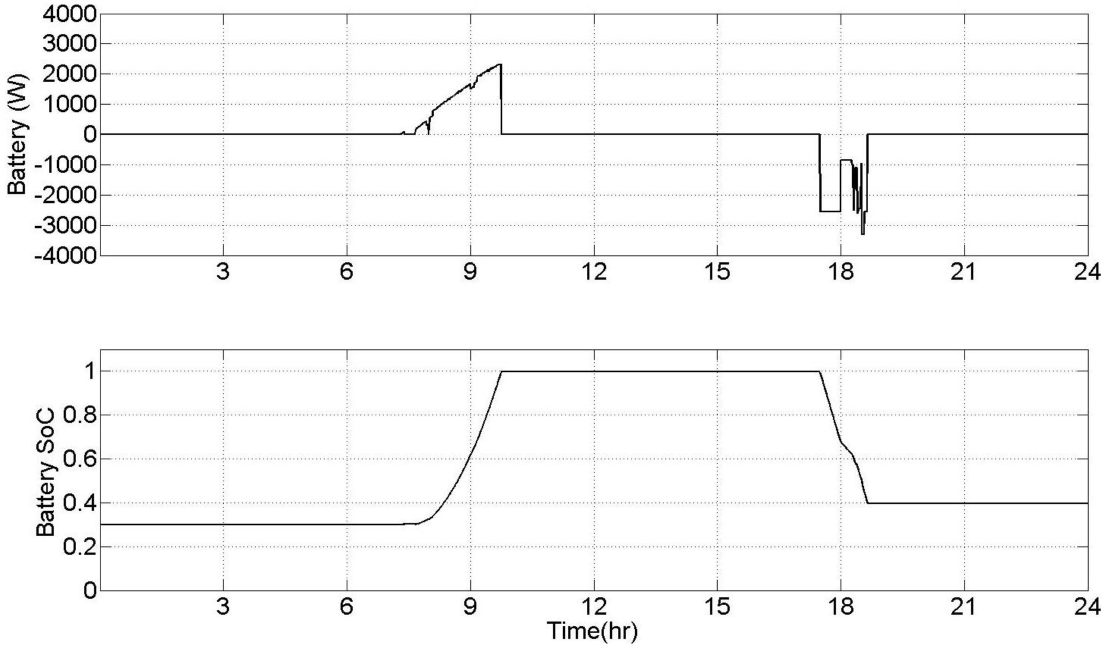

Fig. 5.5. The battery charging / discharging power and the SOC of the battery in DD_2.

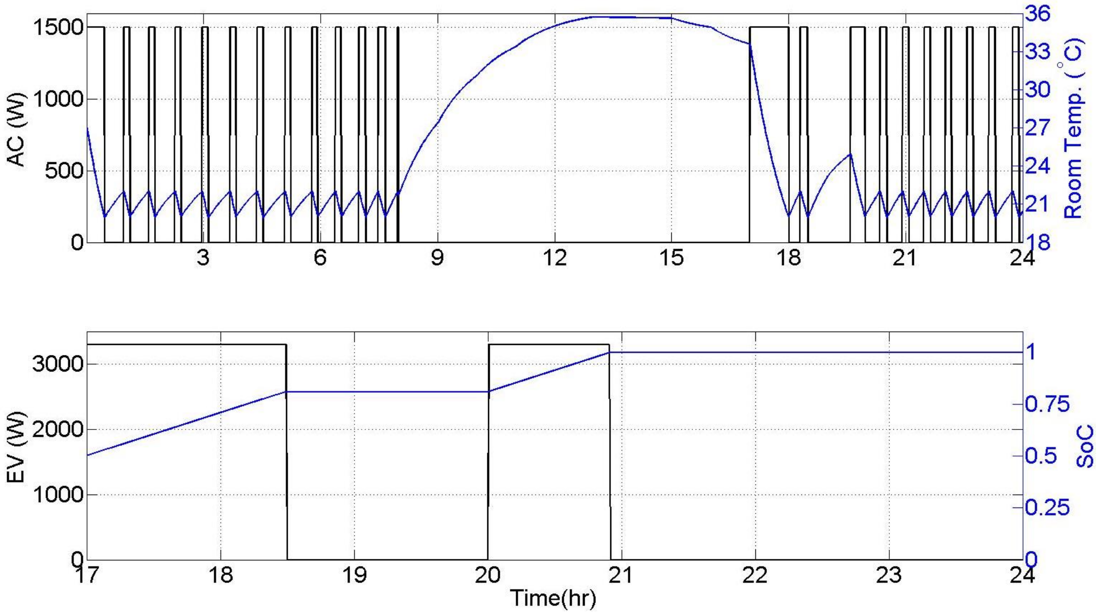

Fig. 5.6. The power consumption of the EV and the AC in DD_2.

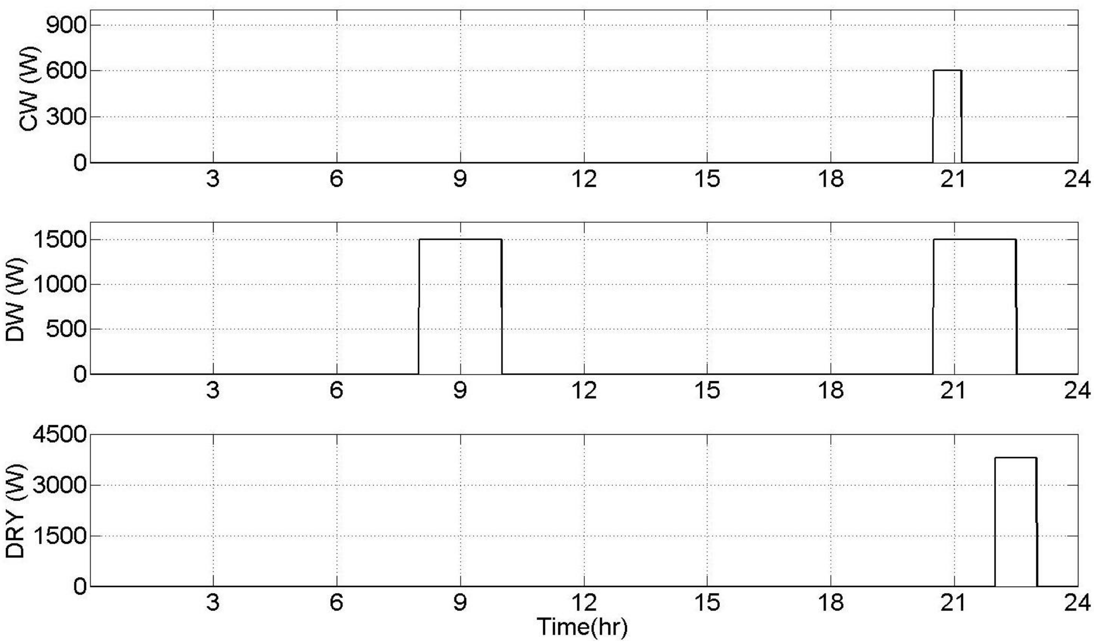

Fig. 5.7. The power consumption of CW, DW, and DRY in DD_2.

As illustrated in Figs. 5.4, the overall power consumption of the house dropped below the demand limit. At 17:30 hrs, the DD has been issued. Then, according to the DD schedule, first the battery is discharged until it reaches the minimum SoC. Afterwards, at 18:30 hrs, the EV's charging process needs to be interrupted. Also, the AC's set point is increased and the tasks of the CW and DRY are postponed for 2 hours to finish their tasks before 23:00 hrs. At 19:00 hrs, the only available appliance is EV. So, at 19:00 hrs the EV's charging process is interrupted again. At 19:30 hrs, the only available appliances are DW, AC, and EV and the power consumption is much higher than the demand limit, all of them participate in DD. However, the EV's charging process has been interrupted for more than 100 minutes which has led the EV's satisfaction to drop to zero. Then, finally, at 20:30 hrs the DD schedule is ended. WH, FR, and PP did not participate in DD as shown in Fig. 5.8.

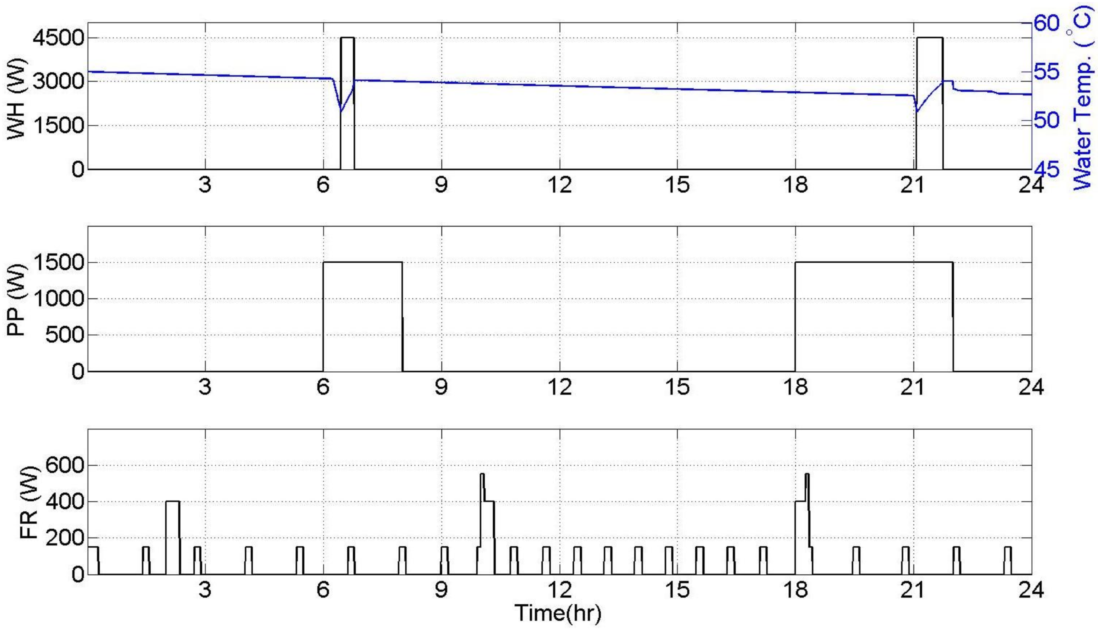

Fig. 5.8. The power consumption of WH, FR, and PP which did not participate in in DD_2.

The OSC factor, CLPU factor, and LF of the smart house are listed in Table 5.4. As can be seen from Table 5.4, the OSC Factor is around 0.8436 which is a bit low as the EV's charging process has been postponed for more than 100 minutes. However, CLPU has decreased significantly to 0.7733 in compare to the semi smart home without PV and battery system. On the other hand, the LF has decreased to 0.6929 in comparison to the semi smart home, which is a drawback of this method.

Table 5.4: The OSC factor, CLPU factor, and LF of the smart house in DD_2.

Parameters	Value
OSC Factor	0.8436
CLPU Factor	0.7733
LF	0.6929
DD participated Appliances	AC, EV, CW, DW , DRY
The Battery's SoC at the end of DD	%40

5.4. THE DD METHOD THREE (DD_3)

In this method, a smart home which is equipped with a PV system and a battery system has been considered. It should be noted that, the specifications of this smart home is similar to the one explained in section 5.3. Similar to DD_2, the battery is charged during the daylight time through the PV system. However, the battery system is discharged instead of the deferrable appliances in time DD event. Postponing task of the deferrable appliances is one of the major reasons of the cold load pick up occurrence. Thus, according to the DD schedule of this method, whenever the starting time of a deferrable appliance is required to be postponed, the battery system will be discharged instead of postponing the appliance. The DD algorithm which has been used in this method is shown in Fig. 5.9.

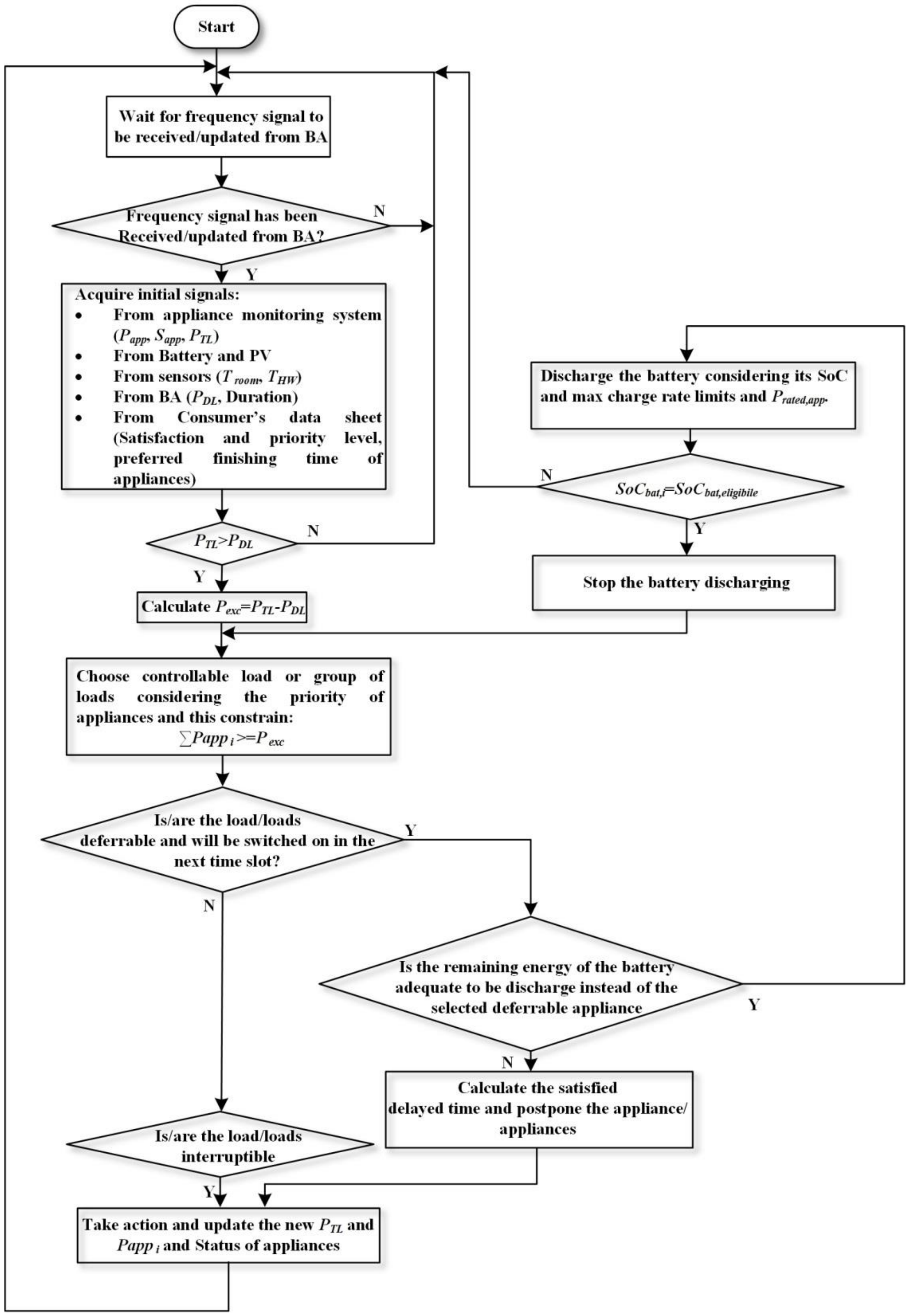

Fig. 5.9. The proposed algorithm in DD_3.

As mentioned above, the battery model used in this method is similar to the previous method except the discharge model. As shown in (5.12), the discharge power of the battery is equal to the rated power of the selected deferrable appliances as long as the rated power is less than $P_{bat,max}$ and SoC of the battery is more than the eligible SoC. If the required demand cut is greater than the $P_{bat,max}$ then the next available interruptible appliances needs to participate in DD along with discharging of the battery.

$$P_{bat,discharge,i} = \begin{cases} P_{rated,app} & \text{if } P_{rated,app} \le P_{bat,\max} \\ & \text{and } E_{req,app} \le E_{rem,bat,i} \\ & \text{and } SoC_{bat,eligible} \le SoC_{bat,i} < SoC_{bat,\max} \\ P_{bat,\max} & \text{if } P_{rated,app} > P_{bat,\max} \\ & \text{and } \left(P_{bat,\max} \times \Delta t_{app}\right) \le E_{rem,bat,i} \\ & \text{and } SoC_{bat,eligible} \le SoC_{bat,i} < SoC_{bat,\max} \\ 0 & \text{if } \left(P_{bat,\max} \times \Delta t_{app}\right) > E_{rem,bat,i} \\ & \text{or } SoC_{bat,i} < SoC_{bat,eligible} \end{cases} \tag{5.12}$$

where $P_{rated,app}$ is the rated power of the selected deferrable appliance (W), Δt_{app} is the time the appliance to finish its task in hr. $E_{req,app}$ is the required energy to run the selected appliance within the specific time (Whr), and $E_{rem,bat,i}$ is the remaining energy of the battery at time interval i in (Whr). The size and the specifications of the PV and the battery system are similar to the ones used in DD_2.

Fig. 5.10 shows the overall power consumption of the house and the PV generation. The negative amount of power means the extra power from the PV system is fed back to the grid.

Fig. 5.11 illustrates the battery discharge power and the SOC of the battery. Fig. 5.12 shows the power consumption of the EV and the AC. In Fig. 5.13, the power consumption of DW and DRY are illustrated. In Fig. 5.14 the power consumption of CW, PP, and FR are illustrated which were not postponed as the battery was discharged instead of them. WH did not participate in DD as shown in Fig. 5.15.

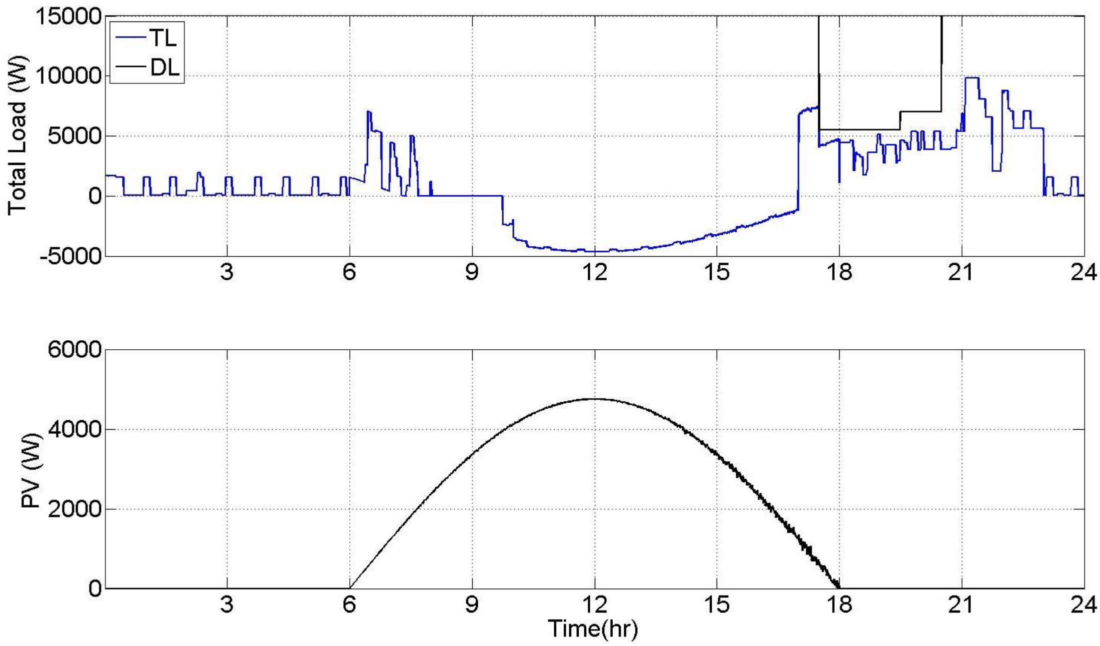

Fig. 5.10. The overall power consumption of the house and the PV generation in DD_3.

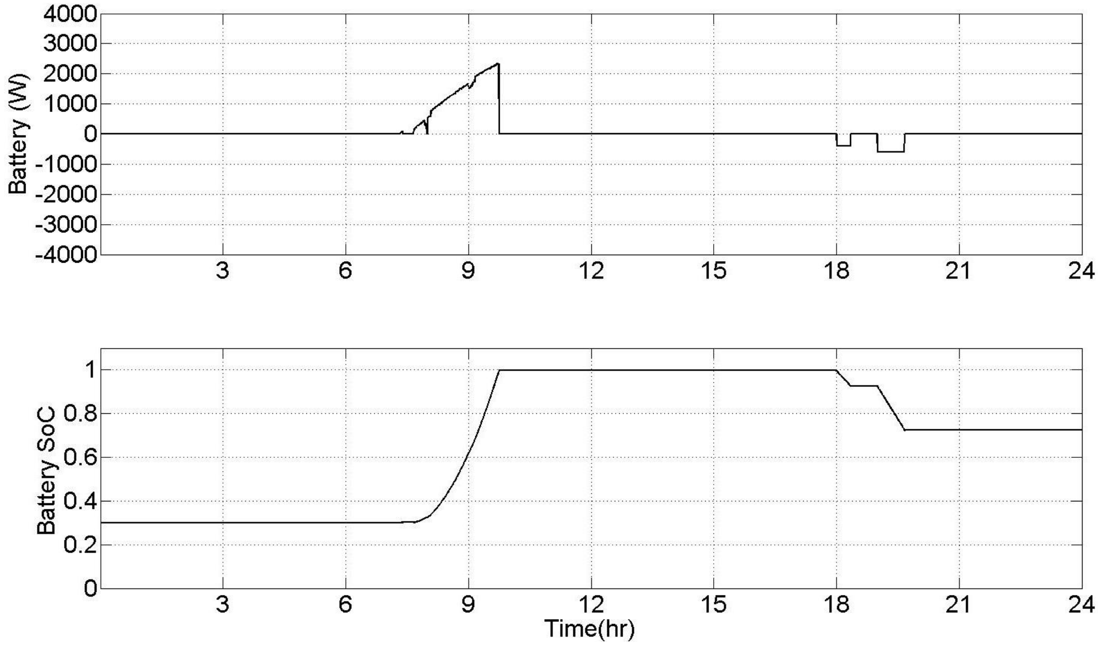

Fig. 5.11. The battery discharge power and the SOC of the battery in DD_3.

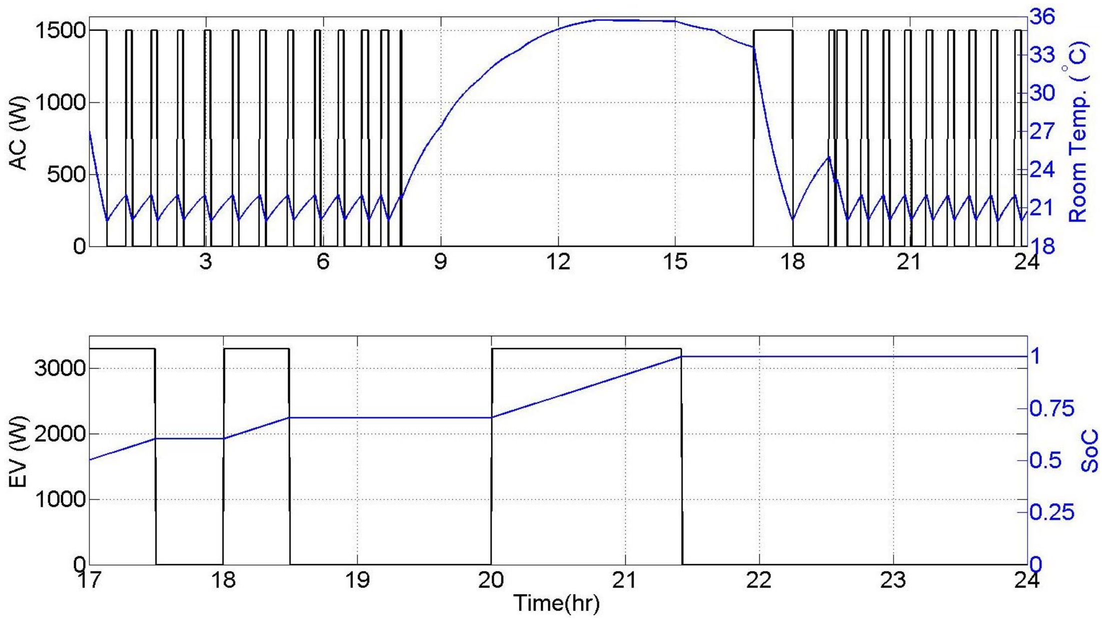

Fig. 5.12. The power consumption of the EV and the AC in DD_3.

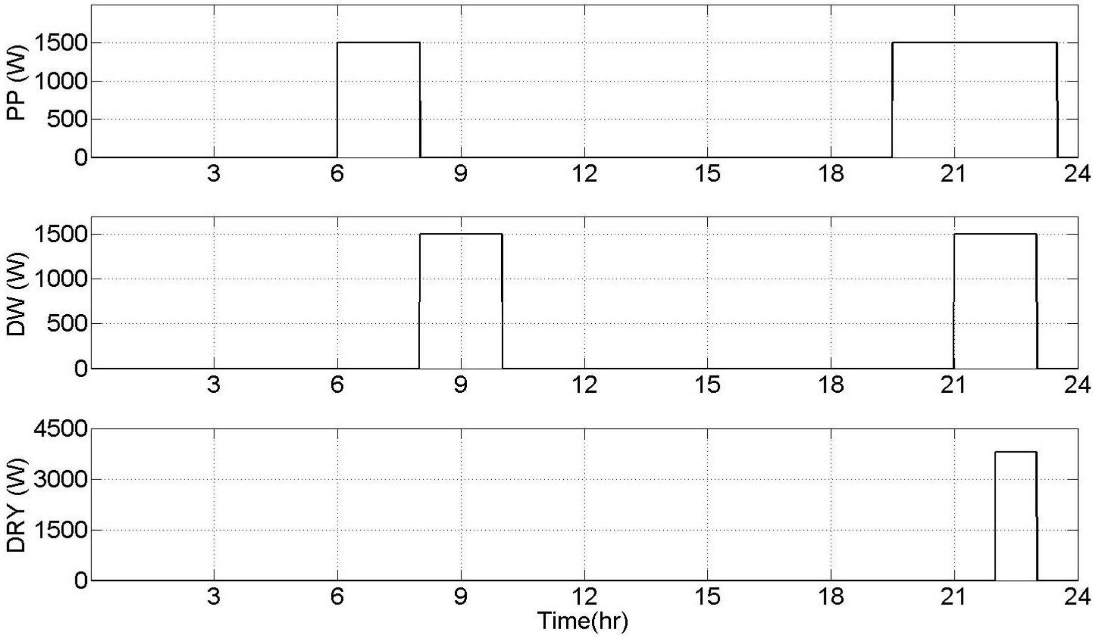

Fig. 5.13. The power consumption of DW, PP, and DRY in DD_3.

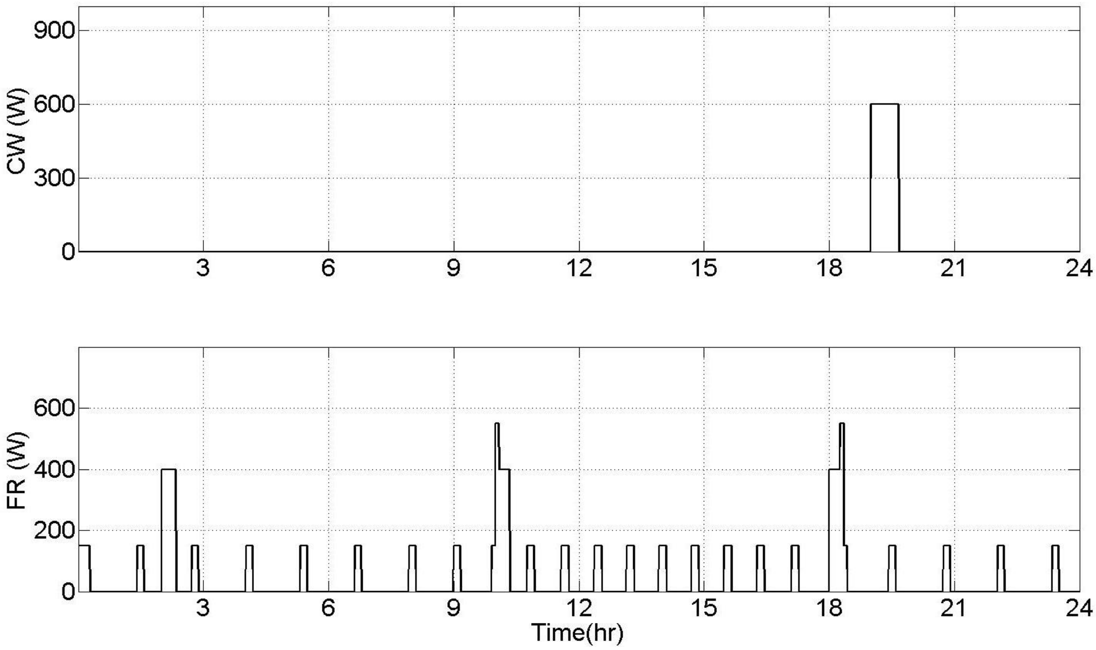

Fig. 5.14. The power consumption of CW, and FR (the battery was discharge instead of postponing them) in DD_3.

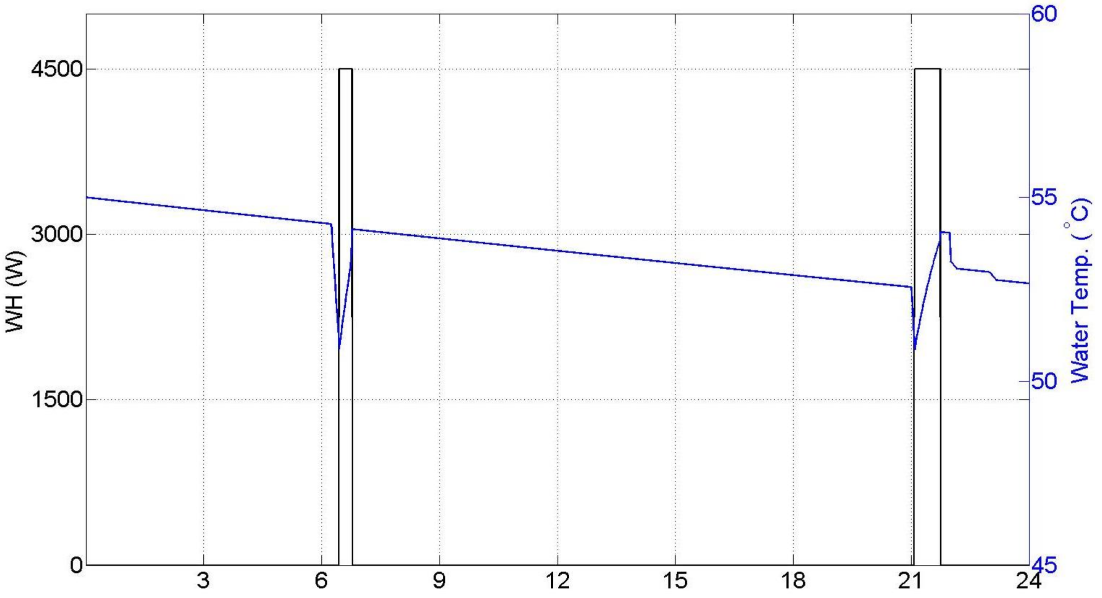

Fig. 5.15. The power consumption of WH which did not participated in DD_3.

As show in Fig. 5.10, the house power consumption has been kept below the demand limit with help of the proposed algorithm. At 17:30 hrs, the DD is issued. According to the proposed algorithm, EV has been chosen to be interrupted. So, EV's charging process is postponed for 30 minutes. Then, at 18:00 hrs FR and PP are required to be postponed but the battery is discharged instead of them. However, the battery remaining energy is not enough for PP. Thus, the battery will be discharged instead of the FR defrost cycle.

Afterwards, at around 18:20 hrs AC's set point is increased for 4˚C. Then, at 18:30 hrs the EV's charging process is interrupted. Afterwards, at 19:00 hrs, CW should be delayed but the battery is discharged instead. However, the rated power of the CW is lower than the demand limit cut. So, at 19:00 hrs, the EV is required to be interrupted. At 19:30 hrs, still the total load is greater than the demand limit. So, EV will be interrupted again which leads to a decrease in the EV's satisfaction as there are no other available controllable appliances at that time. At 19:30 hrs, DW is required to be postponed and the battery cannot be discharged instead because the remaining energy of the battery is not enough. At 20:00 hrs, DRY is postponed and the battery cannot be discharged instead because the remaining energy of the battery is not enough.

The OSC factor, CLPU factor, and LF of the semi smart house are shown in Table 5.5. According to Table 5.5, the OSC factor of this method is less than the one in DD_1 and equal to DD_2. So, in this term it does not show any improvement. On the other hand, the CLPU is better than DD_1 but worse than DD_2. Regarding the LF, it is better than DD_2 but worse than DD_1. However, the battery's final SoC at the end of the DD is around 0.724 which indicates that the battery's capacity has not been used fully. So, the drawback of this method is that the appliances get postponed or delayed Even though the battery has enough capacity.

Table 5.5: The OSC factor, CLPU factor, and LF of the smart house in DD_3.

Parameters	**Value**
OSC Factor	0.8436
CLPU Factor	0.919
LF	0.6191
DD participated Appliances	AC, EV, DW, PP, DRY
The Battery's SoC at the end of DD	0.724

5.5. DEMAND DISPATCH FOUR (DD_4)

In this DD schedule, similar to DD_2 and DD_3 the smart home has been considered with the same specifications. The charging process of the battery is similar to DD_2 and DD_3. However, the discharging scenario is different. In this DD schedule, the battery will be discharged instead of the appliances with high priority such as: WH, AC, CW, DW, and DRY. So, whenever according to the DD schedule, the above mentioned appliances are required to be interrupted or postponed, the battery will be discharged.

The DD algorithm which has been used in this DD schedule is shown in Fig. 5.16. The battery model used in this DD schedule is similar to the previous method. Also, the size and the specifications of the PV and the battery system are similar to the ones used in DD_2 and DD_3.

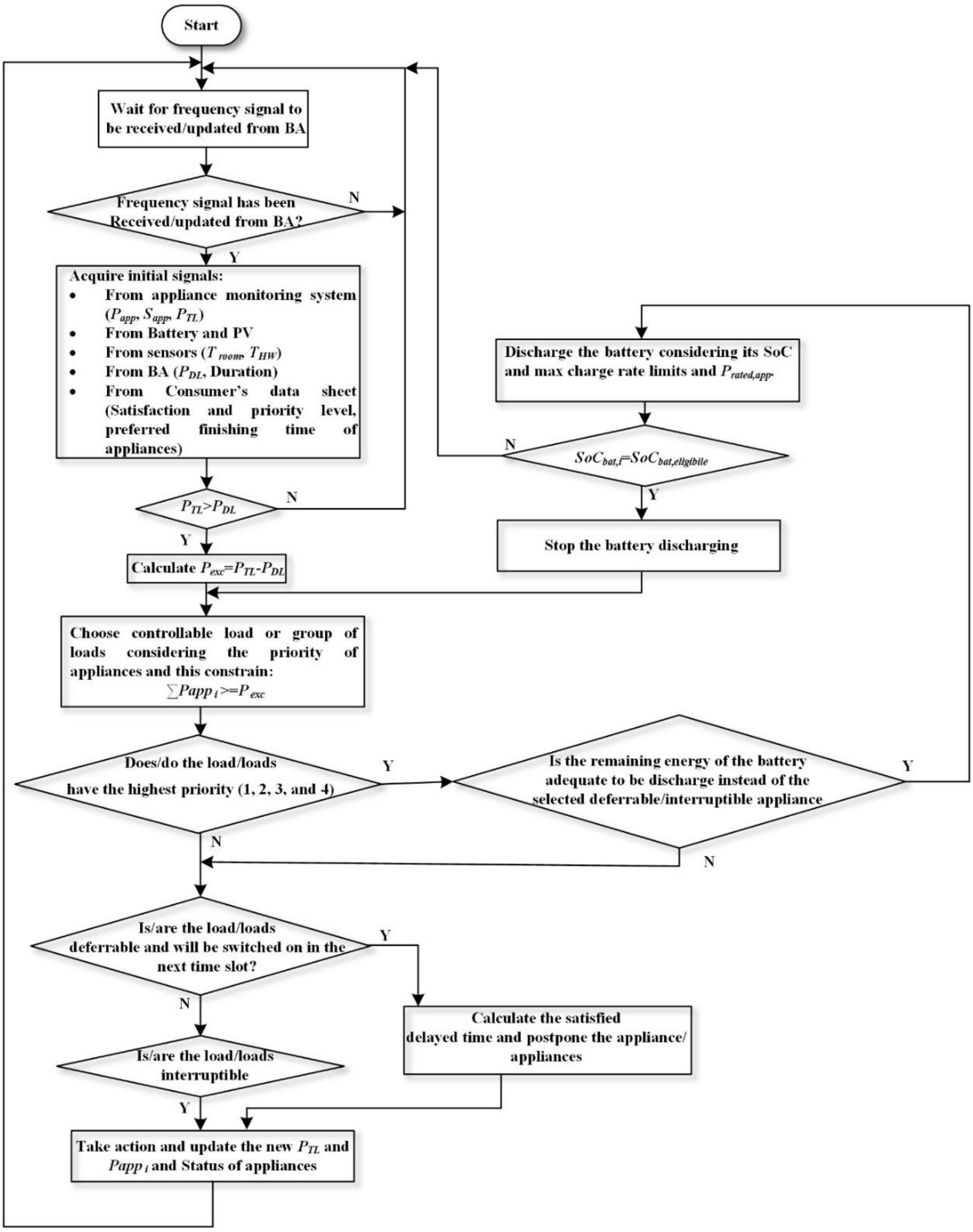

Fig. 5.16. The proposed algorithm in DD4.

Fig. 5.17 shows the overall power consumption of the house and the PV generation. Similar to previous DD schedules, the negative amount of power means the extra power from the PV system is fed back to the grid.

Fig. 5.18 illustrates the battery discharge power and the SOC of the battery. Fig. 5.19 shows the power consumption of the EV and the AC. In Fig. 5.20 the power consumption of CW, DW, and DRY are illustrated. Fig. 5.21 shows the power consumption of FR and PP in DD_4.

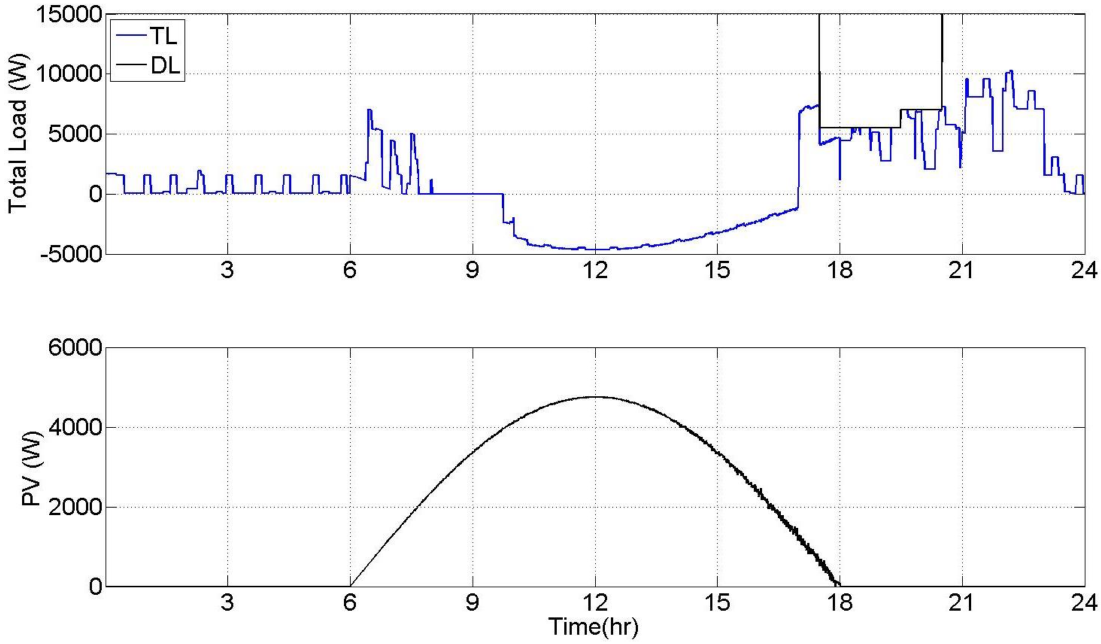

Fig. 5.17. The overall power consumption of the house and the PV generation in DD_4.

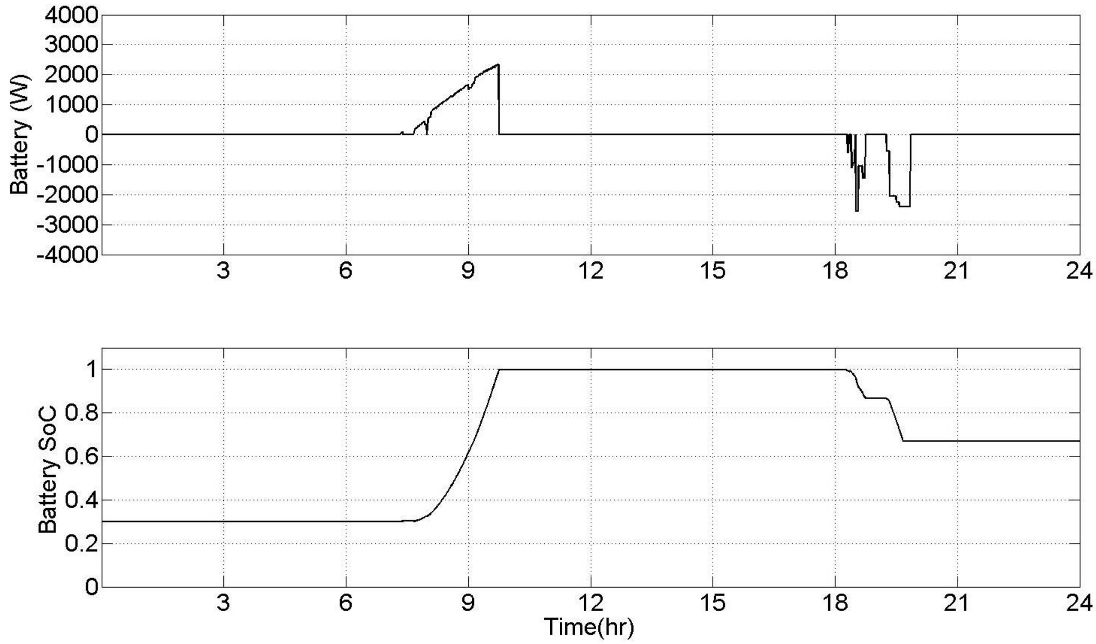

Fig. 5.18. The battery discharge power and the SOC of the battery in DD_4.

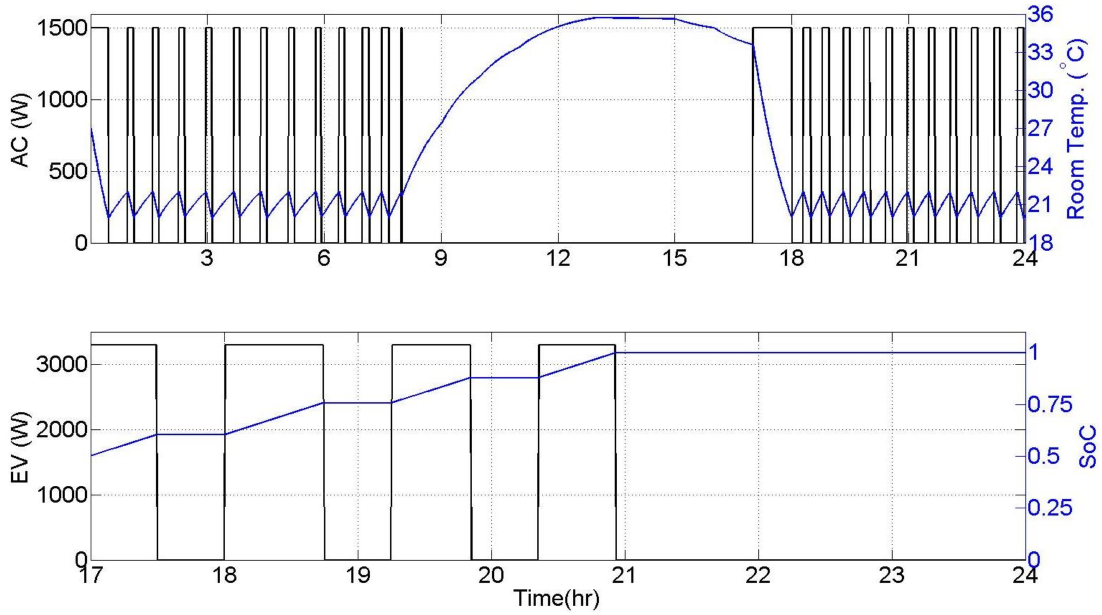

Fig. 5.19. The power consumption of the EV and the AC in DD_4.

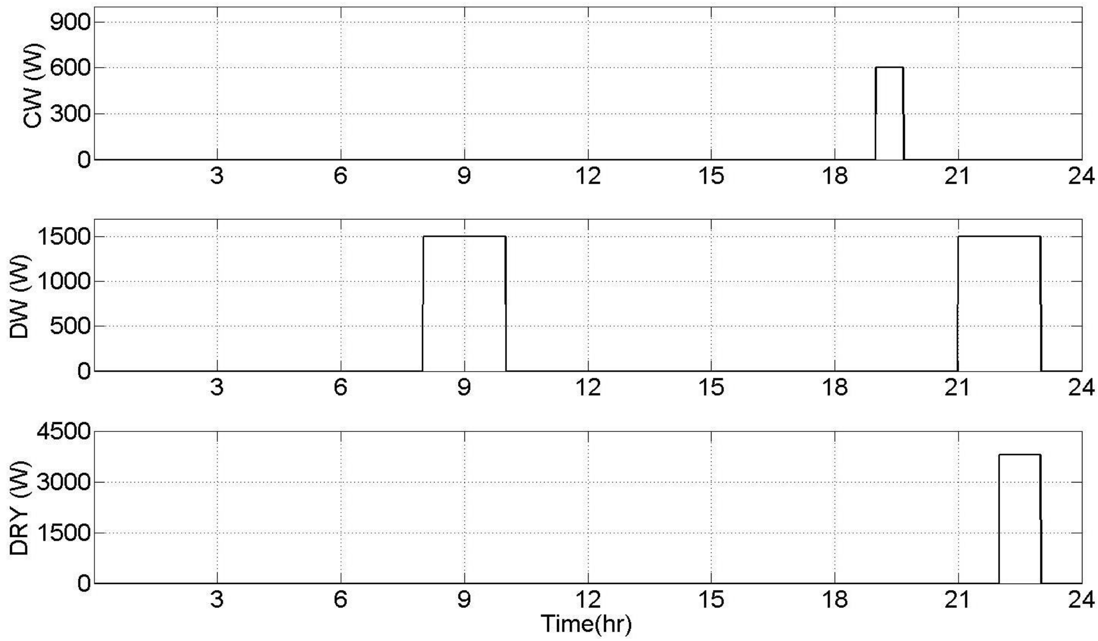

Fig. 5.20. The power consumption of CW, DW, and DRY in DD_4.

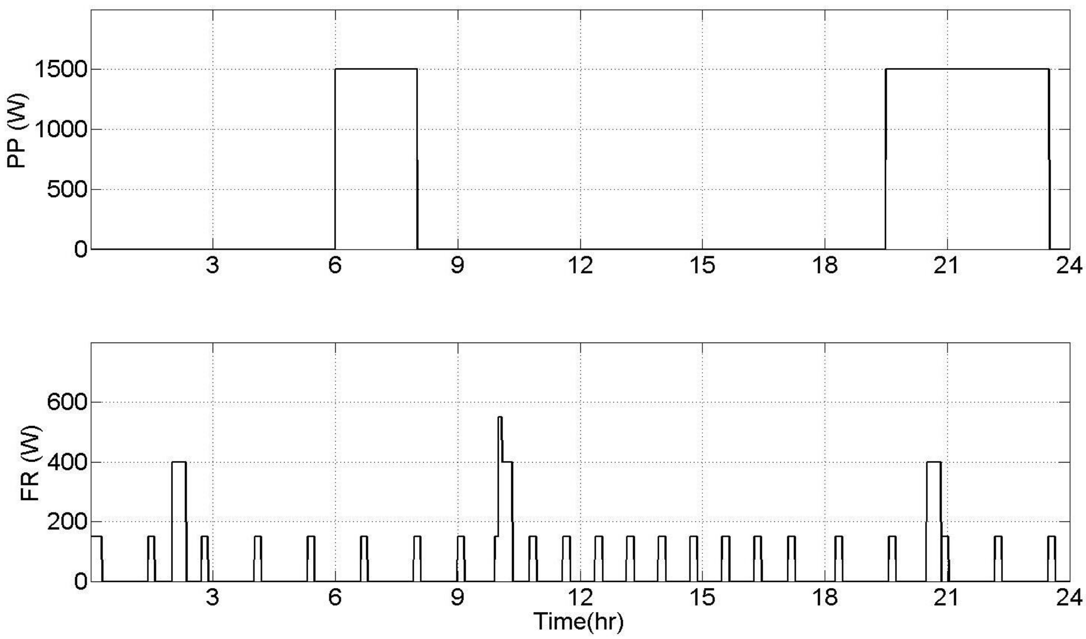

Fig. 5.21. The power consumption of FR and PP in DD_4.

As shown in Fig 5.17, the overall power consumption of the smart house has been kept below the demand limits.

At 17:30 hrs, the DD is issued. At this time, EV and AC are the only controllable appliances which are on. According to the priority, EV's charging process is interrupted for 30 minutes. Then, at 18:00 hrs, FR and PP are postponed as they have the least priorities. At around 18:20 hrs, AC is the only available appliances which can participate in DD schedule. However, according to DD_4, the battery is required to be postponed instead of the AC which is the second appliance in terms of high priority. At 18:45 hrs, the EV is the only available controllable appliance to be interrupted for 30 minutes. At around 19:30 hrs, the AC is required to be interrupted. However, the battery starts to discharge instead of the AC. But, this reduction in power is not enough. So, DW is required to be postponed. However, according to DD_4, the battery must be discharge instead. The required energy to finish the DW's task is greater than the remaining energy of the battery. Thus, DW is required to be postponed. At around

19:50 hrs, EV is interrupted. Afterwards, at 20:00 hrs, DRY is postponed as the battery reached its minimum SoC.

The OSC factor, CLPU factor, and LF of the smart house are shown in Table 5.6. As seen in Table 5.6, the OSC factor is equal to one which means the %100 costumers' satisfaction which is the best among other DD methods. Also, CLPU factor which is required to as less as possible is equal to 0.7733 which the best results among the other DD methods. On the other hand, LF is around 0.6352, which better than DD_3. However, DD_2 and DD_1 acted better in this regards. Moreover, the battery's SoC at the end of the DD is equal to 0.4 which means the battery has been utilised to its minimum SoC.

Table 5.6: The OSC factor, CLPU factor, and LF of the smart house in DD4.

Parameters	**Value**
OSC Factor	1
CLPU Factor	0.7733
LF	0.6352
Number of Appliances participate in DD	EV, FR, PP, DW, DRY
The Battery's SoC at the end of DD	0.4

5.6. CONCLUSION

In this chapter, four different DD method have been considered. The DD_1 method has been applied on a semi smart home and considered as the base method. The three other proposed DD methods have been compared to each other and to the semi smart home.

The CLPU factor in DD_2, DD_3, and DD_4 has improved significantly and dropped below one. It means, integration of the battery and PV system prevents the grid/house from the occurrence of CLPU. Moreover, the DD_4 method was much more successful in this regard.

In terms of load flattening, the DD_4 method was the most successful method. However, DD_1 and DD_2 do not show any improvement in comparison to DD_1.

Similar to LF, the OCS factor has reached to one in DD_4 method. However, it has not improved in DD_1 and DD_2.

Altogether, DD_4 reached the best results as the battery has been replaced for the appliances with the highest priorities. This led to the 100% CLPU factor. In addition, as this group of controllable appliances were among the both combination of interruptible and deferrable appliances, the battery has been utilised in the best possible way.

CHAPTER 6

A COST COMPARISON BETWEEN CONVENTIONAL FOSIL FUEL GENERATORS AND DEMAND DISPATCH FOR PROVIDING SPINNING RESERVE

As the electricity demand changes continuously, maintaining the frequency of the power system has been an ongoing challenge for the power utilities. Frequency Control Ancillary Services (FCAS) is defined by National Electricity Market (NEM) as a set of services, which maintain the frequency of the power system at 50 Hz [83-85]. The mismatch between electricity demand and generation causes deviations in frequency of the power system. The deviations beyond the range of 47 and 52 Hz can lead to power system collapse. There are two types of FCAS to prevent network blackouts [83-85]:

1) Contingency Service:

   a) Primary control:

      i. Fast frequency control, which must act in 6 seconds; generally it is the generators inertial response to the frequency deviations and can be used to either lower the generation or raise the generation [83-85].

      ii. Slow frequency control, which must act in 60 seconds; it is the governor’s response to the frequency deviations and can be for either lowering the generation or raising the generation [83-85].

   b) Secondary control:

It is the delayed response to frequency changes and it must act within 5 minutes such as Automatic generation control (AGC). Similar to the other frequency controls, it can either lower the generation or raise the generation[83-85].

2) Regulation Service:

It must act within (5-15) minutes. The rise in generation is called spinning reserve and lowering generation is called load rejection [83-85].

Usually a group of fossil fuel generators are responsible for providing this spinning reserve service during occurrence of the peak loads. However, the cost of procurement, maintenance, and control of the extra generation is not always reasonable as the peak loads happen in a few days a year. Renewable energy sources can also be considered to provide spinning reserve. However, such sources of energy are usually intermittent, while a spinning reserve source must be highly reliable and available when required. Therefore, these intermittent sources of energy must be combined with storage devices to increase their reliability if to be used to provide the ancillary services. However, integration of the large scale renewable energy resources with the storage devices can be expensive [83-85].

In this chapter, the capability of the proposed DD in providing the spinning reserve has been explored. In addition, the estimated cost of running a fossil fuel generator, which provides the spinning reserve, has been compared to the cost of providing the same service exploiting DD as a readily available spinning reserve.

6.1. DD CAPABILITY IN PROVIDING SPINNING RESERVE

The capability of the DD in providing spinning reserve is equivalent to the load power reduction, which is achieved by the DD. This load reduction can provide a comparable amount of spinning reserve as can be achieved by increasing the generation of a conventional spinning reserve source. Therefore, when DD reduces the network load it has the same effect on the power system as increasing the generation has.

To investigate the capability of the proposed DD in providing spinning reserve, a power system network with an aggregation of 300 houses with 66% penetration of EVs has been considered. The power consumption pattern of the aggregation of these 300 houses, when DD is not utilised, is shown in Fig. 6.1.

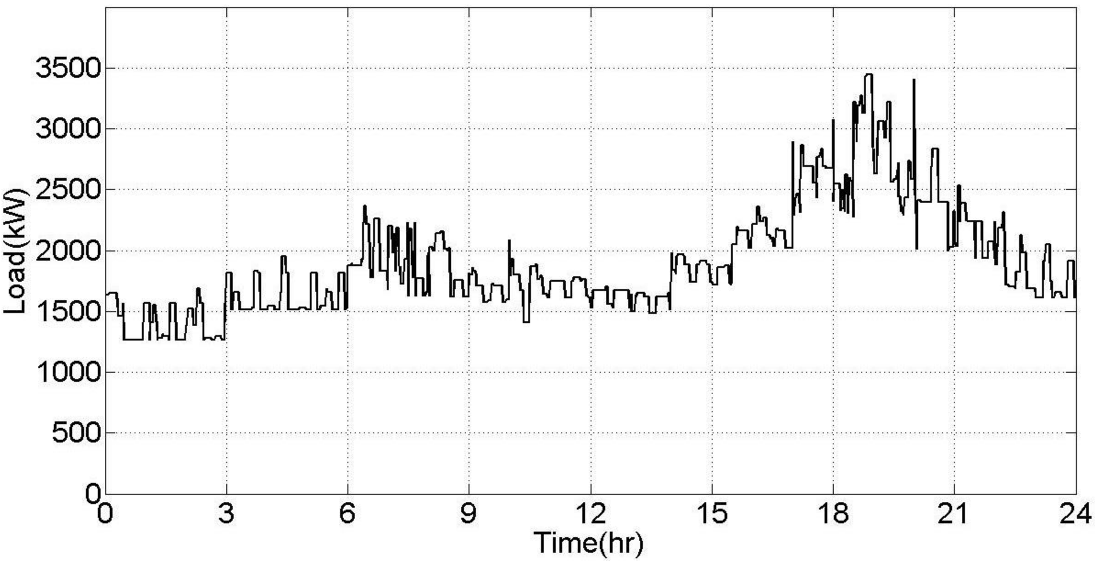

Fig. 6.1. Power consumption pattern of aggregation of the 300 houses.

As sown in Fig. 6.1, the power consumption pattern has the peak value of around 3.5MW. A generator capable of supplying a maximum of 2.5MW supplies this group of houses to support a base load of 2MW in normal operating conditions.

Therefore, when the demand increases beyond 2.5MW, frequency drop occurs as shown in Fig. 6.2. To bring the frequency back to its rated value, around 1MW spinning reserve is required. This spinning reserve can be provided though fossil fuel generators or reduction in power consumption by DD.

According to the DD schedule, the frequency drop forces the BA to issue the DD signals during the peak time. As per the proposed DD schedule outlined in Chapter 4, to bring the frequency within the acceptable range, the power consumption of the aggregated load must be reduced through issuing DD signals to the houses. The acceptable frequency range for providing the spinning reserve has been considered to be within the range of 49.1 and 50.1 Hz. The power consumption of the aggregated load and the frequency of the power system network during peak time after applying DD schedule are illustrated in Fig. 6.3 and 6.4 respectively.

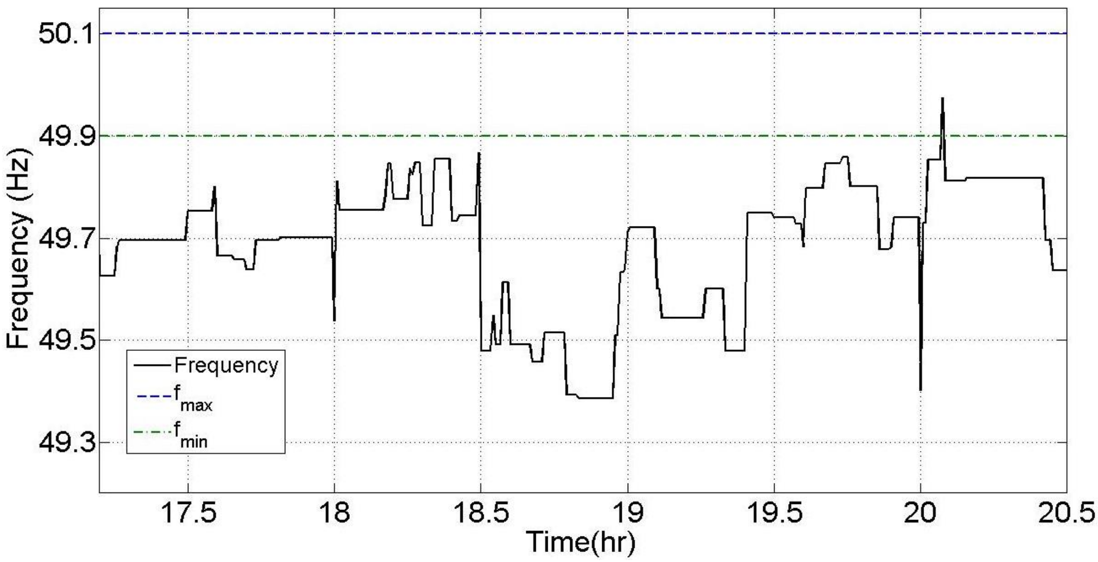

Fig. 6.2. Frequency drop during peak time.

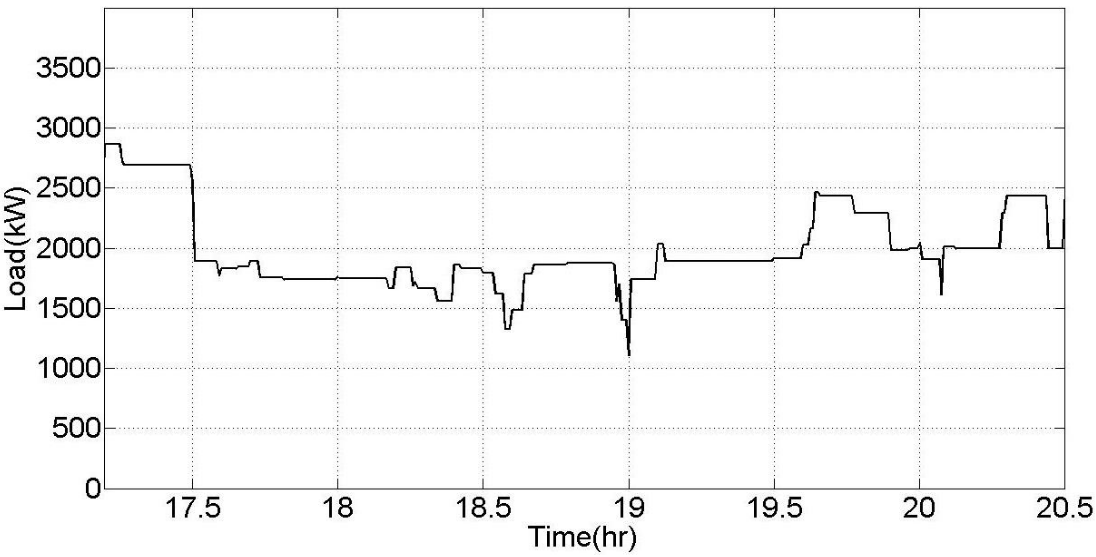

Fig. 6.3. The power consumption of the aggregated load after applying the DD schedule.

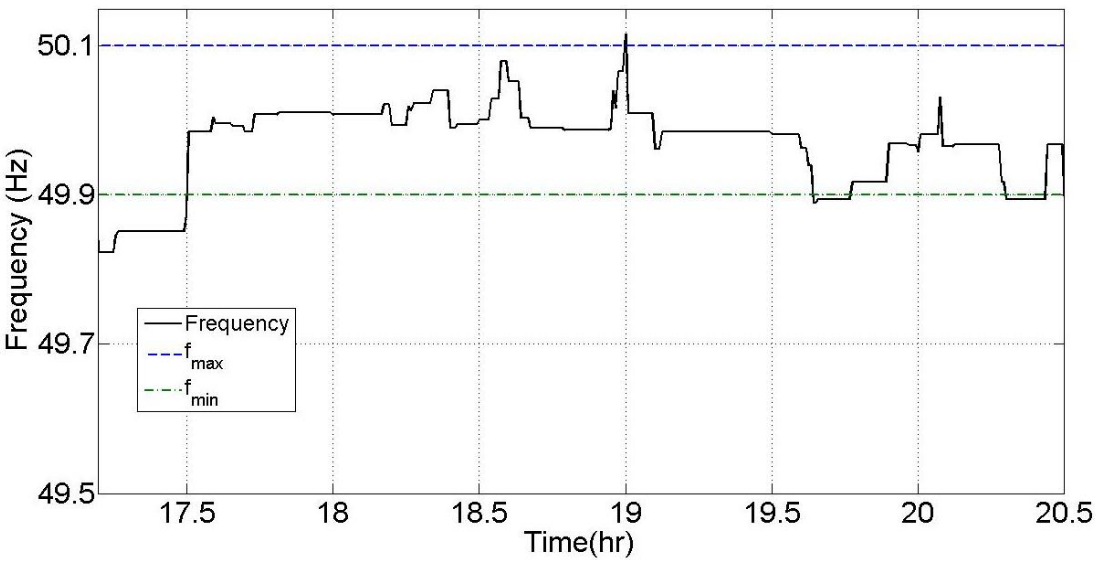

Fig. 6.4. Maintaining the Frequency of the power system during the peak time.

As shown in Figs. 6.1 and 6.3, the peak demand before and after applying the DD are 3447 kW and 2552 kW respectively, which indicates an 895 kW reduction in peak value. The total energy consumption reduction provided by the aggregated load during the peak time, i.e. 17:30 to 20:30, is around 2436 kWh. These results have been tabulated in table 6.1.

Table 6.1: Demand Comparison before and after applying the DD.

Parameter	**Value**	**Unit**
Peak value before applying DD	3447	(kW)
Peak value after applying DD	2552	(kW)
Peak value reduction by applying DD	895	(kW)
Total energy consumption reduction provided during the peak time by applying DD	2436	(kWh)

The spinning reserve obtained through DD can be calculated through (6.1). This equation determines the power reduction achieved through applying the DD to the aggregated load.

$$SRC_i = \begin{cases} TL_{BDD,agg,i} - TL_{ADD,agg,i} & if \quad TL_{BDD,agg,i} > TL_{ADD,agg,i} \\ 0 \quad if \quad TL_{BDD,agg,i} \leq TL_{ADD,agg,i} \end{cases} \qquad (6.1)$$

where SRC_i is the spinning reserve capability of the proposed DD in time interval i (kW), $TL_{BDD,agg,i}$ is the total load of an aggregated load before applying DD in time interval i (kW), $TL_{ADD,agg,i}$ is the total load of an aggregated load after applying DD in time interval i (kW).

Fig. 6.5 illustrates the load demand reduction achieved through using the DD during the peak time. As shown in this figure, the maximum power consumption reduction, which is provided by the aggregated load, is around 1710 kW.

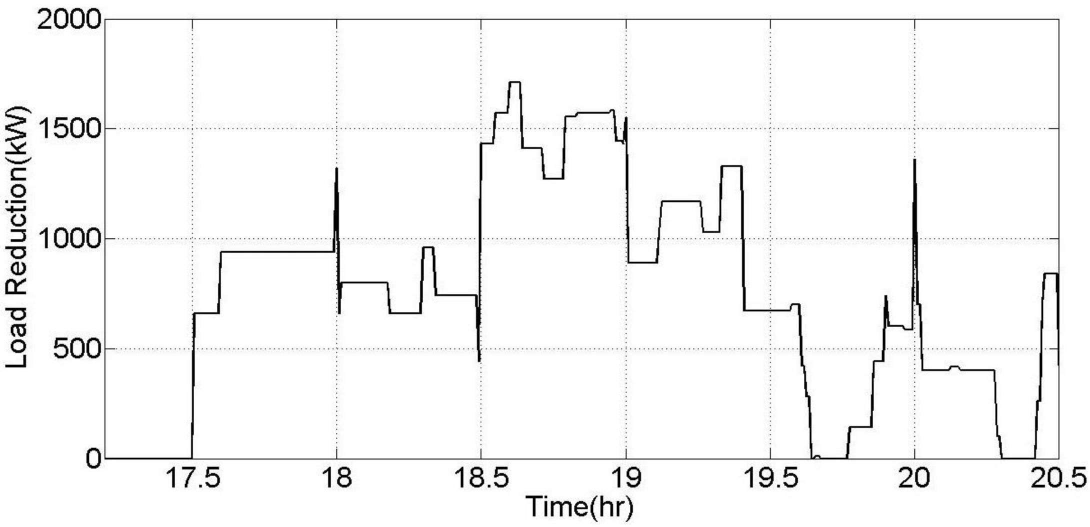

Fig. 6.5. The spinning reserve capability of the aggregated load during peak time.

6.2. COMPARISON OF THE COST OF THE SPINNING RESERVE THROUGH A FOSSIL FUEL GENERATOR AND THE PROPOSED DD

According to the load profile, around 1MW spinning reserve is required to support this power system during peak load periods. This spinning reserve is provided through fossil fuel generator operation. Typically, there are some higher capacity generators that in normal conditions operate on a lower operating point, enabling them to operate on a higher power output when required. The spinning reserve is either provided by such generators or by running an extra generator that operates exclusively for this purpose. The operating cost of this extra generation adds up to the total cost of the power system operation. However, in DD, since the reduction in load is determined based on the frequency droop control, this extra unused generation is not required which leads to a potential saving in operating cost of the power system.

In Subsection 6.2.1, the cost of electricity generation to provide the required 1MW spinning reserve through a fossil fuel generator, which includes the CO_2 emission cost has been calculated. Afterwards, the cost of providing a comparable spinning reserve through DD has been studied in Subsection 6.2.2. In Subsection 6.2.3, a comparison between these two methods of providing spinning reserve has been provided.

6.2.1. COST OF SPINNING RESERVE PROVIDED THROUGH FOSSIL FUEL GENERATOR

When a conventional fossil fuel generator is considered, the spinning reserve is provided by backing-off generation or running additional generators. The associated cost is determined by the availability cost which depends on the margin costs of the generator and the market clearing price [86].

The margin cost in percentage is defined as a fraction of the market determined balancing price which covers the costs associated with the revenue loss due to backing-off the generation and the generator efficiency loss due to operating on a less efficient point on the generator heat rate curve. In other words, if the margin cost is multiplied by the Balancing Price and the quantity of the provided spinning reserve, it provides the lost revenue figure [86].

Typically, the margin costs are different in the peak and off-peak intervals. The Australian Wholesale Electricity Market (WEM) Rules, define the interval between 8 AM and 10 PM as Peak and the interval between 10 PM and 8 AM as Off-Peak [87].

An estimation of the spinning reserve cost which the Network Operator has to pay the Service Provider on a monthly basis is presented in [88]. The payment is estimated using (6.2).

$$AP = \frac{1}{2} M \cdot BP \cdot \max\left[0, Q_{SR} - Q_{LFASR} - Q_{SRC}\right] \tag{6.2}$$

where AP is the availability payment in \$, M is the Margin Peak or Off-Peak depending on the trading interval in percentage, BP is the balancing price in \$/MWh, Q_{SR} is the spinning reserve quantity in MW, Q_{LFASR} is the load following ancillary service raise quantity in MW, and Q_{SRC} is the contracted spinning reserve ancillary service quantity in MW. The details of the parameters and the associated estimating techniques are available in [88].

Table 6.2, provides a summary of the results of the estimation presented in [88].

Table 6.2: Availability Cost Estimation [88].

Device\ Service	**Estimated Value**	**Unit**
Margin Peak	25	%
Margin Off-Peak	50	%
Peak Period Spinning Reserve Available (Annual Average)	224.1	MW
Off-Peak Period Spinning Reserve Available (Annual Average)	189.0	MW

Peak Period Annual Availability Cost	7.97	$m
Off-Peak Period Annual Availability Cost	5.09	$m
Total Annual Availability Cost	13.06	$m

As can be inferred from the abovementioned results, the yearly cost of every 1MW available spinning reserve during peak and off-peak periods is $35.6 k and $26.9 k respectively.

The analysis presented in Subsection 6.1 of this chapter, considers the scenario in which the spinning reserve is only required during peak time as per WEM's definition. Considering the peak period results in Table 6.2, and assuming the spinning reserve is only required for 13 days per year [89] and only for a duration of 2.436 hours each time (to make a reasonable comparison with respect to the results of Table 6.1), the cost of the spinning reserve would be 1123 $/MWh.

6.2.2. DD IMPLEMENTATION COST IN A RESIDENTIAL NETWORK CONSISTING OF 300 HOUSES

There is a three-phase feeder's level aggregator in the power network shown in Fig. 6.6. Ten lower level aggregators are connected to each phase and ten houses are connected to each lower level aggregator. So, all together, an aggregation of 300 houses with 66% EV penetration has been considered. It is assumed, all these houses are committed to participate in the DD response through the official contracts signed up with the BA. In return, a DD rebate rate has been considered as an incentive for the householders' contribution. The DD rebate rate scheme can be adjusted by the BA based on the market price of the spinning reserve and the Return on Investment (ROI) rate of the DD infrastructure. Moreover, the rebate can be defined to be applicable per event, or per event duration, or per kWh potentially not used, or a similar scheme. In this study, it is assumed the BA gives the customer a credit back per kWh not used during the event. Moreover, as each household's AMU should communicate to the designated aggregator, the BA can also cover a portion of the AMU cost for the customers as a part of the incentive scheme.

As the purpose of this study is to evaluate the feasibility and the cost implication of implementing DD as spinning reserve source for the network operator, it is assumed all the DD participating houses are equipped with smart appliances. The smart appliances have built-in features, which enable them to communicate with AMU device. In addition, the built-in features of the controllable appliances consist of a relay circuit, which enables the controllable appliances such as PP, EV, DW, DRY, and CW to be switched on/off in time of receiving the DD signal [90]. There is a built-in smart thermostat for the other controllable appliances such as WH, AC, and FR, which are required to be controlled through temperature set points [90].

The AMUs must be able to establish a bidirectional communication with the Aggregators. There are different communication protocols. However, in this study, the wireless cellular 4G technology is considered, as it is widely available, reliable, and more cost effective compared to the other communication technologies [90, 91]. The AMU device can be a microcontroller or a single board PC with a number of I/O terminals enabling it to control the smart appliances [92, 93]. As the AMU receives the DD signals from the aggregator to control the appliances, the process is fully automated and the customers do not need to actively interact with the AMU.

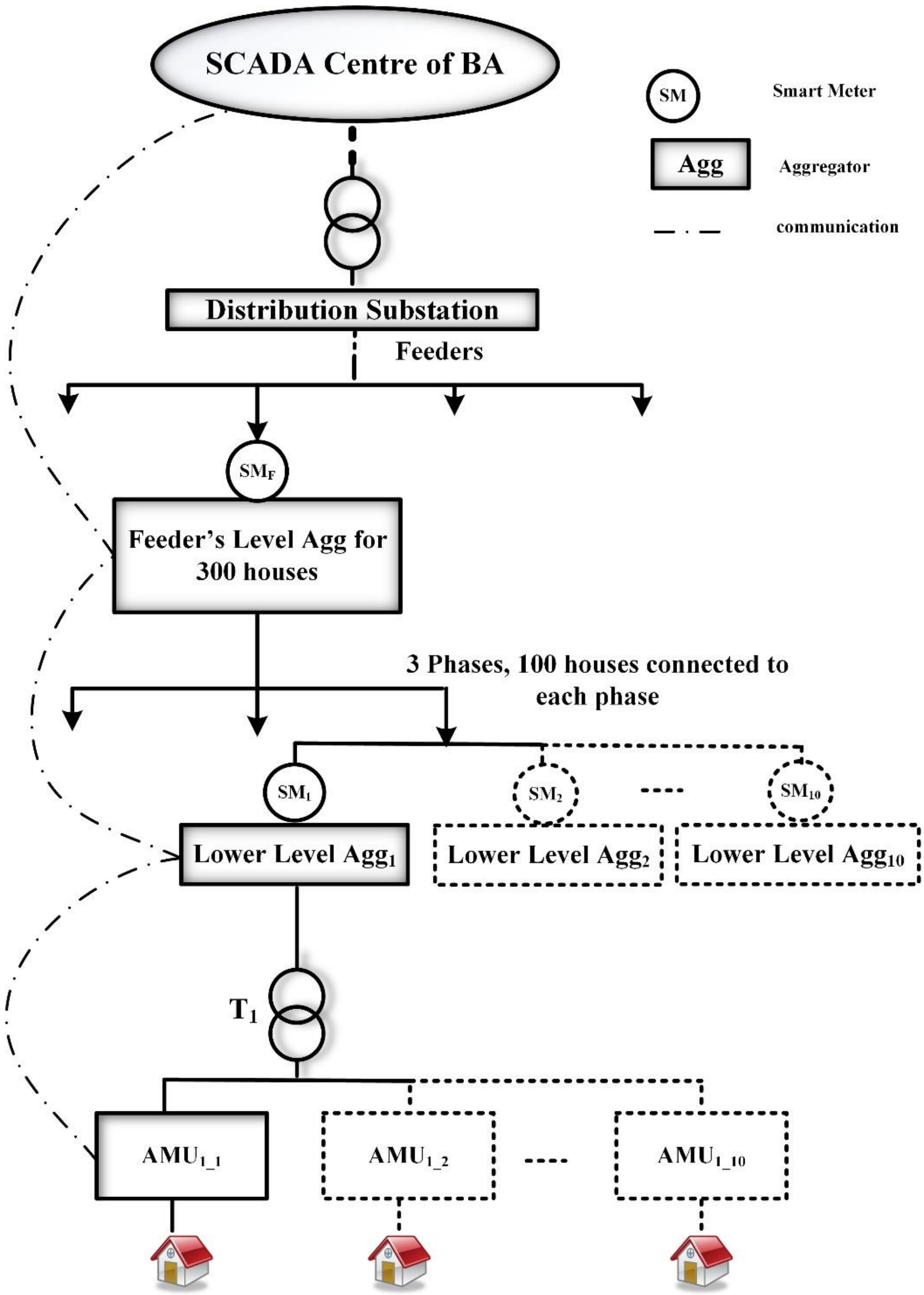

Fig. 6.6. The communication path between the AMUs, the aggregators, and the BA.

It is assumed that the aggregators are programmable equipment capable of communicating with the BA and the AMUs to receive/send the DD signals and the power consumption data [94, 95].

The BA can add the additional features related to the DD to their existing SCADA system. This system can be utilised to perform the required calculations and send/receive the DD signals to/from the aggregators. Therefore, the extra cost incurred by the BA at this level is predominantly the software and programming costs.

Aside from the hardware and software expenses, the labour cost of installing the equipment, programming the devices, and performing the associated commissioning tests are considered in this study. Table 6.3 provides a summary of the costs associated with the DD implementation.

Table 6.3: Estimation of the cost of DD implementation from network operator point of view.

Device \ Service	**Cost Category**	**Unit Cost**	**Quantity**	**Up-front Cost Estimation(AUD)**	**Yearly Cost (AUD)**
Aggregator and Smart Meter	Up front cost	6000 AUD [96] [94] [97] [95]	31 Sets	186000	N/A
Incentives to Costumer - Payback	Continuous cost	0.5 AUD/kWh	300 Houses	N/A	15834

Incentives to Costumer – AMU Cost Share	Up front cost	200 AUD [92] [93]	300 Houses	60000	N/A
Installation, Programming, and Commissioning Labour Cost	Up front cost	100 AUD	1440 Man Hours (12 Weeks, 3 People)	144000	N/A
Database Setup / SCADA Integration	Up front cost	100 AUD	200 Man Hours	20000	N/A

The overall DD cost is calculated over the lifetime of 30 years. The 30-year period has been considered as it is usually the case for financial analysis of the power generating units. DD cost is calculated through (6.3).

$$DDC = DDC_{upf} + DDC_{con} \tag{6.3}$$

where DDC is DD cost in \$/MWh, DDC_{upf} is the levelized up-front cost of DD implementation, and DDC_{con} is the continuous cost of DD implementation.

DDC_{upf} is calculated through (6.4) over a lifetime of 30 years.

$$DDC_{upf} = \frac{\text{Sum of the Up-Front Costs Over 30 Years}}{\text{Sum of the Reduced Electricity by DD over 30 Years}} \tag{6.4}$$

The peak demand events happen normally 13 days per year [89]. Considering the energy reduced through DD shown in Table 6.1, the DDC_{upf} is approximately 431.6 \$/MWh.

DDC_{con} is calculated through (6.5).

$$DDC_{con} = \frac{\text{Yearly Sum of Continuous Costs}}{\text{Yearly Sum of the Reduced Electricity}} \qquad (6.5)$$

Considering (6.5) and Table 6.3, DDC_{con} is equal to 17.8 \$/MWh. Thus, the *DDC* which is the sum of continuous and up-front costs of power consumption reduction through DD schedule is approximately 449.4 \$/MWh.

6.2.3. COMPARISON OF THE COST OF RESERVED PROVIDED THROUGH CONVENTIONAL AND DD SCHEDULE

As described in Subsections 6.2.1 and 6.2.2, the approximate cost of providing 1MW spinning reserve through a conventional generation method and providing the same spinning reserve through consumption reduction by DD is 1123 and 449.4 \$/MWh respectively.

Apparently, the implementation of the DD to provide spinning reserve is more cost effective than the conventional method. The main reason is, in traditional method, the normal operating point of the generators are deliberately lowered in order to maintain enough margin. This approach, however, is not cost effective as the generator is over-sized and runs on a less efficient operating point. The spinning reserve might also be provided by running an extra standby generator. The normally unused margin or the extra generator will only be utilised for a limited period of time during the peak demand and thus is not an economically efficient option. The main costs associated with the DD are upfront expenses which means once it has been set up, it can be utilized with comparatively very low ongoing fees. Table 6.4 provides a summary of the cost of these two methods.

Table 6.4: Cost comparison of the two methods of providing spinning reserve.

Spinning Reserve Source	**Cost ($/MWh)**	**Total Yearly Cost for the Power Network under Study ($k)**
Conventional Fossil Fuel Generator	1123	35.6
DD	449.4	14.23

6.3. CONCLUSION

In this chapter, the approximate implementation cost of two methods of providing spinning reserve have been investigated. According to the results, compared to the conventional fossil fuel based spinning reserve generation, the implementation of the DD method is much more economical. The cost of the spinning reserve provided by the DD mainly consists of some upfront equipment and software expenses. However, the ongoing costs are very low compared to the traditional spinning reserve sources. Moreover, the DD method has the advantage of being environmental friendly as its carbon emission is close to zero.

It should also be noted that, the studies of this chapter consider a test power network of around 3MW, which can be deemed to be a portion of a larger power system. The scope of this study is assumed to be limited to providing a general purpose, simplified procedure and exploring the feasibility and presenting high level cost comparison. The proposed analysis can be used as a general guide to estimate the cost and saving of implementing DD in larger scales.

CHAPTER 7

CONCLUSIONS

The general conclusions and scope for further research work are presented in this chapter.

7.1. GENERAL CONCLUSION

From the finding of the previous chapters, the following general conclusions are drawn.

1) According to DD, loads change according to the generation to keep the demand and supply balanced. The results show that the DD control strategy is capable of tuning aggregated demand-supply mismatch. Consequently, the frequency is kept stable by changing the power set points of dispatchable loads according to the generations' changes based on implementation of droop control on the load side. Only the dispatchable loads participate in DD schedule, while the supply to the non-dispatchable loads are not interrupted.
2) As home appliances play significant role in DD implementation, dynamic model of a wide variety of deferrable and interruptible appliances are studied and utilised in the proposed DD algorithm. It has been observed from the simulation results, the proposed control algorithm for the AMU maintains the total power consumption of a house below the limit issued from BA during a DD event. Since, the focus of the proposed DD is on the residential loads, the AMU algorithm must consider the priority and satisfaction of the householders to defer or interrupt the appliances.

3) The proposed DSFD in the feeder level aggregator calculates the required reduction in power consumption by sensing the frequency deviations. This power consumption limit is issued to the lower level aggregators according to this aggregator specifications and then to the AMU system in each house. Afterwards, the AMU algorithm alters the power consumption of the house accordingly by sending the commands in the form of deferral or interruptible signals to various appliances. The case study results confirm the suitability of the proposed approach.

4) The proposed combination of battery, PV, and DD in individual houses is analysed by introducing three factors: CLPU, LF, and OCS. Four different DD methods are compared to each other based on these factors.

   It is observed from the results, integration of the battery and PV system prevents the grid/house from the occurrence of CLPU. In addition, it can flatten the load profile and increase the customers' satisfaction.

   Moreover, it is found when the battery is replaced by appliances with highest priority the CLPU factor is improved significantly and battery is utilised in the best possible way.

5) The approximate cost of two methods of providing spinning reserve, 1) the conventional method through fossil fuel generator 2) the DD method, are studied. According to the results, the implementation of the DD method is more cost effective than the conventional method. Moreover, the DD method is eco-friendly and its carbon emission is zero. Besides, the DD can provide a much faster spinning reserve than conventional spinning reserve generators.

7.2. RECOMMENDATIONS FOR FUTURE WORK

The following suggestions are recommended in the area of demand dispatch.

1) Voltage dependency consideration along with the frequency droop to calculate the required reduction in power consumption.

2) Investigate the possibility of integration of bulk PV-battery system to the aggregator and compare its functionality vis-à-vis to the individual PV-battery system installed in each house.

3) Considering different incentive-based credits to costumers to motivate more customers to participate in DD while reducing the utility cost.

4) Investigate the more accurate dynamic models of the appliances to participate in DD.

5) Integration of other renewable resources into the DD schedule such as wind energy and improve the uncertainty of wind energy through DD schedule.

6) Investigate the impact of penetration of storage devices in residential power system on DD.

7) Coordination of distribution and transmission network operations by means of transaction-based DD to improve power system balancing.

8) Investigate the impact of combination of storage devices, renewable resources, and DD on power system market services other than spinning reserve.

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