Load Optimization Within Residential Microgrid With Focus On Demand Response

By

Farah Akram

00000118483

Supervisor

Capt. Dr. Sajjad Haider Zaidi - PN

A dissertation submitted to

Pakistan Navy Engineering College

National University of Sciences and Technology (NUST), Islamabad

A thesis submitted in partial fulfillment of requirements for the degree of

Master of Science (MS) in Electrical (Communication) Engineering

December , 2018

Load Optimization Within Residential Microgrid With Focus On Demand Response

By

Farah Akram

0000118483

Supervisor

Capt. Dr. Sajjad Haider Zaidi - PN

G.E.C Committe

Capt. Dr. Attaullah Memon - PN

Dr. Lubna Moin

A thesis submitted in partial fulfillment of requirements for the degree of

Master of Science (MS)

in Electrical (Communication) Engineering

Department of Electronics and Power Engineering

Pakistan Navy Engineering College(PNEC)

National University of Sciences and Technology (NUST), Islamabad

December, 2018

Declaration

I, *Farah Akram* declare that thesis titled **"Load Optimization Within Residential Microgrid With Focus On Demand Response"** also, the work introduced are my own particular and has been created by me accordingly my own unique research.

I endorse that:

1. This work was carried completely or mostly while in candidature for a Master of Science degree at NUST
2. Where any portion of this thesis has not been submitted before for a degree or some other capability at NUST or some other institute, this has been clearly expressed
3. Where ever I have consulted the published work of others, this is always clearly referenced
4. Where ever work of others been used as a reference, the source is always quoted. With the exemption of such quotations, this dissertation is solely my own work
5. I have acknowledged all major sources of database used for current research work

Farah Akram

00000118483

Copyright Notice

This thesis is dedicated to *my beloved parents and siblings*

Abstract

In conventional power supply system, peak demand of electricity occurs very frequently which might lead to such an increase that it exceeds the available capacity of supply. This causes the risk of power failure and a drastic increase in marginal cost of electricity. This continuous increase in the peak demand of electricity is substantially high in residential sector, thus it is being the topic of discussion everywhere. Hydrocarbon Development Institute of Pakistan, Energy Year Book 2014, states that residential sector contributes 47% in this increase in peak demand. According to international research, human behaviour in using the home appliances, attributes mainly in this increase in peak demand. To address this issue, Demand Response programs are introduced which analyze and work on the customer behaviour of using electricity and their communication to supply company to reduce the peak demand problem, improve the power supply system and reduce the electricity costing overall. This may manipulates energy usage analysis, bidirectional communication between user and supply company, smart metering, and advance real time signaling and feedback. Demand Response works very effectively in industrial and commercial sectors, since its users work under controlled and monitored environment and are well aware of the losses they may encounter if it is neglected. However, the users of residential sector are unaware and unconscious of the consequences of irregular and abrupt usage of electricity, thus it is important to have an update in the betterment of user and supply communication to resolve the issue and there can be tremendous amount of data that can be communicated to the user by the supply which includes, information about peak hours, timely varying billing and environmental concerns at different hours so that user may schedule the usage of its appliances accordingly.

Alot of surveys, group discussions and load monitoring has been performed to analyze the impact of spreading awareness in the user about peak hours, including analysis of the activities of many type of users during different circumstances, their electricity usage behaviour, and their motivation in reduction of electricity bills and other types of power supply problems.

Overall, findings of the study done in this regard, conclude that user might become ready to schedule their appliances if proper awareness is circulated but in their day to day busy life, user may find it hard to consider the pricing signal of different hour, peak hours information, and other factors provided to then by supply, while using households, thus they again tend to use the appliances abruptly causing very less improvement in the reduction of peak demand problem. Thus, it is very important to have an automated system that schedules the appliances operation automatically in order to avoid peak hours and reduce electricity cost while considering user requirements and comfort.

This research work covers the development of an algorithm which will optimize the residential load using demand response strategy of communicating pricing signals to the user and user will also communicate the usage of household appliances, their priority and their utilization and preferred time range, then the algorithm will schedule the household appliances considering all the user and power supply constraints as well as the timely pricing of power supply. The algorithm uses the Dynamic Programming Optimization technique. The algorithm has two steps, one is to optimize the households load by cutting off extra load which is not in usage to reduce the cost of electricity and the second is to schedule the appliances such that they may have reduced peak. Multiple levels of appliances operation is considered to make the system more flexible in scheduling and fulfilling the energy demand.

The algorithm is implemented on Matlab and real case studies has been included for the validation of developed algorithm while considering dynamic quadratic pricing strategy.

Keywords: *Demand Response, Residential Load Optimization, Home Appliances Scheduling, Dynamic Pricing, Peak to Average Ratio (PAR), Electricity Cost Reduction*

Acknowledgments

First and foremost, all praises and thanks belong to Allah Almighty for His showers of blessings and mercy on me throughout my research work to complete it successfully.

I would like to express my deepest and sincere gratitude to my thesis supervisor, Dr Sajjad Haider Zaidi, Director of Research and Development, Pakistan Navy Engineering College, National University of Science and Technology, for giving me an opportunity to work with him and for his continuous support in my Masters study and research, for his patience, motivation, enthusiasm, immense knowledge and invaluable guidance. His dynamism, vision, sincerity and motivation have deeply inspired me. He has taught me the methodology to carry out research and to present the research work and make it valuable. The door to Dr. Zaidi was always open whenever I ran into a problem spot or had a question about my research or writing. It was great privilege and honor for me to work under his guidance.

Besides my advisor, I would also like to thank my GEC committee members, Dr. Attaullah Memon and Dr. Lubna for their encouragements and insightful comments which helped me improved myself.

I am extremely grateful to my mother whose affection, prayers, care, help, support, and guidance took me to a place where I am today. She worked as a single parent to raise me as a person who I am today and preparing me to be better day by day by trusting me and instilling self-confidence in me. I would also like to thank and give love to my siblings for their love, care and support in educating me, guiding me in every step of my life. I also grateful to my maternal uncle and his wife for being with us in every thicks and thins of life. I would like to extend my love and prayers to my father who left this world during my thesis phase but taught me and my family many things in different ways.

I have great pleasure in acknowledging my gratitude towards my friends and class fellows as the journey of this degree would have become miserable without them, whom I shared giggles with, bunked classes together, talked hours and hours on call to discuss any minor difficulty, we faced with each other. I owe them a great gratitude.

I would also like to thank United States, Pakistan, Center of Advance Studies in Energy, NUST who sent me for a research exchange program in United States of America to get to have exposure to the state of the art laboratory equipments by working on them and implementing the design simulations on them which helped me alot in better understanding of my work in thesis and gave me real based case study to implement my thesis work on.

Last, but not the least, I would like to thank the management of Department of Electronics and Power Engineering, Pakistan Navy Engineering College for its support and I am thankful to every person who helped and supported me in a direct or indirect way to complete my thesis.

Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

Abbreviations

SF	Schedulable Flexible Appliances
SN	Schedulable Non-flexible Appliances
C	Critical Appliances
L	Luxury Appliances
RTP	Real Time Pricing
ALS	Automated Load Scheduling
UTI	Utility Time Interval
PUTI	Preferred Utility Time Interval
PAR	Peak to Average Ratio
TEC	Total Energy Consumption
LOT	Length of Operation
DR	Demand Response
DSM	Demand Side Management
SG	Smart Grid
SOO	Single Objective Optimization
MOO	Multiple Objective Optimization

HEMS	Home Energy Management System
TOU	Time Of Use
DG	Distributed Generation
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
ACO	Ant Colony Optimization
WDO	Wind Driven Optimization
EA	Evolutionary Algorithm
PTEM	Physical, Technical and Economic Model
PE	Price Elasticity
CPP	Critical Peak Pricing
EPRI	Electric Power Research Institute
DLC	Direct Load Control
PTR	Peak Time Rebate
PEV	Plug-in Electric Vehicle

Chapter 1

Introduction

1.1 Scope and objective of the chapter

The electricity is supplied to all economic sectors; industrial, commercial, residential, agricultural and sometimes to transportation, of a country through the electric supply system. This electric power system consists of power generation, power transmission and power distribution. The controlling of the consumption of this supplied electrical power is called the demand side management. The supply and demand must be balance or equal to each other, and that is why, Peak Demand or peak load of electricity, which occurs to be maximum load or demand during a specified period of time, has been one of the most discussed topics of research for many researchers and industries for many years. The infrastructure of generation, transmission and distribution is designed and developed by keeping in mind the the peak and average load of its existing and anticipated consumers.

Greater peak demand always impacts negatively on the power system reliability. Security and adequacy are the most important aspects of reliability of power system. Security is the ability of a power system to withstand sudden unexpected changes and adequacy is the capacity of the system for how long can it remain secure [3]. The reason of the increased focus on peak demand by the electric supply companies is the increased probability of the system outages during peak hours, which is usually calculated by the Loss Of Load Probability (LOLP). This LOLP is mostly high for a shorter time in a year, making the peaks of the system high [4].

The issue of peak demand is addressed conventionally at the supply side of electricity through the installation of more power plants and increment of more capacity in the power network grid, in order to meet the standard reserve margins. which is the measure of excess of power installed than peak demand for a measuring period of time in percentage, and the recommended percentage is 15 -17% of the peak demand [5]

When the peak demand occurs, the supply company has to fulfil this demand by supplying excess of electric energy from reserves produced by plants, commonly called "peaking plants", which are usually expensive because they are mostly gas and diesel power plants. These plants emit more CO_2 as compared to nuclear and hydro power plants but more than that of coal fired power plants. If the supply reserves fail to fulfill desired demand, then the demand needed to get curtailed. Consequently, the consumer has to face power outages, increased prices of electricity at particular hours and different energy prices for different range of usage. This is done so as to encourage user to shed extra load. Sometimes, customers are also paid credit by the supply for shedding extra load than the routine whereas, power blackout is the last step taken by the supply companies when they are left with no other way out.

The deregulation of the market of the electricity fundamentally modified the frame(executive) in which the decisions of investment are taken in the sector of the electricity and aroused certain serious concerns of a probable important decrement of the capital being invested in the electricity supply infrastructure. The process of planning of the investment has not been any more managed by the safety(security) of the supply, but it is rather reactive in the signals of the market. An evaluation of the safety(security) of the electricity supply presented by organization named as International Energy Agency (IEA) which states that the average spare margins has got decreased in numerous states of the world after the deregulation occur in the electricity market [5],[6]. Prices volatility is being categorized as the major reason behind the deregulated markets, and low reserve margin is the result of greater price volatility. For example, during the energy crisis in California, said that in decrement to the State reserve margin was 3.5% which was very less as compared to 15% , the standard spare capacity of utility. During that time, the wholesale price of electricity got as high as $US 750/MWh, in comparison to the average of the State, which is about 81 $US/MWh[7]

Other causes of variability in prices include the issues in saving electricity in bulk quantities, the reliability and capacity of network and the production capacity constraints, that is it takes a long time for the addition of more capacity and the closure of markets and consumer retail in electricity. These variables make simple and beneficial for the organizations to make utilization of intensity of market, which expands value instability. The vitality advertise is generally characterized as a gainful chance to change costs from aggressive dimensions[3]. Unpredictability builds vulnerability about long haul execution top normal rate of rate of return. This can lessen the security of vitality supply and increment the danger of apportioning power amid times of pinnacle request.

The option of ceaselessly extending framework of power supply framework to satisfy top interest is to concentrate on controlling/dealing with the interest side. Demand Side Management (DSM) is alluded to arranging, executing and checking the use of the power by the buyer with the end goal that the client itself will keep up the coveted load state of utility[8]. Gellings - who presented the concept of Demand Side Management and worked on developing its methods – began DSM utility programs which include: management, strategic behavior of energy conservation, load managing, customer's own part in generation and market share adjustment by the supply companies[8]. DSM can occur in all applications areas; residential, commercial and industrial. An integral subsection of the said procedure is an Integrated Resource Planning (IRP), that is a process of electricity utility in include the evaluation of supply side to demand side alternatives and then the selection of optimal methods of producing resources that will reduce the electricity supply cost while it should fulfil the reliability criteria and other required objectives.

These days, DSM programs that lessen the heap on the power matrix amid times of higher interest are known as Demand Response. The interest reaction is characterized all in all terms as' adjustment in the utilization of power by end clients in connection to their example of ordinary utilization, in light of changes in the cost of power over the given time, or to an installment motivator intended to diminish power utilization when the discount advertise cost is high, or when the unwavering quality of the framework is endangered[9]. Request reaction can be gotten from buyers through a retail power duty that mirrors the time-subordinate expense of power supply and circulation of power or a program that urges customers to change their utilization, which thus diminishes the requirement for expanded framework execution. This incorporates conventional load the executives or direct load control (DLC) and time-changing rates. Load the executives programs attempt to diminish crest request amid specific timeframes by immediately constraining interest or moving the power stack for various eras. In time sensitive duty programs, high costs per unit of electric vitality expended is charged amid pinnacle stack hours to impact buyers to move or reduce their power utilization from pinnacle stack hours to off load crest hours.

Benefits of demand feedback incorporates reducing costs, improving environmental performance/sustainability (if this leads to a reduction in the use of fossil fuels), increasing security of supply and market performance, improving customer service and reducing market power price[10]. For example, a typical estimate in the US market calculates the monetary advantage of transferring five to eight percent of the consumer's load from top tip load hours to off load peak hours, to be $15 billion a year[7]. The other vital and evident national/societal issues that could be stayed away from through dynamic cooperation sought after side administration are control blackouts, ecological outflows from wasteful top of the line generators and the utilization of uncommon earth assets to fabricate vitality supply foundations.

Demand response programs in term of hourly differentiated prices as of now exist in the modern and business end-utilize divisions. Huge clients in these divisions are frequently presented to the discount cost of power, which is reflected in the time separated change in the costs of supply. The large quantity of these big users has energy monitoring and controlling programs that ensure the economic use of electricity. Nevertheless, a review stated in [11] of 43 programs for reacting to continuous value variances in these parts has created blended outcomes. Just a couple have accomplished a noteworthy, total or relative impact on lessening the heap.

In comparison to other sectors, residential sector has highest potential to demand response. Though the residential users should be more responsive to the price based demand response but records show that there is a communication gap between the retail and wholesale market thus making the actual and predicted power reduction far away from each other. As the Ahmad Faruqui, Electric Power Research Institute (EPRI) area manager for retail and power markets[12] said,

"The demand side of the market is not functioning well because customers are not seeing real-time price signals. With real-time pricing options and their supporting technologies in play, we would get the full benefits of deregulation."

However, even if users get to know about the real time pricing or the time based pricing of the electricity, most of the user fail to schedule their load accordingly due to their busy routine, carelessness and being lethargic enough to do so. So, there is a utter need of designing and implementing an automated system that will automatically schedule all of the home appliances a day ahead according to the time based price signal received by the supply company. This automated system will ensure the maximum user satisfaction in terms of their desired schedule of the appliance so that maximum number of users are encouraged to get this system implemented in their homes.

This thesis work is based on the development of an algorithm which will optimize and then schedule the load of households in order to get reduced peak of the load and hence overall cost reduction of the electricity at the end of the month while considering maximum user satisfaction in terms of the hours of scheduling lying inn the desired range of user.

The following area of this section exhibits the recorded setting of free market activity for power and how it has advanced throughout the most recent 30 years. The accompanying area characterizes the issue of pinnacle request and depicts how it was managed before, trailed by the commitment of this work. The last piece of this part gives a diagram of how whatever remains of the postulation is sorted out.

1.2 Background of Demand Side Management

Dependable and helpful power supply has dependably been an essential political objective. In the United States, Canada, European nations, Australia and New Zealand, generous ventures have been made in power age and transmission foundation. Utilities arranged, manufactured and dealt with the power age, transmission and circulation frameworks in the expectation of expanding client request. Amid the underlying period of improvement of incorporated power age, working costs diminished as power plants ended up bigger and more productive. Costs have risen since the late 1960s due to many factors, including slowing technological progress, rising fuel costs, increased environmental controls and the removal of nuclear projects[13], [14]. During the 1970s, the developing interest for power joined with the expansion in power costs because of the worldwide vitality emergency prompted protection activities. Nature protection spokespersons contended then that it is less expensive to decrease request than to build supply. Portage's vitality arrangement venture in the United States could have been the primary investigation that raised that 'protection is as important as supply'. The Ford Foundation presented three below mentioned scenarios of future American energy in [15]:

- **Historical Growth Scenario** - that would lead to continuous supply difficulties/scarcity.
- **Technical Fix Scenario** - that would employ energy efficiently, could cut energy consumption without compromising standard of living, and could have positive impact on the environment.
- **A Zero Energy Growth Scenario** - included more conservation to the extent of some sacrifice of standard of living of expected values and changes in lifestyle

A physicist and energy expert, Amory Lovins, wrote many non-technical and popular books, including "Soft Energy Paths: towards a Durable Peace" [16] and "World Energy Strategies: Facts, Issues and Options" [17], all of which presented the idea that Demand Response is the option that could immensely contribute towards the world's future increasing energy requirements. This concept of demand side management was introduced in 1980s. Meanwhile, integrated resource planning through demand-based management projects were implemented to achieve significant cost savings and to improve network security in the United States[8]. Currently,request side administration takes care of the issue of pinnacle power request in light of interest, commonly called as Demand Response.

1.3 Problem of Peak Load and its management

1.3.1 The Problem of Peak Load

Whenever a specific duration of time arrives, the electricity demand shoots and it is the time in which peak demand od a system is on fire. The peak demand is generally referred to as the daily, annual or seasonal condition and has the power as its unit. End use peak load is referred to as the activities using energy at the peak load hours and the resulting peak load is measured on the consumer's energy meter [18]. The maximum system load is measured on the system busbar and corresponds to the load used by the systems. The simultaneous load at peak hours for all end users (for example, for the entire coverage area) is called coincident peak load.

Pinnacle stack issues happen in power frameworks because of lacking generation or transmission limit. This regularly prompts an irregularity among free market activity.

Utilities have customarily tackled this supply-side issue by building more power plants and expanding the limit of the system framework to guarantee a most extreme edge of supply-request security. Request side arrangements mean to lessen the top by urging clients to diminish request amid these 'basic' hours, keeping away from exorbitant pinnacle stack speculations [19].

Pakistan is one of the countries which come under Organization of Economic Co-operation and Development (OECD) where the reserve mills capacity is decreasing drastically over the years due to deregulation and privatization of electricity supply [20] giving the consequences of continuous scheduled and unscheduled black outs for the time ranging from 6 hours to 20 hours a day throughout the country and to overcome the issue, the government has to buy/ import the electricity reserves from other countries at the cost of alot of assets, China Pakistan Economic Program (CPEC) is one of the programs initiated by the government to solve many issues, and energy requirement fulfilling is one of them. Even the, it can not solve the long term and continued problem of increasing scarcity of energy in Pakistan. A study by Electric Commission [21] ordered the private segment as the biggest supporter of the pinnacle stack, representing the greater part of the framework stack at pinnacle hours. One yearning of this proposition is to contribute in executing a robotized framework which will assist clients with exercising the exercises of pinnacle stack decrease without disposing of satisfying their fundamental need of vitality and without attempting additional endeavors on everyday schedule.

1.3.2 The Peak Demand Management in Residential Sector

In the past, utilities around the world have used two basic strategies to manage residential peak loads: Direct Load Control and time-dependent pricing schemes. Direct Load Control (DLC) programs provide households with monthly credit on their accounts in exchange for the utility that runs some of the major energy-consuming devices. The most regularly controlled private end-utilize machines are focal climate control systems, boilers, electrical space heaters with storage functions and lighting.

Direct Load Control is used in very few countries/areas with few amendments, depending upon the geographical areas, their load pattern and the type of residents. In New Zealand, Ripple Control of water heating cylinders is done which comes under this program, similarly in Australia and United States, DLC is used to control air conditioners in summers and heaters in winters [9], [22].

These programs prove to be successful in many places to reduce the demand for residential areas [23]. DLC programs are available with the existing counting architecture - they do not essential require enhanced counters or interest in direct communication hardware. Commentators contend, be that as it may, that private clients are taking finished control of their gadgets. There are likewise value issues, as clients who don't possess substantial, vitality utilizing gadgets, such as For example, central air conditioners that do not contribute to the peak load of the system are eligible for program services [24] .

Unlike direct load control, time-based pricing is dependent on a clear price signal, a high-rise price per kW of load at the time of peak hours, to encourage customers to transfer from power utilization from ON load peak hours to OFF load peak hours. The consumer's reaction in this case is determined through a process of on board economic settlement committee and that load pattern amendments are monitored.

The sub categories of Time varrying Demand Response are mentioned below:

1. **Time Of Use (TOU)** is the charges of electricity according to the duration of use imposes different prices for the consumption of electricity over a defined period of time. According to this scheme, the price per kilo watt hour of electricity consumed when peak load occurs is greater than that consumed outside peak periods (see Figure 1.1).

2. **Critical peak pricing (CPP)** entail greater prices of power used for periods designated as important by the supply of beneficial. The arrangement of program resembles to the TOU prices, with the difference between schedules and prices not resolved (see Figure 1.1b). On the basis of the expected condition of supply and demand, the utility supply could denote a certain time as critical. CPP events are a few hours a year and are sent at relatively short notice. CPP is illustrated in Figure 1.2. The dotted line means that the maximum rate of prices is not fixed and can vary from event to event.

3. **Real Time Pricing (RTP)** is the scheme in which prices of the electricity vary continuously according to the wholesale prices or regional demand. Unlike Time Of Use pricing and Critical Peak Pricing, real-time pricing offer different prices to power consumers every hour of the day. Figure 1.3 below shows schematic drawing

of different types of price programs that vary over time.

4. **Peak Time Rebate (PTR)** is a simple to-utilize way to deal with CPP settlements. It is sent similarly as CPP. Clients get power on the current costs, yet get limits on the off chance that they decrease utilization amid pinnacle periods. The rebate is typically founded on lessened utilization with respect to a determined base (contingent upon the date of the occasion).

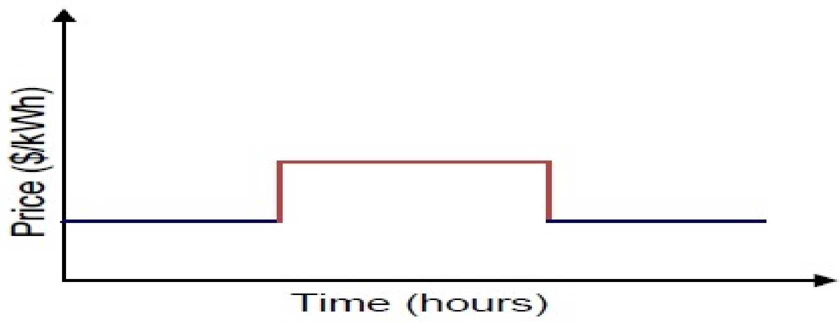

Figure 1.1: Graphical presentation of Time Of Use Demand Response.

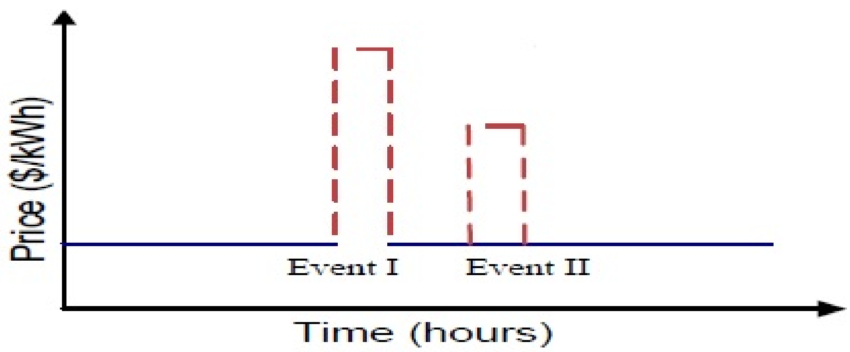

Figure 1.2: Graphical presentation of Critical Peak Pricing Demand Response.

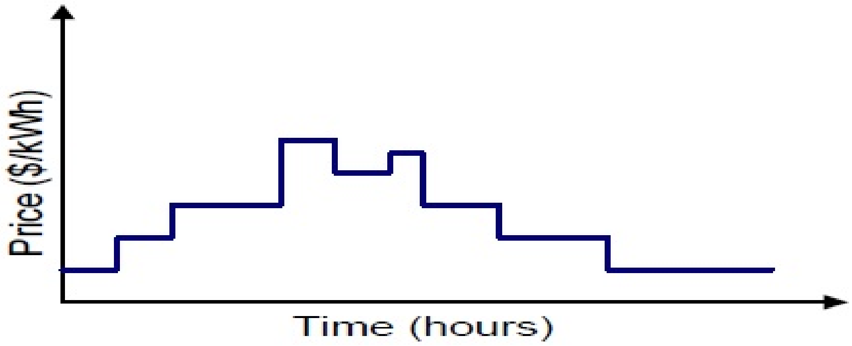

Figure 1.3: Graphical presentation of Real Time Pricing Demand Response.

Time based pricing tariffs have not been fully accepted over period of time, as it can have some serious financial consequences for households having low income. It is interpreted as that when a vital need, like energy, becomes expensive and scarce, the world market procedures hit the poor sector harder. Critiques of the electricity price which varies over time claim that the price levels which might be needed to fulfill the peak demand required might be greater than those reasonable for low socioeconomic households and may lead to "lifestyle reductions" [25].

1.4 Problem Statement

The industry of electricity supply is rapidly approaching a major gridlock in energy supply, which can lead to a global energy crisis in the coming years. The problem is not essentially in how much power is generated, but in the amount of energy wasted or misused, mainly due to the lack of an energy management system to control and monitor, in real time, energy resources. Real-time pricing is supposed as a viable alternative that can help stabilize the supply and demand curve in the energy sector by cutting down the peak demand of the utility.

Real Time Price (RTP) implementation is strongly being considered by utility companies to control and regulate their system load especially during peak hours. The RTP concept illustrates how prices will change with certain frequencies based on demand and power generation. Similarly, RTP will use renewable energy sources and other types of technology that are more appropriate as energy production can be divided into optimum time, i.e. only produced when the demand exceeds supply. The RTP helps to smoothen the load curve and make full use of these resources.

1.5 The Contribution of this Work

This thesis presents an algorithm to optimize and schedule residential load in order to reduce the peak to average ratio of power and electricity cost of a household, such that the user comfort is not disturbed by dividing the household appliances into two main categories; schedulable and non- schedulable which are further divided into sub categories. The load of a household is automatically scheduled such that it is evenly distributed throughout twenty four hours in such a way that we may have them scheduled to achieve minimum peak to average ratio as well as cost, considering user's maximum comfort concern. Mixed Integer Nonlinear Programming technique is used in an iterative manner following the dynamic quadratic pricing model throughout the day considering the total demand of the user and market electricity pricing. The algorithm is validated by applying it on a real data of a household of United States and its results show its effectiveness in minimizing the peak to average ratio of power and thus cost of electricity bills keeping the comfort of user intact.

1.6 Thesis Outline

Thesis comprises of nine major chapters. First chapter gives the introduction to the problem faced not only by the people of Pakistan but by the people around the globe in terms of electricity and its proposed solution. Chapter 2,**The power system in Pakistan**, reviews of the electricity supply system in Pakistan and its state of the art. Chapter 3, **Problems of Peak Demand and its management in the residential sector**, describes the problems of the peak demand/load and how they are being managed through demand response. Chapter 4,**Behaviour in the use of energy use by domestic consumer**, gives the overview of the impact of energy use behaviour of the consumer on peak load. Chapter 5, **Framework of the Automated Load Scheduling Algorithm**, discusses the framework of the algorithm developed which includes the infrastructure of system on which the algorithm will be implemented. Chapter 6, **Technical Overview of Relative Optimizing Techniques**, gives the overview of all major optimization techniques used till date. Chapter 7, **Modelling of Automated Load Scheduling System**, discusses the modelling methodology used to implement the algorithm. In Chapter 8, The discussed modelling methodology and the ALS framework in chapter 5 and 7 is implemented on the **case study** in the households of single dwelling in different scenarios to estimate the impact of developed algorithm based on day ahead scheduling demand response under dynamic pricing on the electricity load and cost graph of the consumer. In the end, chapter 9, **Conclusion**, summarizes the proposed algorithm and its advantages on user as well as on utility side. Chapter 9 also discusses future work of the researcher.

Chapter 2

The Power system in Pakistan

2.1 Scope and Objective of the Chapter

This chapter discusses about the state of the art condition of electricity in Pakistan including its generation, transmission, distribution, retail and market. It also discusses about the state of the art electricity demand trends and its implications on the electricity supply requirement fulfilment and also the strategies that are currently being adopted to compensate these insecurities.

2.2 The Electricity Industry in Pakistan

Pakistan's energy infrastructure is considered to be underdeveloped or not controlled well. Currently, the country currently has an energy deflation crisis. Despite strong economic growth and increased demand for energy over the last ten years, no effort has been made to install a new generation capacity. In addition, the rapidly growing situation is increasing demand, losses are lost due to lost infrastructure, electricity transmission and seasonal reductions in the availability of hydropower. Because demand is more than supply, the burden is a common phenomenon. Under independence, Pakistan had a 60 MW electricity production capacity for an estimated population of total 31.5 million, or in terms of units of 4.5 units per consumption, This generation capacity increased up to 119MW in 1959 when WAPDA was established.

The rate of acceleration of the development of power got increased by 1970, towards five more years, by increasing the capacity of 636MW to 1331 MW by charging power and hydraulics. In 1980, the system combined with 3000 MW increased with the land to more than 7000 MW in 1990-91.

In the 1990s, Karachi experienced a sharp increase, as large industrial and commercial homes were created, leading to an increase in electricity demand. In this way, KESC has been authorized for age, transmission and dissemination of power in its authorized region. In 2000s, yearly power utilization per client expanded, and the yearly use of each mechanical customer achieved the most abnormal amount, expanding the hole among supply and supply. According to estimates of the Asian Development Bank, in 2006, 45 percent of Pakistanis have no access to electricity.

The crisis of power got exacerbated in Pakistan in 2008, as power shortages have risen to 4,000 MW. Pakistani industrial consumers have a shortfall because of low water levels in hydroelectric dams. The year 2011 began with the lack of power and the heaviest burden in history, ending in the same situation. The worst time for Pakistanis is the population, where in some regions although the burden of 16 to 18 hours is considered as cargo dumping. Electricity prices continue to grow. Lack of electricity leads to industrial losses, which has led to many jobs and losses for the people of Pakistan.

2.3 Structure of Electricity Sector in Pakistan

The energy sector of Pakistan was reestablished with the establishment of PEPCO (Pakistan Electric Power Company) in 1998. Before this year, there were two parallel integrated infrastructures, KESC, serving in the Karachi and WAPDA regions, serving the other regions of the country. After a while, the power wing of WAPDA got categorized into distinct corporate entities incorporating 10 DISCOs, 4 GENCOs and one TransCO (NTDC). These ten DIStribution Companies (DISCOs) perform the task of distributing electricity to the end users. While KESC (now called K.Electric) fulfils the overall demand at its own expense or through the purchase from National Transmission and Dispatch Company (NTDC) Independent Power Producers (IPPs), and Karachi Nuclear Power. The structure of the electricity sector is presented below in figure 2.1.

2.3.1 Sources of Electricity in Pakistan

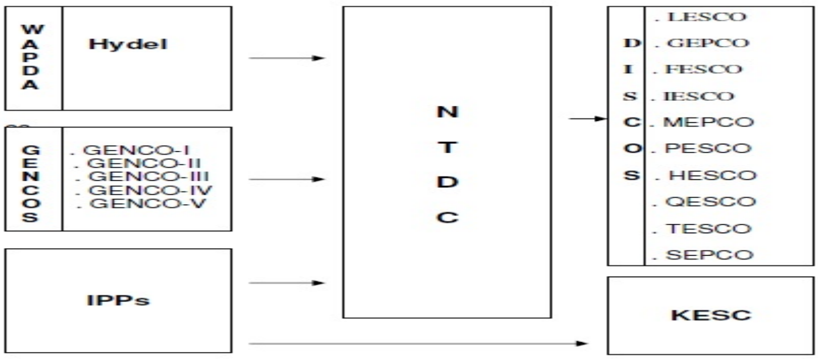

Figure 2.1: Current Structure of Power Sector of Pakistan [1].

Pakistan utilizes a number of resources for the generation of power which are discussed below.

2.3.1.1 Thermal Power Plant

Currently the thermal energy production is 8,300 MW, be that as it may, these establishments are portrayed by transformation productivity and are costly to keep up and utilize. Most warm plants introduced by IPPs utilize oil from the stove, which has turned out to be pricey as of late. The heater oil utilized for it must be transported in which perfect outside stores of the nation. A portion of these power plants can likewise utilize gaseous petrol as fuel, however the nation is beginning to have a deficiency of gas as well.

2.3.1.2 Hydal Power Plant

Electricity from Hydro power plants is generated by means of power generators which utilizes energy from water which is moving. Pakistan has rich energy sources of water that can be utilized in running hydropower plants, but only 34% of the total electricity production comes from hydro power. The country currently have 6555 MW in relation to the potential of 41,000 MW to 45,000 MW.

2.3.1.3 Wind Power Plant

Wind power plants/generators use wind energy to propel windmills. These turbines cause the rotation of magnets that produce electricity. Although Pakistan's wind potential is going from 10,000 MW to 50,000 MW, electricity generation from wind mills is still very less in Pakistan. At present time, only 6 MW of power is being installed in the first phase at Jhampir and soon 50 MW will also be installed through Turkish assistance. Other wind mills will be installed in Gharo, Jhimpir, Keti Bandar and Bin Qasim Karachi.

2.3.1.4 Solar Energy

Solar energy incorporates the use of solar cells which convert photons present in the sunlight into electrons to make electricity. Pakistan has a potential of generating more than 100,000 MW of solar thermal panels. Construction of sustainable solar power plants in Kashmir, Punjab, Sindh and Balochistan are in progress. However, private suppliers import solar panels and solar water heaters having better efficiency to sell in the market, whereas Alternative Energy Development Board (AEDB) works for 20,000 solar panels or solar water heaters in Gilgit Baltistan. In this regards, telecommunication companies have also been called by the government to transfer energy from oil for their transmission towers to solar panels.

2.3.1.5 Biomass

Electricity production from biomass includes the use of waste or other renewable sources such as corn, sugarcane or other vegetation to produce electricity. After tanning, methane is produced and trapped in the pipes and then transmuted into electricity. Vegetation and wood can be ignited directly to produce energy, for example fossil fuels or remnant for the production of alcohols. Brazil is conducting one of the biggest sustainable biomass / bio diesel energy programs from all over the world, which is then followed by the United States. Alternative Energy Development Board (AEDB) from Pakistan plans to produce 10 MW of power from urban waste in Karachi, followed by identical projects in twenty other cities in the country.

2.3.1.6 Nuclear Energy

Nuclear power plants use nuclear fission reactions to produce energy through uranium reactions in nuclear reactors. Pakistan has very less nuclear power generation programs with a capacity of 425 MW, but it is expected to be increased considerably in coming years. Since Pakistan is not covered by Non Proliferation Treaty , it is being prohibited from trade for nuclear plants and products, which prevent the generation of nuclear energy for civil purposes. The other problems in nuclear energy production are the enrichment of uranium from U_{235} to U_{238}, control of chain reactions and solid waste removal.

The percentage of each of the above mentioned energy resources in the contribution of the total energy production of Pakistan is summarized by International Energy Agency (IEA) in the figure 2.2 mentioned below:

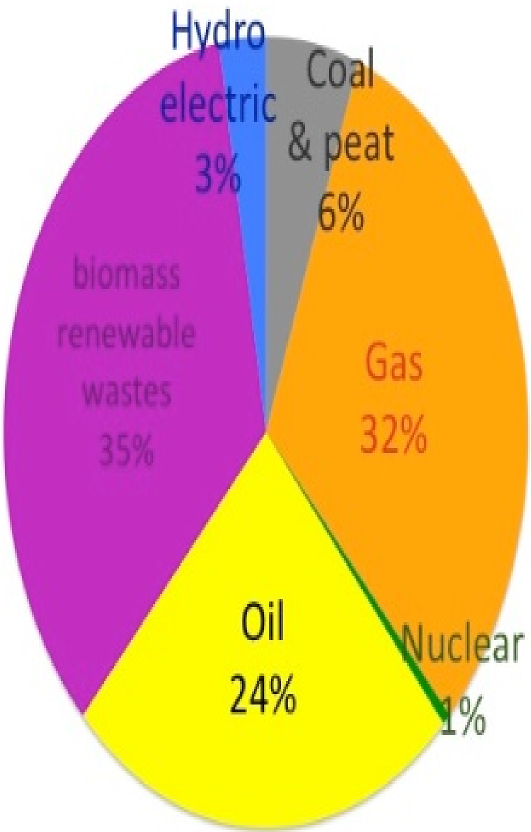

Figure 2.2: Percentage of different Energy Resources in Total Energy Production in Pakistan given by IEA.

2.4 Total Install Capacity of Pakistan

There are four main electricity power producers in Pakistan which are:

(a) **Water and Power Development Authority (WAPDA)**

The main role of WAPDA development has been reactivated. It now focuses solely on hydal development and water related projects to support the economy and reduce poverty through better thermal mix of energy production, affordable electricity supply as well as the most relevant perspectives and rapid implementation of water based projects to meet and feed the problem of the country's growing population, agriculture and industry. In March 2010-11, hydroelectricity production increased by 14.4%, while thermal energy decreased by 2.4% year-on-year. In addition, hydro power production accounted for 36% of total energy production, while it gained 64% thermal gain over the period.

(b) **Karachi Electric Supply Company (K.Electric)**

This supply company is primarily involved in the generation, transmission and distribution of electrical energy to industrial, commercial, agricultural and residential consumers under the Electricity Act of 1910, and the NEPRA Act, 1997, in its granted areas. . The authorized area of K.Electric extends throughout Karachi and its commuter belts to Dhabeji and Gharo in Sindh and Hub, Vindhar, Uthal and Bela in Balochistan. The total area covered is about 6000 square kilometers. 316MW Korangi turbine thermal power plant, Korangi 80MW gas turbine power plant, 100MW SITE gas turbine power plant, 1260MW Bin Qasim thermal power station. The total installed capacity of KESC is 1,756 MW.

(c) **Independent power producers (IPPs)**

Pakistan has 24 IPPs with a capacity of 7.678 MW installed. However, the reliability of these units is about 7100 MW. As part of the 2002 energy policy, the GoP proves the company's performance obligations, including purchasing energy, fuel supply, etc., while ensuring political or tax changes or changes in taxes and tariffs. In addition, tariffs are structured to compare IPPs to a dissenting change in exchange rates. Energy buyers will also get affected and charged accordingly if there occur any change in the fuel prices. According to PPIB, there are 27 IPPs with a total capacity of over 8,000 MW expected online within the next seven years.

(d) **Pakistan Atomic Energy Commission (PAEC)**

Total electricity generated from PAEC is 802 MW including 137 MW from KANNUP, 325 MW from CHASNUPP-1 and 340 MW from CHASNUPP-2.

The percentage breakdown and the total installed capacity of the total electricity generated by these four electricity providers of the country is presented in figure 2.3 and figure 2.4 below.

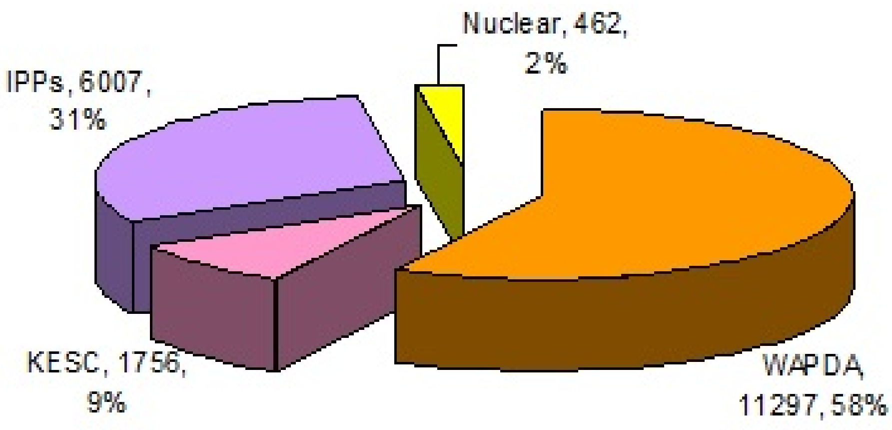

Figure 2.3: Energy Production Breakdown of Pakistan [2].

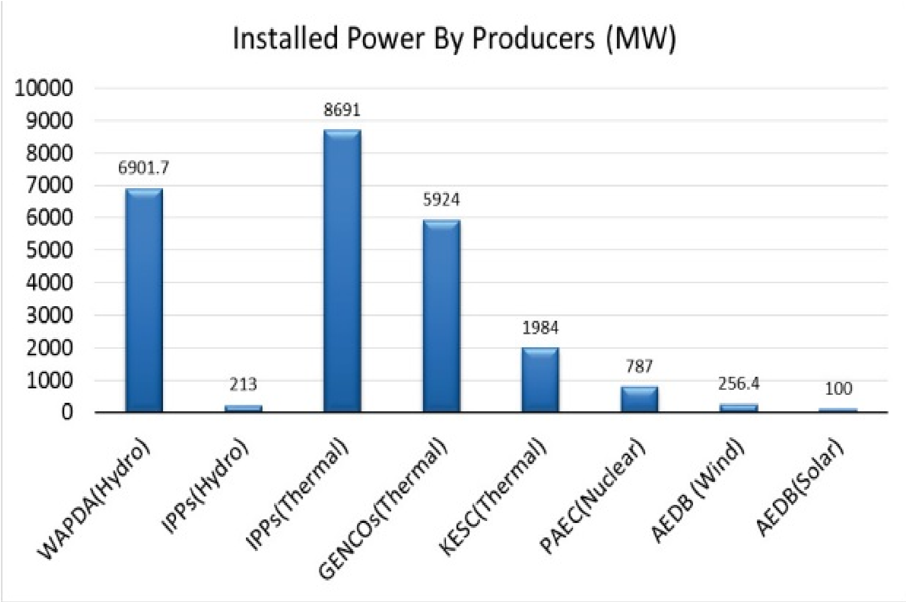

Figure 2.4: Installed Capacity of Pakistan by Different Producers

2.4.1 Electricity Consumption

Power utilization expanded by and large by 4.9% every year over the period 2001-2002 to 2009-2010, while power utilization expanded by 2.8% in the period July-March 2010-2011. Power utilization focuses to a recuperation in monetary action, as the expansion is chiefly from the mechanical division, where there was an increment of 7.3%. Except for the agribusiness and road lighting parts, every other area recorded extreme development from July to March 2010/11.

2.5 Rental Power Plants

Rental Power is an innovation that will give an answer for momentary power requirements for a rent time of 5 to 7 years while looking for long haul arrangements. The power age organizations possessed by the administration are the purchasers of the vitality created by lease control plants. There are at present 19 ventures with a sum of 2734 MW impacts at various phases of treatment. On these activities, eight bonds with a limit of 1156 MW have gained further ground in the legally binding commitments of the purchaser, while six different ventures with a limit of 738 MW have been gone into, yet have made development installments. There are at present five ventures marked without contact.

Pakistan has enough ability to create power alone, yet there isn't sufficient monetary assets to purchase fuel for its present generation limit. Along these lines, it neglects to purchase rental power plants and there are power outages, stack shedding everywhere throughout the year.

2.6 Solutions to End Electricity Shortage

Considering the existing condition of country due to insufficiency of energy, the government of Pakistan has taken some short term and long terms steps to reduce the increasing shortage of electricity.

2.6.1 Adapted Short Term Solutions

Short term solutions for the immediate cope up for the shortage of electricity proposed and performed by the country are:

- Installation of wind turbines has been increased as it takes shorter time to installed as compared to other power plants.
- All existing power plants are being overhauled to achieve maximum generation and also to prevent them from overloading which becomes the vital reason of blackouts.
- Allowing private sectors to set up power plants with renewable resources with their own equity and also providing loans to them according to their project feasibility.
- Reviving some non operating power plants which require little investments to resolve their technical issues.
- The business centers, markets, offices and shopping centers are closed after the day time in majority cities of the country to ensure the efficient way of using energy.
- Steps are being taken in terms of strict check and balance and installments of advance meters to make sure that no theft of electricity is being occurred, and heavy penalty is imposed if anyone caught in doing electricity theft.

2.6.2 Adapted Long Term Solutions

Long term steps for the continual yet cost effective solutions for the shortage of electricity proposed and performed by the country are:

- Planning of installments of more coal powered power plants as Pakistan is know as the world's thirst largest coal producer country.
- PAEC is determined to do research and development for generating power from nuclear resources in a cost effective way to fulfill the major peak demand of the country.
- Replacement and rehabilitation of older transmission and distribution networks and installments of underground cables.
- Extending hand of collaboration with foreign countries to develop better economic and advance infrastructure of energy and other sectors for the betterment of both of the countries.

2.7 Supply and Demand Gap in Pakistan

The Power Division as of late announced expanding power misfortunes and receivables, lesser recuperations and relatively unaltered power request, supply and shortage circumstance in the course of the most recent one year while ascribing a large portion of the area's ills to the nonattendance of political will to address incessant emergency. The normal power deficiency remained at 4,530 MW in July 2017 and remained relatively unaltered at 4,559MW in first seven day stretch of June 2018 and is likely to increase upto 5,000 MW by September 2018 according to the article titled as "Power system gaps growing despite increase in generation" in DAWN published on June 12, 2018 [26].

This means the the country is in dire need to have Demand Response programs that will manage the increasing load on the end user side in order to avoid increasing load shedding as well as the cost of electricity.

Chapter 3

Problems of Peak Demand and its management in the residential sector

3.1 Scope and Objective of the Chapter

This chapter discusses about the peak load issues that often occur on the distribution network and describes its specific occurrence in Pakistan. The contribution of this problem to the residential sector is discussed. Then the role of demand side management is discussed to address the issue.

3.2 The problem of Peak Load

Vitality request is the measure of vitality that would be utilized if the voltage and recurrence in the framework were equivalent to the objective incentive for all shoppers [3]. The pinnacle interest for an establishment or framework is really the most astounding interest for a given time frame. Pinnacle request is typically happened as yearly, day by day or regular popularity which has unit equivalent to that of intensity. The pinnacle heap of end client applies to exercises that utilization top vitality and the subsequent pinnacle request is estimated on the client's meter. Most extreme framework stack is estimated on the framework transport and is identical to the heap upheld by the establishment. A concurrent use of high load for all end clients (for instance, for the whole ease of use run) is known as the correspondent pinnacle stack. Appliances which consumes high rated power contribute in the occurrence of peak load and in residential sector, toaster, air conditioners, kettle and washing machine are considered among them [27]. Figure 3.1 elaborates the electric energy demand outline of typical household of a day, where the time is mentioned in minutes.

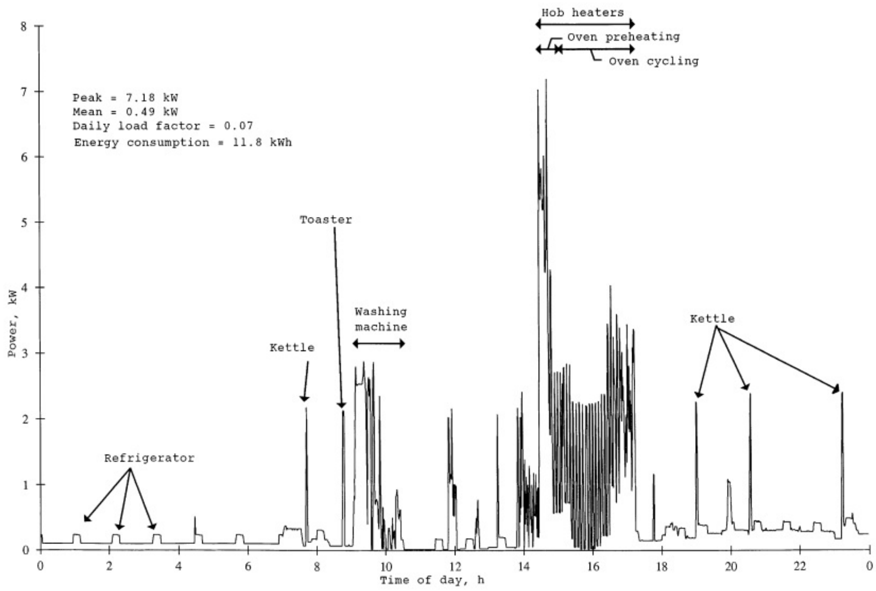

Figure 3.1: Electricity Profile of a Typical Household in a Day

The incapability of transmission or generation of electricity power are the key sources for the peak load problems in the supply infrastructure causing a huge gap between demand and supply. This imbalance between demand and supply , in the short term, is voltage levels shows and, more particularly, by frequency. A decrease in the voltage and / or frequency under its set values indicates that the demand has overreached the supply. Likewise, increment in the frequency and voltage than its target values, it means that the supply has overreached the demand.

At the time when demand is low, only power plants with the lowest marginal costs operate, while in peak periods, almost all power plants have to work to meet demand and avoid system failures. The least end-of-line plants having lower negligible expense are frequently the most eco-friendly. In Pakistan, for example, the basic power is generated by thermal power plants (65.2%) and hydel (33.9%), and top interest is met by atomic power plants and some non-renewable energy source control plants bolstered gaseous petrol and diesel generators. These offices are considered as costly to work and are connected with huge ommissions and unfriendly effect on ecological and worldwide qualities.

The other troubling phase of the peak load issue is because of the network and transmission limitations. Electricity distribution and transmission networks are becoming increasingly dense in times of high demand. Both spatial and temporal parameters are considered i energy systems classified as network limitations[6]. Classfication of this peak period can be broad or narrow as well. The tight system impediment happens right now of the system top interest and stops for a brief span. Wide pinnacle limits take a few hours or days. As for the spatial measurement, arrange requirements could be available in a specific territory with geographic angle in at least one specific system components, for example, substations. Figure 3.2 illustrates different types of peak Load problems with their solutions on the supply side.

Peak Load Problem	Time Dimension	Spatial Dimension	Supply Side Solution
Problem with insufficient generation capacity	System peak, lasting few seconds, minutes, or hours	Occurring at a particular geographical location	Start reserve generator
	Seasonal peaks, lasting several days or months	Occurring throughout the entire system	Build additional power plants
Problem with insufficient transmission capacity	System peak, lasting few seconds, minutes, or hours	Associated with specific network element e.g. substation	Pay penalty for exceeding the peak limit
	Across the electrical load curve lasting several hours	Occurring across the network of a particular region	Network argumentation

Figure 3.2: Peak Load Problems with their Supply Side Solutions

Peak demand issue is conventionally being addressed in Pakistan by making attempts of increasing supply side which is costly and resource limited.

3.3 Demand Side Management

The management of demand is the alternative of the supply side management. The concept of demand management in the power and energy sector is to plan, implement and monitor energy utilization activities to manage the customer's use of electricity to produce the desired results. Instead of providing an infrastructure capable of delivering the required peak load a few hours a year, demand side management requires controlling customers' need not to increase peak loads.

3.3.1 DSM Concept

The phrase 'Demand side Management' (DSM) was first instigate in 1981 in Electrical Power Industry by Clark Gellings, who is a senior director of the Electric Power Research Institute (EPRI) in the USA [8]. DSM measures are introduced to influence and, if necessary, amend the customer behavior to obtain advantages for the consumer and the power companies.. This program has given individual customers the options to curtail the use of energy services, such as boiling liquids and usage of cooling equipments, during peak hours in exchange for rates lower than the previous. Several activities that fall within the scope of DSM protection include:

- Taking measures on the customers' end to improve meter productivity in terms of efficiency, for example, installation of smart meters
- Implementation of intelligent load reduction programs such as Direct Load Control, Time varying Demand Response.
- Utilization of small capacity installed renewable sources individually by every consumer.
- Switching fuel for generation of power plants intelligently considering the nature of demand.

These measures can be taken to achieve a specific desired shape of the load in residential sector from end user. Figure 3.3 shows the different objectives of achieving diverse load shapes which employs DSM. On the horizontal axis, time is given in a day and on the vertical axis, there is electricity demand. The objectives of these load shapes are discussed below:

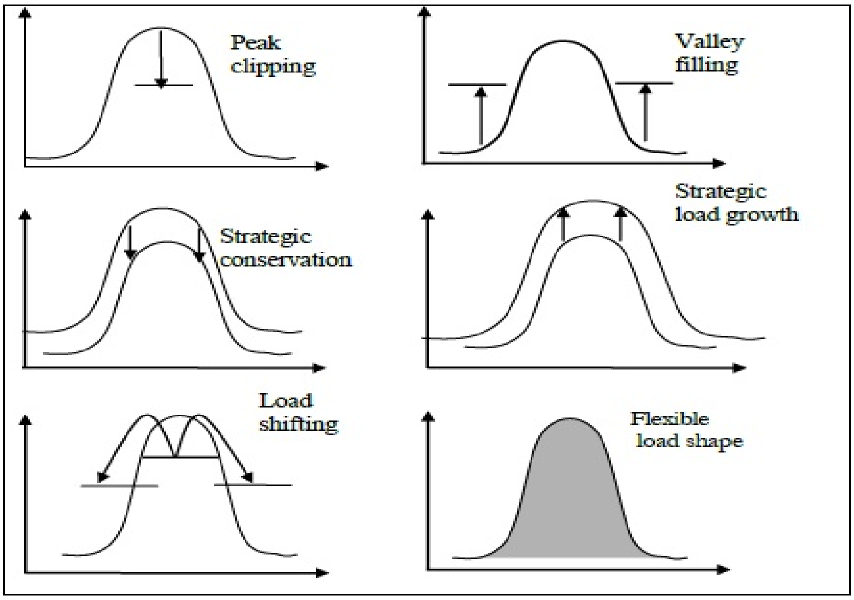

Figure 3.3: Different Load Shape Objectives

- **Peak Clipping** minimizing load at peak hours using DLC
- **Valley Filling** Developing load strategically during off peak hours.
- **Strategic Conservation** Reducing overall load through efficient steps by decreasing wastage and power losses. Example of this case is power factor improvement of appliances.
- **Strategic Load Growth** Increasing the load strategically consuming to improve economy considering the increase in demand.
- **Load Shifting** transferring the burden of customer usage to the off peak hours from peak hours.
- **Flexible Load Shape** decreasing and increasing particular loads and tariffs while targeting to handle appliances flexibly.

3.4 Demand Response as a solution

Demand response is a form of DSM that serves to adjust the load behaviour for a short-term to reduce maximum usage required to balance the edge of safety among demand, production and transmission capacity. The phrase has recently emerged to describe a number of price architecture, technologies, programs and related facilities that allow users to amend their power needs due to usage signals. The most precise definition of demand response is given by the US Department of Energy (USDOE) as; "Changes in end user power consumption compared to their normal usage patterns in response to an incentive or dynamic prices designed to reduce power consumption in times of high wholesale prices or at the time when network reliability is concerned" [28].

The demand response gives benefits as asset funds, which enhances the proficiency of intensity supply. These advantages can be separated into two principle gatherings: benefits that straightforwardly aggregate clients, and advantages that can not be estimated in numbers but rather that they can significantly affect the working of the power advertise. Figure 3.4 shows the direct and indirect benefits of the demand response [9].

Direct Benefits	Indirect Benefits
participant bill saving- bill savings and incentive payments earned by customers that adjust their demand in response to changes in supply cost or other incentives	**Market performance** – reduces the ability of generators to excise market power
Bill saving for other customers - lower wholesale price that results from demand response that translate into lower electricity rate for all customers	**Improved choice**- customers have more options for managing their electricity cost
Reliability benefits- reduction in the likelihood and the consequence of forced outages that translate into reduced financial costs and inconvenience to customers	**Reduce Emission** -Depending on supply mix and the way it is deployed, demand response may result in reduced environmental emissions (Keith, Biewald et al. 2003)

Figure 3.4: Benefits of Demand Response - Direct and Indirect

3.5 Demand response' microeconomic analysis

Economic theory states that the most efficiently resources are used when consumer choice is based on the price that contemplates marginal utility costs. In a power advertise this is translated by the purpose of crossing point of the free market activity lines. This intersection point is defined by the equilibrium point which indicates the prices and consumption levels compensated in the market. Figure 3.5 shows the demand and supply curve applied to the electricity market, indicating an equilibrium point (Q *, P *).

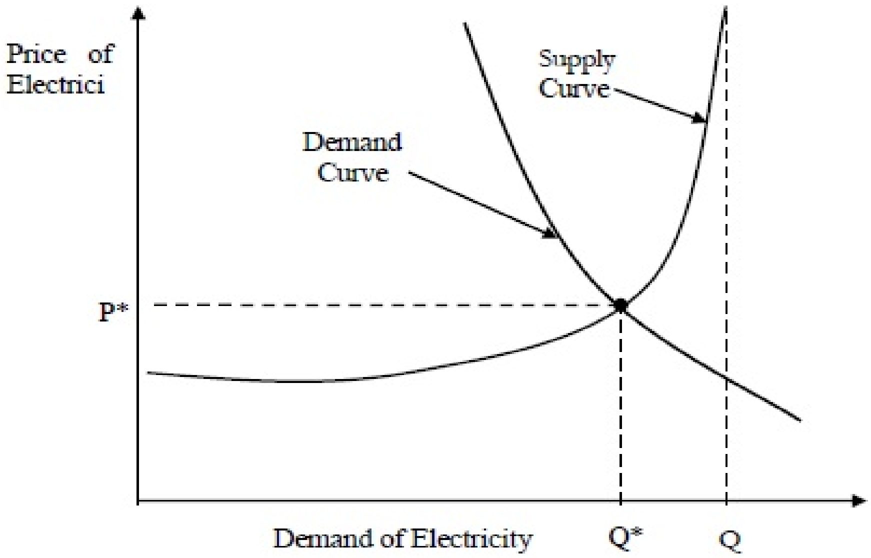

Figure 3.5: Demand and supply curve showing equilibrium at point (Q*,P*)

In the power advertises, the minimal supply bend is shaped by requesting generators from lower to higher working expenses. Because of the specialized parameters (e.g. limit constrains), the supply bend for the most part rises essentially to its furthest cutoff points and closures at the greatest generation limit Q, making the bend soak and non-direct. This implies when the interest approaches the most extreme introduced limit, each expansion sought after causes ever more elevated expenses contrasted with the past esteem. The interest bend drops from left to right and demonstrates a diminishing quality.

In the event that the cost paid by the shopper never shifts, the interest shows up totally inelastic and is portrayed by a vertical line. Notwithstanding, in contrast to different products, power request changes after some time in accordance with business exercises and the examples of life and utilization of private buyers. Since this adjustment sought after is because of components other than value, it very well may be spoken to by changing the interest bend in a standard microeconomic example. Figure 3.6 shows the change in the graph of demand from a peak usage required according to demand to a high usage required according to demand. When demand is below the level set, the wholesale market disappears ($Q_{offf-peak}$, $P_{0ff-peak}$ and in times of high demand, the wholesale market appears at the point (Q_{peak}, P_{peak}).

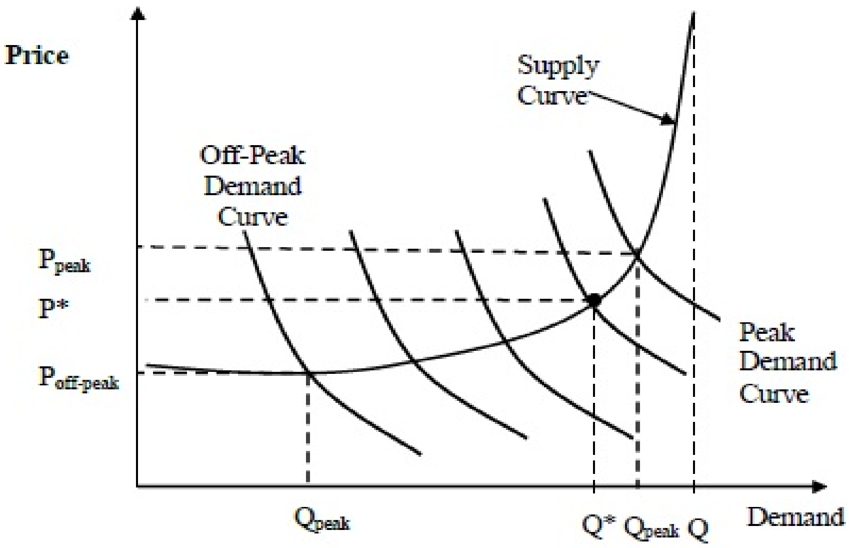

Figure 3.6: Multiple demand curves at different points of equilibrium on supply

3.6 Advantages of Demand Response

Advantages of demand management incorporates economic efficiency improvements, greater supply security, lower price volatility and incentives for exercising market power, and lower investment in maximum production. The accompanying areas clarify a portion of the advantages of microeconomic examination.

3.6.1 Advantages of Demand Response on utility side

Benefits of Demand Response on the utility / consumer side are [9]:

- **The financial benefits of participants** incorporate charging and motivator installments gotten by clients that alter their power request in light of variable power rates or impetus programs.
- **The financial benefits throughout the market** are lower wholesale market prices because the response to demand avoids having to use the most expensive plants to manage in times of high demand, resulting in lower costs. Production and cost of electricity for buyers. In the long run, a much flexible demand response reduces the overall potential needs of the system, allowing collection service providers (utilities

and other retail providers) to buy or develop less new volume. In the end, these adjustments can be transferred to most first hand user or customers.

- **Advantages in terms of reliability** are security in operations and adequate savings, as the management of demand reduces the likelihood and consequences of forced interruptions/outages/black outs, which results in commercial prices and disadvantages for users as well.
- **Market performance** points of interest allude to estimation of interest reaction in mitigating the capacity of provider to practice showcase control by expanding power costs fundamentally more than the generation costs.

3.6.2 Quantifiable National Benefits of Demand Response

DOE recently shows statics that discussed quantifiable benefits of demand response, assessed systematic methods used, and observe ten studies that evaluated the advantages of proposed or actual response scheme for particular areas. The observations show significant instantiates in today's demand measurement.

So far, the quantification of the response to demand is very inconsistent. In order to judge the advantages of demand response three different category has been presented; The surveyed time horizons and performance categories are vary widely.

- **Illustrative analyses** measure the financial effects of interest reaction; the four examinations inspected here search inside sorted out discount markets. These investigations report moderately elevated amounts of advantages to some degree since they expect abnormal amounts of interest reaction entrance over a vast client base and long haul supported advantages.
- **Integrated resource planning** ponders take a gander at whether and the amount to utilize request reaction assets as a major aspect of a long haul asset plan. These examinations accept local effects over quite a while period and report abnormal amounts of interest reaction benefits.
- **Program performance** contemplates measure the genuine conveyed estimation of interest reaction programs actualized by a few free framework administrators stated that the most minimal dimension of demand response advantages, to a limited extent

since they reflect economic situations over a brief span period and don't really catch the full scope of market conditions or esteem long haul impacts.

Figure shows the impact of Demand reaction in the enhancement of power showcase when user knows that he/she will be benefited to use lesser power during peak hours. It shows that, during peak hours, the demand reduces from Q_{peak} to $Q*_{peak}$ having lesser price of $P*_{peak}$ instead of P_{peak}. It would have a vertical line on curve if user won't be getting any incentive as shown in figure 3.6

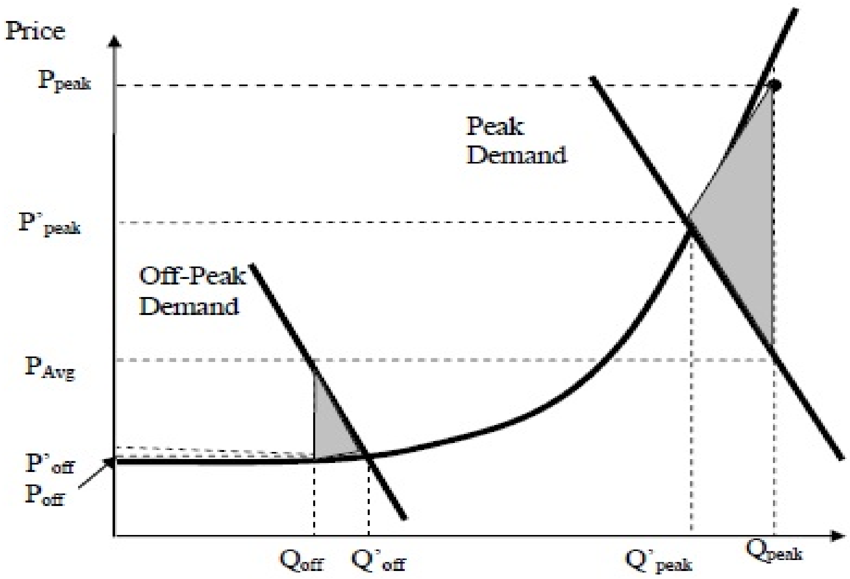

Figure 3.7: Effects of Demand Response on Economy Value of Market

Figure illustrates the effect of demand response on the system reliability. It shows that if reserve mills of the supply system is not sufficient to cater peak demand (i.e. it is not about 17% as mentioned earlier in the introduction section), then there may come a time when demand exceeds supply to be D1, and in such cases electricity outage occurs. The demand is reduced to D2 to overcome with this problem.

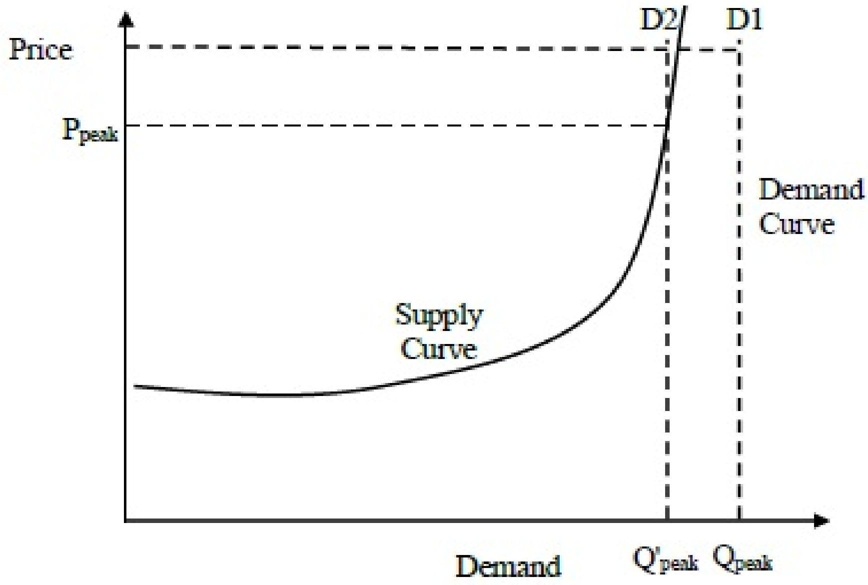

Figure 3.8: Effects of Demand Response on Reliability of the Network

Chapter 4

Behaviour in the use of energy use by domestic consumer

4.1 Scope and Objective of the Chapter

There are three fundamental ways to reduce electricity consumption in residential sector:

1. Reconstructing the domestic infrastructure (houses) with thermal efficient material and design.

2. Replacing the existing appliances with the energy efficient ones.

3. Changing user behaviour of how to use appliances by giving them awareness about load management or by making them change it by implementing automatically controlling infrastructure.

Power demand analysis always tries to centre on the two above mentioned methods. Lutzenhiser emphasizes in his literature research on socio-behavioral energy particularly on research and political paradigms that limit the analysis of energy consumption and its usage; "a physical, technical and economic model (PTEM) of electricity consumption" that work on examination of energy demand forecasting and planning of its policy [29]. "PTEM" considers the energy consumption of houses depends mostly exclusively on the physical properties of the houses and the efficiency of the appliances of the houses. The Lutzenhiser study showed that these models highly underestimated and sometimes neglected, for example, the importance of human behavior for the energy consumption of residential buildings.

This chapter discusses about the researches about human behaviour of using energy and how it is effected by the price change to determine what method should be best chosen for demand response and how that should be implemented in order to attain maximum peak reduction from maximum number of users.

4.2 Behaviour of Energy Consumption of Households

Different dwellings in households use energy differently, and this variation in the energy usage is enormous. These variation can be related to differences in technical and economic factors, type of appliances used and home environment (like number of dwellings, age group of the dwellings, ethnicity or race). Even though when these factors are controlled, individual homes still vary enormously in their energy use.. This was demonstrated for the first time in the study done at Princeton Center for Energy and Environmental Research [30]. In this study, Sokolow and his team claimed that houses having the same size, occupied by similar occupants with same devices and in the same geographical location, vary up to 200% of energy consumption. When these households were checked again after switching to the same standard, significant changes in energy consumption were observed again [30].

Similarly, another study that analyze the usage behaviour of ten, 100% of the same, habitat for homes with the same equipment and appliances claimed that from the lowest to highest consumer, energy consumption can vary by 260% [31]. Investigations of this type of research conducted by Lutzenhiser in the year from 1970s to 1990s analyzed that 'consumption in the domestic region seems to have diversity and change characteristics, with human behavior that contribute in start-up and maintenance of both long-term and short-term improvement in power usage [29]. These results show that a strategy of intervention designed to promote sustainable behavior can lead to significant savings.

4.2.1 Analysis of Behaviour of Energy Consumption by Households

The study of energy consumption behavior focuses on how energy is commonly consumed and what it means to the user, and how it can predict the likely success of efforts to influence preferences, behavior and consequent decisions. Studies of energy consumption behavior identifies that human behavior is one of the main drivers of energy demand [32]. When it is practiced in single way, the energy and power usage and merged issues decrease, and when it is triggered in a different direction, it is increased. These studies also assume that individual behavior is attractive and, therefore, the search for social, monetary and mental improvements to produce the subjected result [33] and [19].

The study of energy consumption behavior by an individual can be generally classified in the subject of economics, calculating electricity /load/demand based on price and income elasticity, and collecting psychological research that affects behavioral and behavioral attribute information of individual decision-making to improve energy efficiency and give up some of the benefits of energy consumption [34]. There is a document which specifically classifies household energy usage as a very common social issue.

4.3 Elasticity of price in Electricity Demand

Many studies on the electricity demand in the housing sector have identified the flexibility of electricity demand associated with price changes. The measure of flexibility is the revise in customer usage during the same duration as cost changes, called as own price elasticity (often referred to as price elasticity). It is written technically and mathematically [19]:

$$PE = \frac{\Delta Q}{\Delta P} * 100\% \tag{4.3.1}$$

Where PE is the price elasticity, ΔQ is the change in electricity demand resulting from ΔP price change[19].

A second computation of load displacement behavior is called as the elasticity of substitution. It is described as the anti percentage change in the peak to peak peak ratio, divided by the percentage change in the peak to contour ratio. Mathematically, it is written as:

$$PE = \frac{-\Delta Q_{peak}/Q_{offpeak}}{\Delta P_{peak}/P_{offpeak}} * 100\% \tag{4.3.2}$$

Where, PE is the price elasticity of substitution or price of incentive provided in case of shifting from peak to off peak, the elasticity in price of substitution is calculated as the ratio of percent change in relation to the electricity peak price to off load peak price, $\Delta P_{peak}/P_{offpeak}$ and the percent change in the peak demand to off peak load demand, $\Delta P_{peak}/P_{offpeak}$. Price elasticity of substitution can be matched to the own price elasticity when the complete information is available [35].

This price elasticity in electricity demand can be considered for both short term and long term improvements. In short term improvement, user make no changes in the infrastructure of the existing appliances rather change the lifestyle behaviour to manage the load, while the case of long term is vice versa whee user change the whole infrastructure of its household in order to consider the price elasticity in electricity demand. Example of long term improvement is the intruction of IoT (Internet of Things) technology and example of short term yet cost and quick results effective is Demand Response.

4.4 Dynamic Pricing impact on Electricity Demand

Programs of dynamic pricing of electricity include Critical Peak Pricing (CPP) and Real Time Pricing (RTP). These type of scheme typically include a demand side management as households are informed about the change in prices over the period of time in a day. In the literature, a residential dynamic pricing program is described by the Commonwealth Edison of Chicago in the United States [19]. The sceheme utilizes less expensive technology like Internet, SMS) to give information its subscribers of current electricity prices. Customers are informed about the Internet one day before the hourly rates, who then receive a special message or 'Price Alert' of SMS and email The cost of energy consume overreach the designed particular level that is, for example, 0.13 cents / kWh in 2006 [36]. The participants of this program in the domestic sector amounted to around 350,000. This temporary increase in the electricity tariff led to an average reduction of 1 kW per customer [6] with a high price elasticity of electricity of -0.79, which was being recorded for peak demand and for the off load peak demand, it was -0.18. [37].

4.5 Price Unresponsiveness

The previous study focus on the impact of behaviour of consumer in the electricity consumption, and the results of many studies depict that domestic consumers are responding to a variable prices over time, an analysis presented by Reise und White depicts that a considerable amount of domestic consumers don't respond to changing electricity price. Based on comprehensive data for a sample of around 1,300 families of California, the analysis of the model depicted an extremely asymmetric transmission of household price elasticities in the overall price elasticity of electricity of -0.39 as an aggregate of the overall households. A significant percentage of households, 44% did not put any pust for any price reaction. Families have reacted more with large appliances such as cooling and heating of indoor units. Based on their conclusions, White and Reise [38] came us with an analysis that families have been categorized in 2 main bodies: those who used electricity for heating or cooling i.e using big appliances and they respond to the changing prices and the other group do not frequently use these biug appliances and thus don not participate in the changing price having zero response in the price elasticity. Figure 4.1 shows the survey results done by Reise and White to determine the response of households participating in price elasticity on the houses of California.

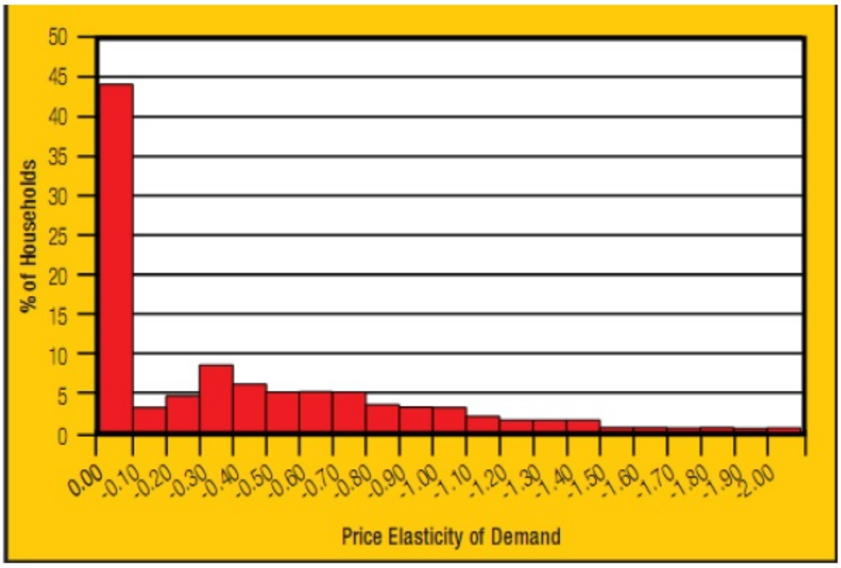

Figure 4.1: Response of households to the Dynamic Pricing; Survey

Chapter 5

Framework of the Automated Load Scheduling Algorithm

5.1 Scope and Objective of the Chapter

This section presents

5.2 Classification of Household Appliances

A typical household appliances are categorized into two main categories; schedulable and non-schedulable and each of them are further divided into two sub-categories [39] explained below.

5.2.1 Schedulable Appliances

Schedulable appliances are the ones which can be scheduled at any time throughout the day such that they fulfill user requirement. These type of appliances are further divided into two categories.

5.2.1.1 Schedulable Flexible Appliances

These are the ones which can be scheduled at any time in a day and their operation can also be stopped at any time and can be resumed some time later. Example of these type of appliances includes, charging of appliances like plug-in electrical vehicle (PEV), laptop etc and any other appliances depending upon user priority and type of household.

5.2.1.2 Schedulable Non-Flexible Appliances

This schedulable category of appliances can also be scheduled at any time in a day according of user preferred timings but once they are started operated, their operation can not be interrupted as it can ruin the task performed by them. Example of this kind of appliances include, washing machine, Oven, Food processor etc.

5.2.2 Non-Schedulable Appliances

This category includes appliances which can not be scheduled as their operation is meant to be performed throughout the day or is uncertain. Further classification of this type of appliances are mentioned below.

5.2.2.1 Critical Appliances

This kind of appliances are the ones which are required to be operated throughout the day without any interruption, except for some uncertain and unplanned events, to meat the user requirement of a comfortable lifestyle. Example of such appliances include refrigerator, central air-conditioning or heating system etc.

5.2.2.2 Luxury Appliances

Television, Cell phone, gaming station and other similar appliances fall under this category whose operation purely depends upon user mood and user does not want them to be scheduled at some particular timing.

5.3 Controller Inputs

The controller receives the pricing model from the utility supply for the whole day and schedule the load accordingly and the user is being informed. Any changes in the market pricing model, or the sudden changes in the peak load hours due to increased demand of the user is also received by the controller and it changes its schedule accordingly.

The increased pricing for an hour is the indication of the peak load hour, thus the controller reschedule the appliances in the run time, as the system follows Real Time Pricing (RTP) model. In addition, the controller also receives the user settings for its priorities and requirement of every appliances. Since a domestic dwelling can have a limited demand, it is also signaled by the controller if its demand exceeds a particular threshold thus making the entire supply system organized automatically.

5.4 Decision Making of Automated Load Scheduling (ALS) Algorithm

The aim of this proposed ALS algorithm is to schedule the appliances fall under schedulable category as per the user desirable timing in a best possible manner and is targeted that the total load can be maximally evenly distributed throughout the day, thus satisfying user comfort level and reducing the peak to average power consumption thus reducing the user billing amount as the billing cost increases with increase in the total consumption of load at one particular time since quadratic cost function is applied with Real Time Pricing formula so that user can be encouraged to curtail extra load.

To achieve this goal, dynamic programming algorithm is applied in an iterative manner such that the whole time zone of a day is broken into 24h time. Each appliance is scheduled within the range of timing preference given by the user. The appliances with higher priority level are scheduled first. The cost function also includes the energy consumption of the already scheduled appliances while calculating the cost for the current scheduling appliance as the quadratic function of the cost suggests increase in load will increase the cost. The cost coefficients for every hour is different to compensate for the reduction in peak load and its evenly distribution by every user.

As mentioned in figure 1, according to the proposed algorithm, when the controller will receive the pricing signal for the whole day with different prices at each hour, the appliance with highest priority level will be scheduled over the span of 24h. After that, the appliance with next high priority level will be scheduled for 24h time keeping in consideration the schedule of the already scheduled appliance. The target for this appliance will be to have a schedule with the least overlapping considering the user desired operating timings thus reducing the peak level. Same procedure is repeated with the next schedul-

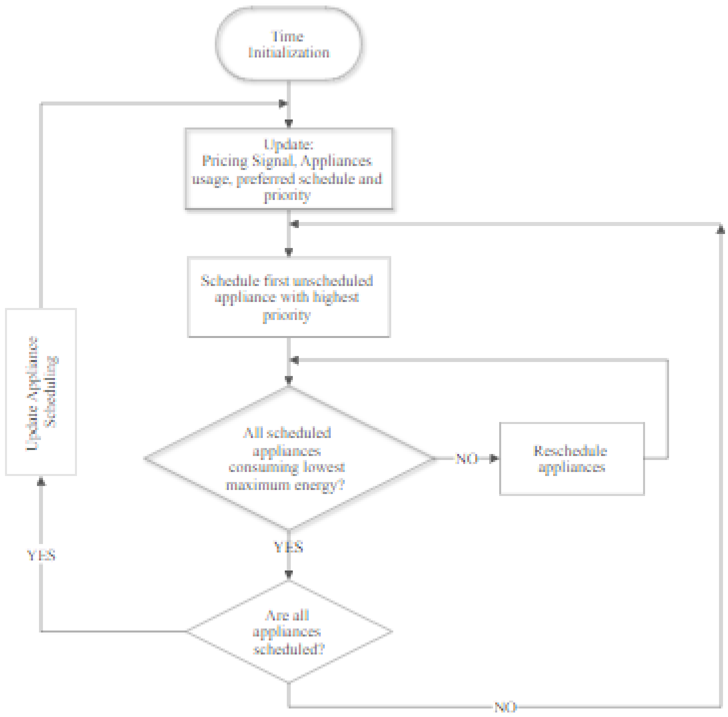

Figure 5.1: Automated Load Scheduling Algorithm.

ing appliances. This target is achieved by multiple iterations until the desired outcome is achieved. For example, if three appliances are to be scheduled which have same desired time range of of operation lets say 6h to 10h, then the appliance with highest priority level will be scheduled at the earliest let say at 6h to 8h, then while scheduling the second one, it will aimed to have it not scheduled between 6h to 8h rather it will be scheduled between 8h to 10h. Then the third one's schedule will overlap the timing of the one having least consumption among all the already scheduled appliances.

The constraint of this algorithm is the user satisfaction level which is measured by user desired timing and priority level for each appliances.

Chapter 6

Technical Overview of Relative Optimizing Techniques

6.1 Scope and Objective of the Chapter

In this chapter, the work on the optimization of various programs of Demand Response is being reviewed. Since optimization is defined as determining the conditions that provide the maximum benefit or cost for a process [40], most of the published studies on how to optimize DR programs focus to minimize overall energy use and / or maximize social welfare. The term, social welfare refers to all the parameters which benefits the society including supplier as well as consumer in terms of reducing Peak to Average Reduction of power (PAR), minimizing the CO2 and other waste emission and many other benefits [41]. Therefore, the achievement of maximum social welfare is focused in most of the studies as it is directly or indirectly related to national benefit.

The goal of the optimization is to determine the set of variables that minimize (or maximize) a function (or set of functions) of that set of variables while subjecting these variables to a set of limitations/constraints. This set of variables is known as the design vector, while the function is called the objective function. This design vector is defined by the conditions or objective function variables of the specific Demand Response problem. For example, in load scheduling, the design vector might be determined by the beginning time of the demand request, the time of operation of the load, the type of load (e.g. the type of device in the consumer's residence) and the priority of the load. In a system based on energy management, the design vector can also be defined by the type of load, the amount of reduced power and the duration of the load at reduced load.

The objective function is defined on the basis of desired property that is optimized, for example, total energy consumption or social welfare. After that, the constraints are determined on the basis of conditions of the DR system being tested. Typical parameters that limit the optimization problem are associated with the system performance reduction function, energy storage constraints and device constraints (e.g., the total energy required to operate a particular appliance).

6.2 Related Work

Optimizing the components of SG with DSM and DR is a difficult task. Several solutions have been proposed and implemented that aim at optimizing a single target, i.e. Single Objective Optimization (SOO) or optimizing multiple targets i.e. Multi Objective Optimization (MOO) with a compromise between different specific objectives/targets. Some are cited in [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63] and [64]. Due to its importance and evolving needs, the DSM has been an active topic for over two decades. The articles focus on user comfort, cost-cutting on the consumer side and lowering the PAR, which use directly or indirectly the study of mathematical, statistical and biologically and artificial intelligence inspired techniques for optimization. These approaches reduce the electricity load of consumers by shifting electrical power load to the system's own energy resources and maximizing user comfort under many different constraints. Algorithms proposed in [45], [59] and [61] formulate the problem of optimization as MOO, where as algorithm presented in articles other than these three, formulate the problem of SOO.

Therefore, the local optimization method in the field of energy consumption optimization of electrical power load was discussed [42] - [46], [47] - [50]. In [42], a 30-minute time interval of a mixed model using real-time price planning (RTP) and a finite time horizon including mixed nonlinear programming were formulated. The proposed plan includes smart electrical and thermal appliance. In this mode, the maximum cost is reduced by 22.2% and the current pricing scheme is reduced by 11.7% while changing the peak load from electrical to the thermal source. The author of [43] focused on energy storage and proposed an optimal planning method based on linear programming to minimize energy costs. The method discussed saved the average cost of 20.39% and made it possible to reduce average peak load by 21.6%. Likewise, researchers in [44] tried to minimize costs and reduce peaks in order to balance single house loads using mixed integer linear programming. The results of the simulation formulated cost in real time in the Czech Republic. The objective functions of [45] and [46] are to minimize the total cost of electricity production and individual electricity charges.

The formulated model of [45] depends on socioeconomic factors (family distribution, employment status and number of people) and load priorities given by users. The simulation results are based on the actual data of UK, Department of Energy and Climate Change and the actual electricity price is used for implementation of multifunction mixed integer plan. The authors of [46] and [47] conducted dual cooperation game theory for energy management. Multiple utilities and multiple consumers are considered with plug-in electric vehicle (PEV) by [46] and [48] while plug-in bicycle is considered by [47] and also selling out surplus electricity to the respective utilities is considered by them thus resulting in the beneficiaries for both the consumer and the electricity provider.

The determination of peak demand model in residential areas is discussed in [49] using the RTP of the four scenarios. Quasi Random Process has been introduced to represent the number of finite home appliances, and recursive formula to determine peak demand are being implemented. The result of this approach is compared with the number of undefined number of appliances that can cause significantly high peaks. HEMS Intelligent Algorithm was developed in [50] to reduce cost and overall energy consumption as part of the TOU method without compromise/limiting user comfort.

Artificial intelligence technology using bio-inspiration is used in [51] - [57]. In the research of [51], the author has defined a distributed framework to cover cost under a grid for various consumers and an algorithm based on greedy iterative methodology is developed that optimize the home appliances according to the number of dwellings it has (low, medium, high) and to the RTP (real time pricing) signals. Depending upon the total load on the network, the electricity rates is known to each user a day ahead. In this task, a penalty cost function has been defined to achieve coordination between consumers. Experimental and analytical results show that this proposed algorithm reduces user's electricity costs and minimizes power generation costs considering peak loads. The author in [52] proposed an autonomous system that uses Genetic Algorithm (GA) as a method based on artificial intelligence and evolves communication technologies. The proposed system based on the distributed generation (DG) pattern in [52] allowed bi-directional flow to maximize user-friendliness at minimum costs for electrical and air energy. The experimental results from the four scenarios show a high saving of 32.73% electricity costs among all scenarios. But the author completely ignored the cost of maintenance and installation by DG.

Demand Response problems such as user comfort level disturbance are explained in [53]. In this research paper, based on Markov's decision model, energy management problem is formulated as problem of strength training. The simulation result is expressed by the planner's Q learning algorithm. Another phenomenon called DR peak cutting within microgrid is considered in [54]. The author analyzed the peak cutting, corrected the load curve, compensated for the uncertainty of photoelectric and wind energy. The Binary Particle Swarm Optimization algorithm is used for simultaneous controlling schedule of participant loads and electric vehicles in the presence of photovoltaic and wind turbine power. This approach reduces cost and emissions according to the mentioned simulation results.

The authors introduced DSM controllers to avoid peak loads using BPSO, GA and Ant Colony Optimization (ACO) algorithms in [55]. GA was proved to perform better among other two algorithm shown through the experimental simulation results. User comfort function is formulated to minimize cost and limit appliance operation latency in [56]. In this research, the adaption of the WDO (Wind Driven Optimization) algorithm is done and the problem of home appliance scheduling is targeted based on minimum minmax regret based knapsack technique, minimizing the electricity cost and peak load. The observation result shows the PAR reduction of 8.7% and the energy cost reduction of 39.04% in the TOU tariff schedule. In addition to these problems such as high cost, user comfort, maximum load reduction, researchers also focus on predicting the burden beforehand in order to cope with the price level situation one day before the usage. This problem was focused by [57] and its solution was presented using artificial neural network to schedule the home appliances a day ahead by forecasting their load and it became successful to achieve 97.11% of accuracy.

The author in [59] targets SOO and MOO. Dynamic programming was adapted to do single objective optimization while targeting objectives of maximization of total power usage limit, and minimization of total electricity cost and carbon dioxide emissions. In contrast, evolutionary algorithm (EA) is adapted to solve multi objective optimization problem. The objectives targeted in this research paper are to minimize the cost of electricity, to maximize the total number of allowable electricity usage and to minimize CO2 emissions. In [61], the author has introduced different levels of comfort to calculate the level of user comfort to solve the problem using MOO. The simulation is done using PSO which is modified to resolve the most complexed goals such as minimization of cost and maximization of user comfort level.

6.3 Summary

Table summarizes the entire major research done in this field while highlighting the optimization techniques used, the objective functions targeted and their limitations [65].

Table 6.1: Comparison of Techniques used in Optimization of Appliances (Part 1)

Technique	Domain	Features	Findinds	Limitations
Linear Programming [43]	Smart charging and scheduling	Battery storage and utility of plug-in hybrid vehicle (PHEV)	Minimize PAR and electricity cost	User comfort was sacrificed completely
Mixed Integer Linear Programming [44]	Residential appliances scheduling using Home Area Network	Triple Control Service simulations	Peak load and cost minimization	User comfort/ satisfaction avoided
Multi-objective Mixed Integer Linear Programming (MILP) [45]	Appliances modelled considering multi level preferences	Electricity bills reduction as well as its production	User preferences considered while lowers the production cost	PAR unconsidered and real time changes are not catered
Double cooperative game theory [46]	Incorporated multiple users and multiple utilities, and PHEV is also considered while scheduling other appliances	Appliance scheduling and selling back energy using PEV	Electricity cost reduced at both user and utilities side	PHEV unconsidered
Wind Driven Optimization (WDO) [56]	Single home scheduling	RES integration to schedule appliances	Waiting time reduced along with cost	Maintenance and installation cost not considered with electricity cost
Reinforcement Learning [53]	Appliance scheduling of domestic and commercial users based on decision making	Forecasting price and then scheduling appliances	Cost minimization and user comfort maximization	Peak can be increased while maximizing user comfort and reducing cost

Table 6.2: Comparison of Techniques used in Optimization of Appliances (Part 2)

Technique	Domain	Features	Findinds	Limitations
Game Theoretic Energy Management [47]	Appliances scheduling using Plug in bicycles and utility electricity	Energy selling back to supply	Consumer bill reduction and load minimization	Overlook user comfort level
Quassi Random Process [49]	Estimation of peak demand	Peak demand determination without considering number of appliances	Load shifting is done using recursive formula while calculating peak demand	User comfort not considered and peak demand can overburden utility when particular number of appliances are not considered
TOU based scheduling [50]	Appliance scheduling for multiple users	Time and energy consumption optimization for appliances	Peak load and cost minimization	User is forced to cut the load thus sacrificing its comfort
Greedy iterative algorithm [51]	Appliance scheduling considering aggregated load	Energy usage and cost minimization without effecting user comfort	Cost minimization, peak load reduction and load shifting	Burdened utility, increased electricity cost due to aggregate impact of personal benefit and neglected user benefit
Genetic Algorithm [52]	Various DG's cooperation within multiple home scheduling for both electrical and thermal loads.	Electrical and Thermal load calculation	High degree of user comfort and operating cost minimized	No measuring parameters are considered for PAR
GA, BPSO and ACO [55]	Knapsack based single and multiple home appliance scheduling	Peak load control using RES	PAR and cost reduction and user comfort maximization	RES installation and maintenance cost not calculated

Chapter 7

Modelling of Automated Load Scheduling System

7.1 Scope and Objective of the Chapter

In this section, mathematical modelling of the problem which is solved, the objective function of the ALS algorithm and its constraints with respect to each category of appliances is presented.

7.2 Problem formulation

The controller takes the information from user for the usage of different types of appliances in terms of wattages for the whole day, utility time interval (UTI), preferred utility time interval (PUTI) and power levels. Discrete power level scheme is used in this algorithm which represents that some appliances may be operated at different power levels consuming different energies at each power level and it can be selected according to the requirement and constraints, making the system more flexible [66].

The pricing model applied for the usage of electricity is a quadratic function of total energy demand and load which is given by

$$y_t = a_t.x_t^2 + b_t.x_t + c_t \tag{7.2.1}$$

where y_t is the total cost of the demand or load x_t at time t, whereas a_t, b_t and c_t are the costing coefficients whose values are set by the utility supply after considering the user behavior in electricity usage and market congestion to reduce peak to average ratio (PAR) od load. Whereas, t $\in$ T = 24, which represents the values of the variables at tth hour. Figure 2 illustrates the change in trend of cost function for different values of a_t, b_t and c_t at different time intervals.

The day ahead quadratic pricing model used for the scheduling of appliance [67] implies that the increase in energy demand or load will make the cost high in a non-linear manner thus convincing the user to reduce the electricity usage [68]. Refer to 7.1 for the understanding of this pricing strategy. The pricing signal obtained from utility supply is applied as a quadratic function of the load scheduled at time t, and the next scheduled appliance at the same time t will have an amount w_t added to its load, which is the load of all previous appliances scheduled at that time while calculating the cost at that time and then that cost will be subtracted by the cost of all previously scheduled appliances. For example, to calculate the cost of n^{th} appliance at time t, the load of all previously scheduled appliances at time t will be added to the load of nth appliance, shown as

$$cost_{t,n+w} = a_t.(load_{t,n} + w_t)^2 + b_t(load_{t,n} + w_t) + c_t \tag{7.2.2}$$

where, w_t is the sum of all previously scheduled appliances at time t, and is given by

$$w_t = \sum_{i=1}^{n-1} load_{t,i} \tag{7.2.3}$$

Cost calculation of the previous load scheduled is given by

$$cost_{t,w} = a_t.w_t^2 + b_t w_t \tag{7.2.4}$$

The cost of the n^{th} appliance is then given by

$$cost_{t,n} = cost_{t,n+w} - cost_{t,w} \tag{7.2.5}$$

7.3 Modeling of Appliances

The mathematical modeling of power consumption for the appliances are given below.

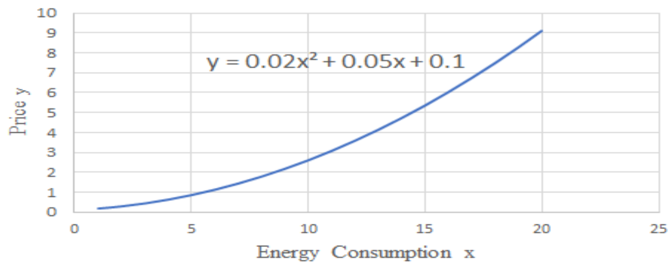

Figure 7.1: Quadratic Pricing Function

7.3.1 Model of Schedulable Flexible Appliances

The power consumption of fth schedulable flexible appliance f $\in$ **F** at tth hour at jth power level is given by

$$P_{f,j}^{t} = s_{f}^{t} E_{f,j} Fpp_{f}^{t} \quad \forall f \in F, j \in J, t \in T \tag{7.3.1}$$

where, s_f^t is the binary parameter that represents the operational status of that particular appliance whether it is on or off, $E_{f,j}$ is the energy consumption of fth appliance at jth power level and Fpp_f^t tells us about the operation of the flexible appliances in the used preferred time period i.e PUTI.

This type of modeling is done in [69] for multi-operation cycles but here, single operation cycle is considered with multiple power levels which makes it more efficient.

7.3.2 Model of Schedulable Non Flexible Appliances

The power consumption of non flexible appliances whose operation should not be interrupted once it is started, can be formulated as the convolution of energy consumption and the binary decision variable representing the starting time of the operation.

$$P_{n,j}^{t} = \sum_{t=ts}^{tf} E_{n,j}^{t} s_{n,j}^{T-t+1} \quad \forall n \in N, j \in J, t \in T \tag{7.3.2}$$

ts and tf are the preferable starting time and the finishing time respectively of the appliance.

Similar kind of modeling is done in [70], [71], [72] , [73] and [74] for single operation cycle and in [69] for multioperation cycle, and in this paper, single cycle is considered with multiple discrete power levels.

7.3.3 Model of Non Schedulable Appliances

Although, the controller does not control the appliances fall under this category but it is important to model its power consumption in order to calculate the cost for these appliances, which will be added as a background cost with the total cost calculated for the schedulable appliances.

Thus, the power consumption for the non schedulable appliance i ∈ I at time t ∈ T can be measured by total energy consumption TEC_i, operational status $s_i(t)$ which is 1 if the appliance is operational and 0 if appliance is non operational, and length of operational time LOT_i and is given by

$$P_i(t) = \frac{TEC_i}{LOT_i} s_i(t) \tag{7.3.3}$$

7.3.4 Objective Function

The objective functions are of the problem stated above are similar to [75] with some modifications and are stated below.

7.3.5 Minimization of Total Peak to Average Ratio (PAR) of power consumed

The peak to average ratio hence load factor is aimed to reduce so that the cost of buying electricity from the supply company can be reduced as well as the supply company may have reduced cost of supplying power to the user by installing thinner power lines according to the requirement, hence both may get equally benefits. The mathematical model for this objective function can be given by

$$Min : PAR(t) = \frac{load_{max}(t)}{load_{average}(t)} \tag{7.3.4}$$

7.3.5.1 Minimization of Operation Cost

The cost of buying electricity from the utility supply is targeted to be minimized by cutting down or by balanced scheduling of the households.

$$Min : Cost = \sum_{t=1}^{T} \rho_{supply}(t) load(t) \tag{7.3.5}$$

where, $\rho_{supply}(t)$ represents the real time pricing of the household appliances which is the quadratic function of the total load and $load(t)$ is the load consumption of a household.

7.3.6 Maximization of User Satisfaction Level (USL)

The first and the foremost objective of the proposed algorithm is to have maximum user satisfaction level which is achieved by scheduling the appliances within UTIs and PUTIs. The mathematical formulation of this objective function is given by

$$Max : USL = \sum_{k=1}^{K} w_k CV_k(t) \tag{7.3.6}$$

Here, subscript k ∈ **K** includes all the appliances in a household, schedulable as well as non-schedulable. w_k is the weight factor representing priority level of the appliance k and $CV_k(t)$ is the user convenience level in using the appliance k at time t. This convenience level is measured by

$$CV_k(t) = \begin{cases} 1; & t \in PTI_k \\ \Big(H(t_{e,k} - t).(\alpha_e.exp(t - t_{e,k})) & \\ +H(t - t_{l,k}).(\alpha_l.exp(t_{l,k} - t)) \Big); \text{otherwise} & \end{cases} \tag{7.3.7}$$

where, H(.) is a Heaviside step function and α_e , α_l are the coefficients of natural exponential functions of the penalty values over the optimization process.

7.4 Constraints

While achieving the objective functions of reduced power consumption for appliances of each category, following constraints must also be kept in consideration.

7.4.1 Constraints for Non Flexible Schedulable Appliances

Since these appliances are the ones which should not be turned off once they have started operated until their energy requirement is fulfilled. This implies the following constraint while scheduling it.

$$\sum_{t=t_{s,n}}^{t_{f,n}} |s_n(t) - s_n(t-1)| \leq 2 \quad \forall n \in N \tag{7.4.1}$$

7.4.2 Constraints for Schedulable Flexible Appliances

The power consumption for the schedulable flexible appliances P_f^t is subject to the following constraint

$$\sum_{t=ts}^{tf} \frac{T=24}{t_f - t_s}.(P_f(t)) = E_f \quad \forall f \in F \tag{7.4.2}$$

Beside the aforementioned constraints, there is a common constraint for both of the schedulable categories which implies that the energy consumption requirement of an appliance must be fulfilled within the user time interval, UTI.

$$\sum_{t=t_s,n,f}^{t_f,n,f} s_{n,f}(t) \leq UTI_{n,f} \quad \forall n \in N,\ f \in F \tag{7.4.3}$$

Moreover, there is a constraint for the user as well that its total power consumption should not exceed maximum power limit of a household and is given by

$$P_K(t) = P_F(t) + P_N(t) + P_I(t) \leq P_{maxHouse} \tag{7.4.4}$$

7.5 Description of Algorithm and Implementation

This optimization problem is divided into two parts Optimization i.e curtailing extra load which is not required to obtain minimum peak and Scheduling the appliances such that to obtain minimum cost as well as peak.

To achieve the above mentioned objective functions, which are summarized in algorithm 1 and 2. In the first step, extra energy, consumed by households, is cut down according to the Total Energy Consumption (TEC) by the user of that appliance. Multiple power levels on which an appliance can be operated are considered to have more options in optimization so that an appliance can be operated on a lower power level for some hours if the pricing is high and necessity of the usage is there in that time interval. So, after optimization of appliances in this step, the energy utilization is optimized thus the reduced peak and average energy consumption is achieved which lead to the reduced cost in every hour.

In the second step, the operation of the optimized appliances' load profile obtained from algorithm 2, is scheduled iteratively at different using dynamic programming technique such that the appliances may be operated in hours that lie inside the utilization time interval specified by user, should achieve the total energy requirement in a day and should also consider the individual constraint of appliance of every category to achieve the minimum cost as well as the minimum peak to average ratio.

User satisfaction level, s_t is also considered and measured while scheduling/optimizing each appliance in accordance to their schedule such that if the operation of an appliance is scheduled under its PUTI, then s_t is assigned with 1, if not then it is measured according to (8), but it is made sure that schedule of every appliance should lie under UTI so that we can have maximum number of willingness to implement this infrastructure in their homes.

Algorithm 1 Algorithm To Optimize Energy

Divide time horizon into $T = 24$ hours

Set the cost formulation for every time interval t and user input to controller

Optimize power profile of each appliance such that $\sum_{t=1}^{t=24} load = TEC$ of every appliance to minimize cost using objective function 2 subject to the constraints given for each appliance category starting from appliance with highest priority to lowest

While $\sum_{t=1}^{t=24} load \neq TEC$ or $s_t = 1$ for not lying inside UTI

Optimize again

End while

Algorithm 2 Algorithm To Schedule Appliances

Set Optimized energy and its corresponding cost profile obtained from algo 1

Solve for Dynamic Programming to minimize PAR such that $s_t = 0$ for t not lying inside UTI considering constraints given for each appliance category starting from appliance with highest priority to lowest

While $s_t = 1$ for t not lying inside UTI

Solve for Dynamic Programming again

End while

Chapter 8

Case Study

8.1 Scope and Objective of the Chapter

In this chapter, the implementation of the proposed algorithm is presented on different case studies.

8.2 Description of Case Study

An hourly profile of power consumption is taken from [76] for the moderately cold week for the month of November for California State in United States of America for their TMY3 updated locations data. The data is generated based on the load consumption, monitored every hour for all days in a year which helped in creating the UTI and PUTI of every load and this data is modified with respect to the corresponding appliance. The residential data of this model is categorized as base, low and high according to the number of dwellings in a home, and LOW category is considered for the testing of this algorithm.

Appliances are put into the above proposed categories according to their usage by the user for a weekday as well as for a weekend and are listed in each category according to their priority in the usage by user as shown in table 8.1 and 8.2 for weekday and weekend respectively. Along with it, total energy consumption TEC by the user for the whole day in kWh is mentioned and power levels of each appliance on which it can be operated is mentioned in kW.

Schedulable and non-flexible are prioritized more as compared to schedulable and

Table 8.1: Controller Input Parameters for a weekday in winters

Appliances	Category	UTI	PUTI	TEC	PL
Cooker Oven	S.N	21:00-24:00	17:00-21:00	6	1.5, 2, 3, 5
Toaster	S.N	17:00-08:00	06:00-08:00	2	0.2, 0.8, 1
Iron	S.N	17:00-07:00	05:00-08:00	2.1	1
Dish Washer	S.N	15:00-24:00	21:00-24:00	3	1.2, 1.5
Washer Dryer	S.N	09:00-18:00	10:00-16:00	4	0.8, 1.2
Vacuum Cleaner	S.N	18:00-24:00	21:00-23-00	1	0.5
Thermostat	S.F	17:00-09:00	17:00-09:00	20.4	1.2
PHEV	S.F	01:00-09:00	01:00-08:00	12	1.9, 3
Refrigerator	C	06:00-06:00	06:00-05:00	1.2	0.05
Gyzer	C	17:00-24:00	22:00-24:00	1	0.12

flexible. Since it is a day ahead scheduling, that is why energy consumption and cost of non-schedulable critical appliances are also calculated to have an estimate of cost and overall peak of the load. However, luxury appliances are not included in the cost and energy calculation as their usage is solely dependent upon user mood. Also, lightning of the home is also not scheduled as it may disturb user satisfaction and user might get discouraged to have this system implemented, so it is controlled using occupancy sensor.

Figure8.1 and 8.2 show the adopted quadratic pricing strategy along with its components a,b and c for each hour for a weekday and for a weekend respectively for winter season. The cost of energy for each hour is taken from Southern California Edison [77].

8.3 Result Analysis

Two different cases have been considered of a same households having same dwellings but different routines on weekday and on weekend to analyse the effects of change in routine i.e having suitable UTI and PUTI on the reduction of cost and Peak Power consumption.

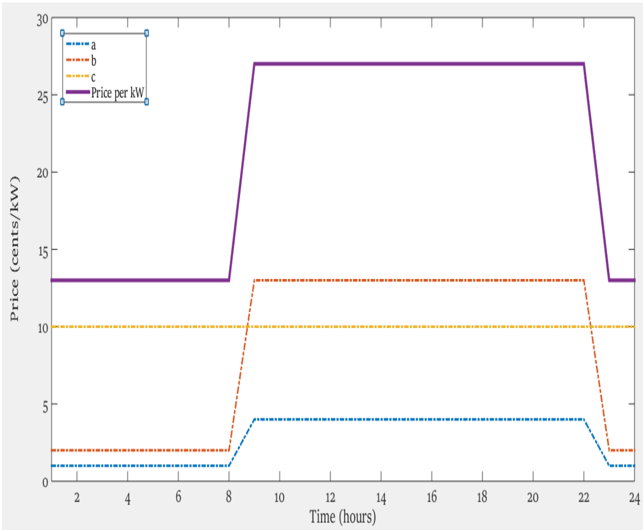

Figure 8.1: Pricing Strategy for Weekend

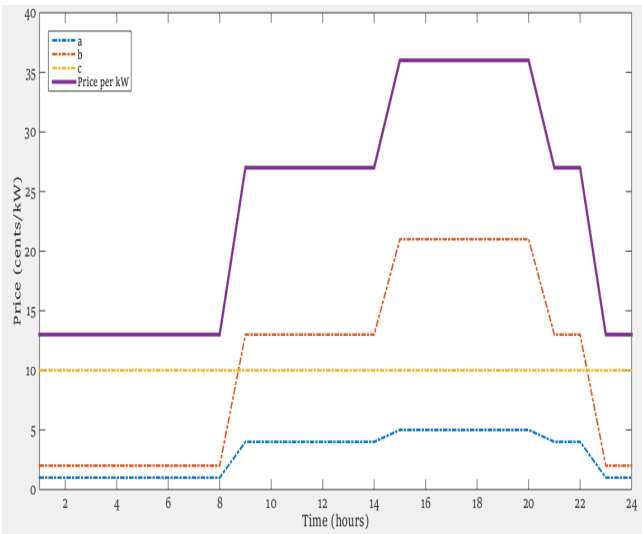

Figure 8.2: Pricing Strategy for Weekday

Table 8.2: Controller Input Parameters for a weekend in winters

Appliances	Category	UTI	PUTI	TEC	PL
Cooker Oven	S.N	19:00-24:00	19:00-21:00	4.5	1.5, 2, 4, 5
Toaster	S.N	07:00-12:00	09:00-12:00	2	0.2, 0.8, 1
Iron	S.N	05:00-18:00	09:00-13:00	2	1
Dish Washer	S.N	19:00-24:00	20:00-24:00	5.7	1.2, 1.5
Washer Dryer	S.N	01:00-18:00	01:00-09:00	5.5	0.8, 1.2
Vacuum Cleaner	S.N	08:00-24:00	09:00-15-00	2	0.5
Gyzer	S.F	10:00-24:00	12:00-24:00	1.4	0.12
PHEV	S.F	22:00-09:00	23:00-09:00	12	1.9, 3
Thermostat	C	06:00-06:00	01:00-09:00	10.8	1.2
Refrigerator	C	12:00-12:00	12:00-10:00	1	0.05

The unoptimized load of the whole day of a week and its corresponding cost is analyzed in figures 8.6 and 8.3 then after applying algo 1 the load profile gets optimized but unscheduled, this along with its cost profile is shown in figures 8.7 and 8.4 and after applying algo 2 the load and cost profile of scheduled appliances are shown in figures 8.8 and 8.5. Similarly, the load and cost profile of weekend for unoptimized, unscheduled and scheduled appliances are shown in figures 8.12, 8.9, 8.13, 8.14, 8.10 and 8.11.

Table 8.3 shows the comparison of peak and average power consumption and cost calculation for both the cases. Since, in the first algorithm, while going from unoptimized results to optimized results, the excess use of load is cut down and is remained only the required load i.e TEC, thus this automatic system installed in a home causes all the operating appliances whose energy wasted, to be shut down and have significance decrease in the cost of electricity while in the second algorithm, the load is scheduled in such a way that it may have lesser PAR which may also result in the more reduction of cost.

While scheduling the optimized appliances through the application of second algorithm reduced PAR from 2.11 to 1.9 having the difference of 21% on a weekday and from 2.99 to 2.73 making the difference of 26%. This great reduction in PAR in weekend causes the greater reduction in cost i.e from 329.8 cents to 130.3 cents that makes up to the difference of 60% while the reduction in cost on a weekday is from 241.6 cents to 138.4

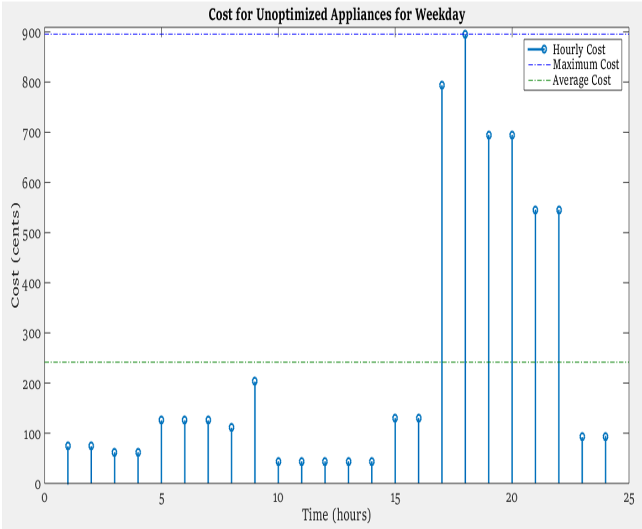

Figure 8.3: Hourly Cost Profile for Unoptimized Appliances for weekday

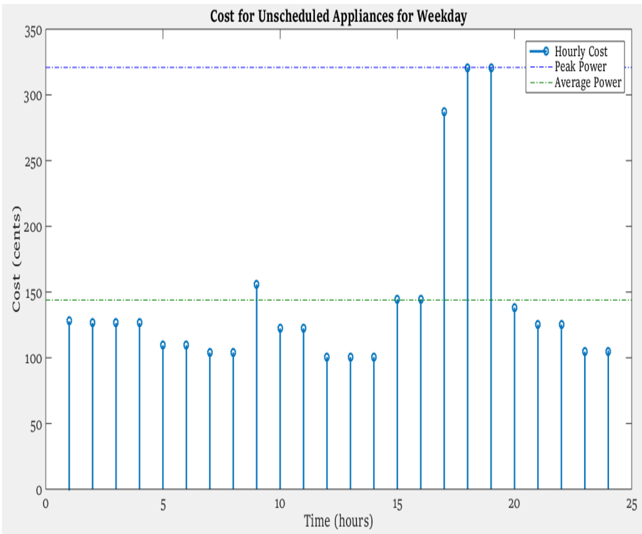

Figure 8.4: Hourly Cost Profile for Unscheduled Appliances for weekday

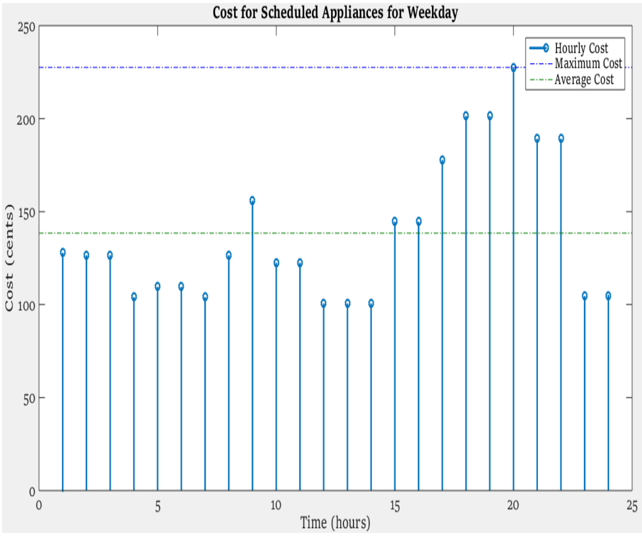

Figure 8.5: Hourly Cost Profile for Scheduled Appliances for weekday

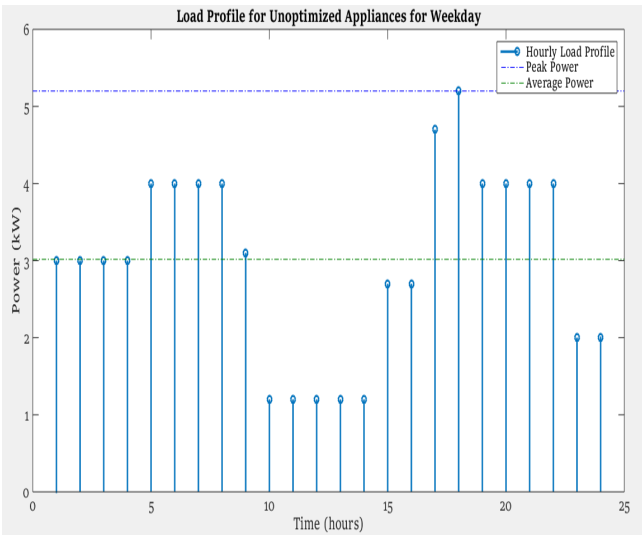

Figure 8.6: Load Profile for Unoptimized Appliances for weekday

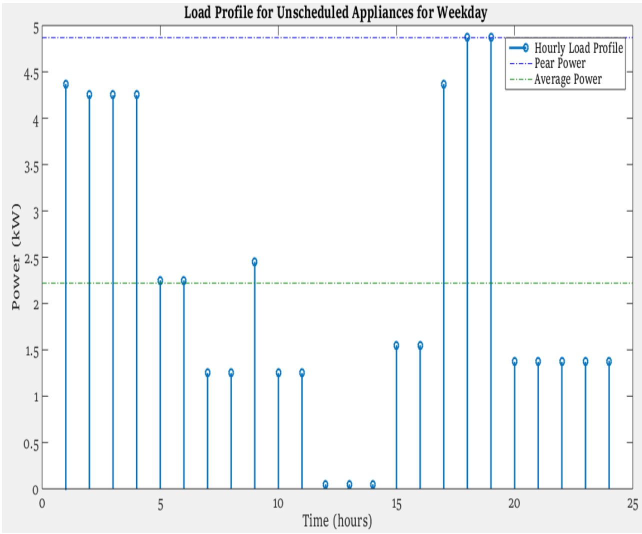

Figure 8.7: Load Profile for Unscheduled Appliances for weekday

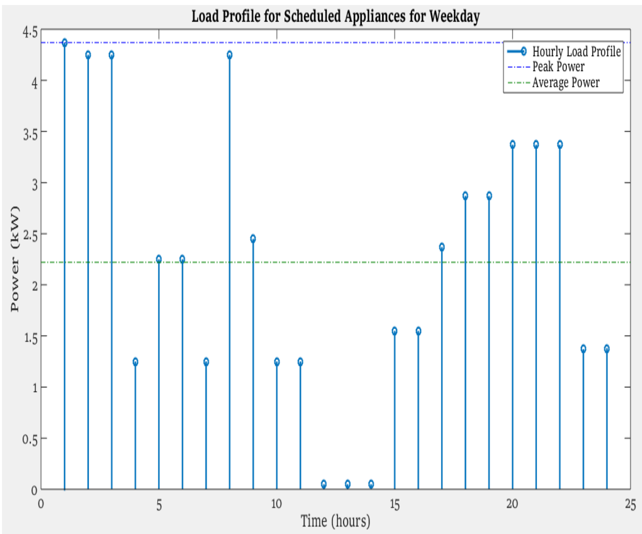

Figure 8.8: Load Profile for Scheduled Appliances for weekday

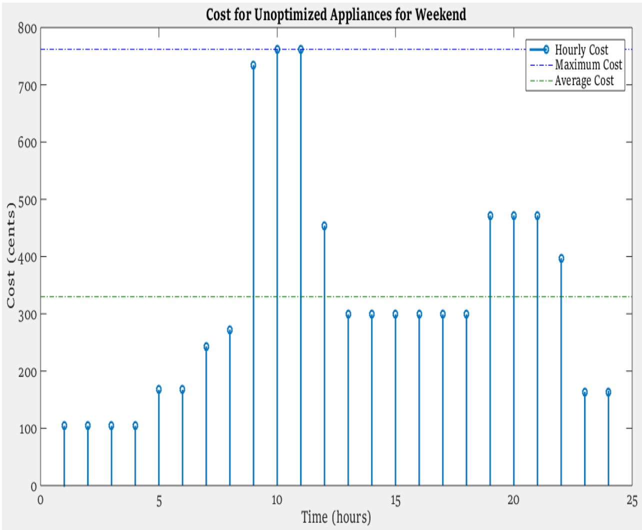

Figure 8.9: Hourly Cost Profile for Unoptimized Appliances for weekend

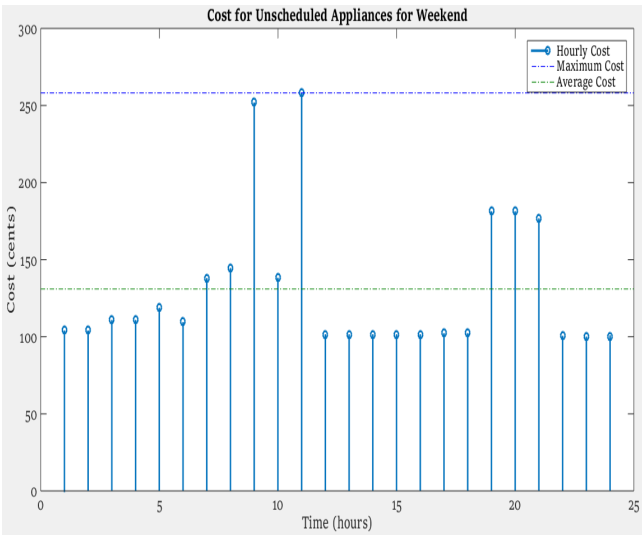

Figure 8.10: Hourly Cost Profile for Unscheduled Appliances for weekend

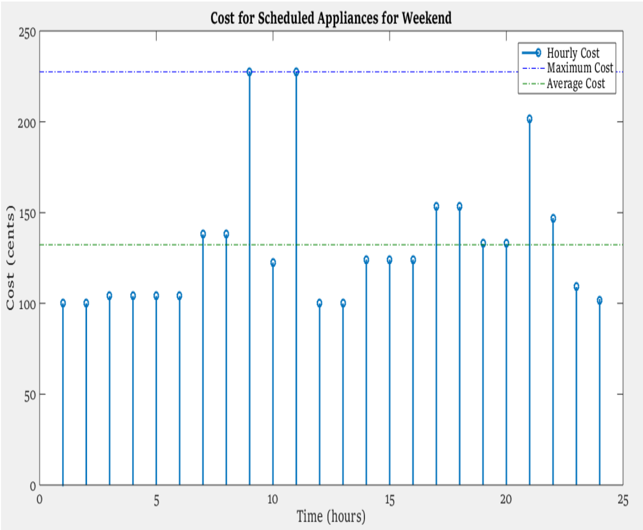

Figure 8.11: Hourly Cost Profile for Scheduled Appliances for weekend

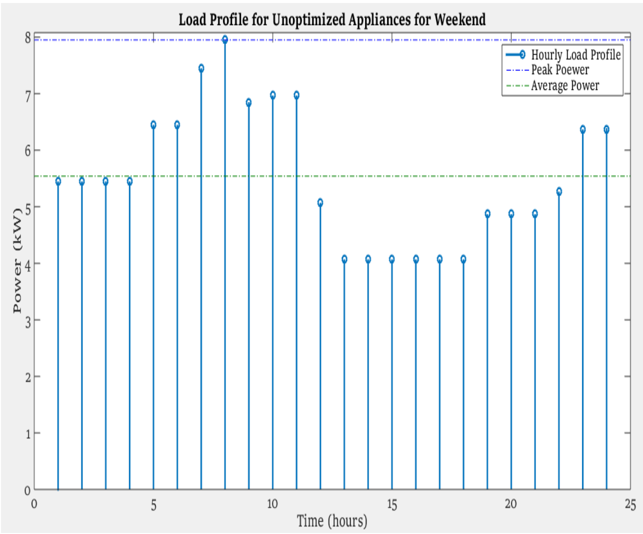

Figure 8.12: Load Profile for Unoptimized Appliances for weekend

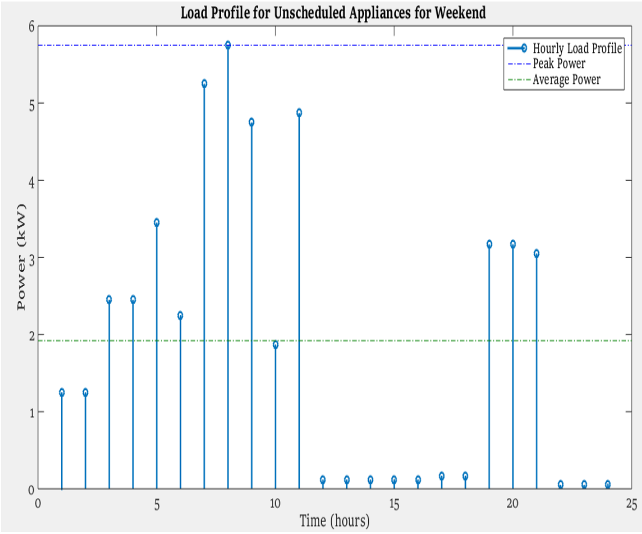

Figure 8.13: Load Profile for Unscheduled Appliances for weekend

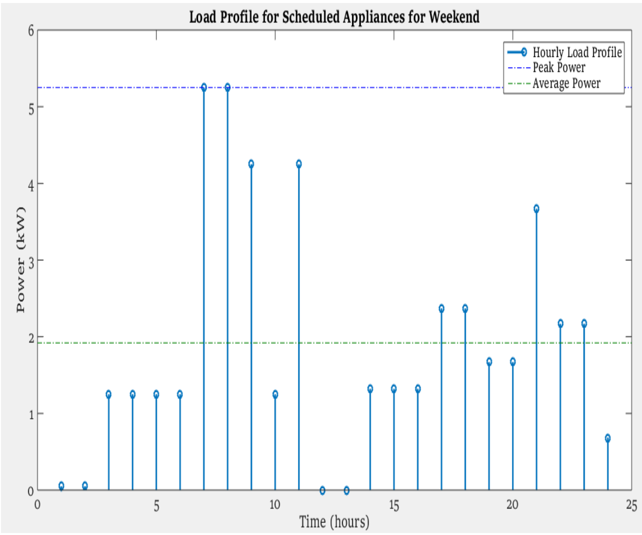

Figure 8.14: Load Profile for Scheduled Appliances for weekend

Table 8.3: Results Analysis

Day	Parameter	Unit	Unoptimized Results	Optimized Results	Scheduled Results
Weekday	Peak Power	kW	5.2	4.87	4.37
	Average Power	kW	3.01	2.22	2.22
	Average Cost	cents	241.6	143.9	138.4
	Peak Cost	cents	895.7	320.9	227.6
Weekend	Peak Power	kW	7.95	5.75	5.25
	Average Power	kW	5.542	1.92	1.92
	Average Cost	cents	329.8	132.9	130.3
	Peak Cost	cents	329.8	132.9	130.3

cents making up to the difference of 42.7%. Thus, in this way the user will quantify and analyse the difference in cost reduction and will also be compelled to reduce more PAR by adjusting his schedule fully balanced throughout the time horizon and will schedule when the electricity prices are low so that the user may have greater cost reduction in his electricity bill. So, in this way, both the utility supply and user will get benefit simultaneously by helping each other in reducing average load, PAR and cost of the electricity and the wastage of energy issue will also get addressed.

Chapter 9

Conclusion and Future Suggestion

9.1 Conclusion

A comprehensive controlling mechanism has been proposed to optimize and schedule the operation of household appliances which are divided into different categories according to their operation to reduce user's electricity bill as well as PAR of power consumption of appliance. The controlling algorithm ALS exploits fully different categories of appliances so that each appliance can be schedule according to its usage and in their UTIs and PUTIs to ensure maximum user satisfaction. Multiple power levels of appliances are also considered to operate them optimally at suitable power level after calculation of cost at the time of use and the user requirement and priority. The realistic cost estimation is done by incorporating the hourly pricing signal in a quadratic manner such that the increase in load is charged more and the no load scheduled is charged a basic utility charges. Also, the modelling of critical load (unschedulable) is incorporated in the cost calculation to have a more closer cost figure to the actual figure by the supply. Furthermore, the technique is also suggested to the user through the results analysis to monitor and change their UTIs and PUTIs of appliances to have balanced distribution of load through out the time horizon of 24 hours to reduce PAR in order to benefit the utility supply so that they may reduce their basic electricity supply charges throughout.

9.2 Future Work Suggestion

The model is applied to a realistic case study and pricing signal is also considered of a real supply company of that area being different on weekday and on weeekend, and how the change in routine of the user might effect their reduction in the electricity bill which also helps to see the actual rather than overestimated benefits of ALS model. . In future, the model will be applied to different seasons and the renewable sources will also be incorporated and its hardware implementation will be done.

References

[1] Power industry of pakistan. http://www.merapc-pk.com/powerl. Accessed: 2018-12-05.

[2] South asia regional initiative for energy integration. https://sari-energy.org/oldsite/PageFiles/Countries/Pakistan_Energy_detail.html. Accessed: 2018-12-05.

[3] Steven Stoft. *Reliability, Price Spikes, and Investment*. IEEE, 2002. doi: 10.1109/9780470545584.part2.

[4] Jonathan G. Koomey and Richard E. Brown. The role of building technologies in reducing and controlling peak electricity demand. Technical report, Lawrence Berkeley National Laboratory, Berkeley, CA, 09/2002 2002.

[5] C. Ocaña, A. Hariton, Organisation for Economic Co-operation, Development, and International Energy Agency. *Security of supply in electricity markets: evidence and policy issues*. Energy market reform. OECD/IEA, 2002.

[6] Mara Madaleno, Carlos Pinho, and Cláudia Ribeiro. Commodity price interaction: Co 2 allowances, fuel sources and electricity, 2014.

[7] Eric Hirst. The financial and physical insurance benefits of price-responsive demand. *The Electricity Journal*, 15(4):66–73, 2002.

[8] Clark W Gellings and Kelly E Parmenter. Demand-side management. In *Energy Efficiency and Renewable Energy Handbook*, volume 289, pages 289–310. ROUTLEDGE in association with GSE Research, 2016.

[9] Q Qdr. Benefits of demand response in electricity markets and recommendations for achieving them. *US Dept. Energy, Washington, DC, USA, Tech. Rep*, 2006.

[10] Demand response: Principles for regulatory guidance, 2002.

[11] Galen Barbose, Charles Goldman, and Bernie Neenan. A survey of utility experience with real time pricing. 2004.

[12] Study shows real time pricing can reduce energy bills. https://www.electricnet.com/doc/study-shows-real-time-pricing-can-reduce-ener-0001. Accessed: 2018-11-06.

[13] Joseph Eto. The past, present, and future of us utility demand-side management programs. Technical report, Lawrence Berkeley National Lab., 1996.

[14] Load management becomes demand response as programs evolve. https://www.elp.com/articles/powergrid_international/print/volume-6/issue-6/departments/news/load-management-becomes-demand-response-as-programs-evolve.html, 2002. Accessed: 2018-11-07.

[15] Books. *Environmental Science & Technology*, 8(13):1125–1125, 1974. doi: 10.1021/es60098a613. URL https://doi.org/10.1021/es60098a613.

[16] AB Lovins. Soft energy paths: Towards a durable peace. 1977. *Cambridge, MA: Ballinger*.

[17] Amory B Lovins. World energy strategies: Facts, issues and options for policies that transcend today's 'ad-hocracy'. *Bulletin of the Atomic Scientists*, 30(5):14–32, 1974.

[18] James A Momoh. *Electric power system applications of optimization*. CRC press, 2008.

[19] Demand response assessment and modelling of peak electricity demand in the residential sector: Information and communication requirements. https://ir.canterbury.ac.nz/bitstream/handle/10092/5063/Thesis_fulltext.pdf?sequence=2. Accessed: 2018-11-06.

[20] Electricity information. https://www.iea.org/classicstats/relateddatabases/electricityinformation/, . Accessed: 2018-11-08.

[21] Security of supply policy - obsolete. https://www.ea.govt.nz/search/?q=Security+of+Supply+forecasting+and+information+policy. Accessed: 2018-11-08.

[22] Samuel Gyamfi and Susan Krumdieck. Price, environment and security: Exploring multi-modal motivation in voluntary residential peak demand response. *Energy Policy*, 39(5):2993–3004, 2011.

[23] Assessment and development of network-driven demand-side management measures. http://www.ieadsm.org/publications/key-publications/, . Accessed: 2018-11-06.

[24] Karen Herter. Residential implementation of critical-peak pricing of electricity. *Energy policy*, 35(4):2121–2130, 2007.

[25] Don A Dillman, Eugene A Rosa, and Joye J Dillman. Lifestyle and home energy conservation in the united states: the poor accept lifestyle cutbacks while the wealthy invest in conservation. *Journal of Economic Psychology*, 3(3-4):299–315, 1983.

[26] Power system gaps growing despite increase in generation. https://www.dawn.com/news/1413532/power-system-gaps-growing-despite-increase-in-generation. Accessed: 2018-12-02.

[27] Georgina Wood and Marcus Newborough. Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. *Energy and buildings*, 35 (8):821–841, 2003.

[28] Bruce Biewald, Lucy Johnston, and Synapse Energy Economics. The other side of competitive markets: Developing effective load response in new england"s electricity market. *Synapse Energy Economics, Cambridge, MA, June*, 13, 2001.

[29] Loren Lutzenhiser. Social and behavioral aspects of energy use. *Annual review of Energy and the Environment*, 18(1):247–289, 1993.

[30] Sherman Hanna. Saving energy in the home: Princeton's experiment at twin rivers. *Housing and Society*, 6(2):129–130, 1979.

[31] Danny S Parker, Maria D Mazzara, and John R Sherwin. Monitored energy use patterns in low-income housing in a hot and humid climate. 1996.

[32] Paul C Stern. What psychology knows about energy conservation. *American Psychologist*, 47(10):1224, 1992.

[33] Elizabeth Shove. Changing human behaviour and lifestyle: a challenge for sustainable consumption? 2005.

[34] Paul Parker, Ian H Rowlands, and Daniel Scott. Innovations to reduce residential energy use and carbon emissions: an integrated approach. *Canadian Geographer/Le Géographe canadien*, 47(2):169–184, 2003.

[35] Ontario Energy Board et al. Ontario energy board smart price pilot final report. 2007.

[36] Ahmad Faruqui and Sanem Sergici. Household response to dynamic pricing of electricity: a survey of 15 experiments. *Journal of regulatory Economics*, 38(2):193–225, 2010.

[37] Ameren Illinois. Real-time pricing for residential customers, 2014.

[38] Peter C Reiss and Matthew W White. Household electricity demand, revisited. *The Review of Economic Studies*, 72(3):853–883, 2005.

[39] Bin Zhou, Wentao Li, Ka Wing Chan, Yijia Cao, Yonghong Kuang, Xi Liu, and Xiong Wang. Smart home energy management systems: Concept, configurations, and scheduling strategies. *Renewable and Sustainable Energy Reviews*, 61:30–40, 2016.

[40] Singiresu S Rao. *Engineering optimization: theory and practice*. John Wiley & Sons, 2009.

[41] Qifen Dong, Li Yu, Wen-Zhan Song, Lang Tong, and Shaojie Tang. Distributed demand and response algorithm for optimizing social-welfare in smart grid. In *Parallel & Distributed Processing Symposium (IPDPS), 2012 IEEE 26th International*, pages 1228–1239. IEEE, 2012.

[42] Qifen Dong, Li Yu, Wen-Zhan Song, Lang Tong, and Shaojie Tang. Distributed demand and response algorithm for optimizing social-welfare in smart grid. In *Parallel & Distributed Processing Symposium (IPDPS), 2012 IEEE 26th International*, pages 1228–1239. IEEE, 2012.

[43] Christopher O Adika and Lingfeng Wang. Smart charging and appliance scheduling approaches to demand side management. *International Journal of Electrical Power & Energy Systems*, 57:232–240, 2014.

[44] Zdenek Bradac, Vaclav Kaczmarczyk, and Petr Fiedler. Optimal scheduling of domestic appliances via milp. *Energies*, 8(1):217–232, 2014.

[45] Raka Jovanovic, Abdelkader Bousselham, and Islam Safak Bayram. Residential demand response scheduling with consideration of consumer preferences. *Applied Sciences*, 6(1):16, 2016.

[46] Bingtuan Gao, Xiaofeng Liu, Wenhu Zhang, and Yi Tang. Autonomous household energy management based on a double cooperative game approach in the smart grid. *Energies*, 8(7):7326–7343, 2015.

[47] Bingtuan Gao, Wenhu Zhang, Yi Tang, Mingjin Hu, Mingcheng Zhu, and Huiyu Zhan. Game-theoretic energy management for residential users with dischargeable plug-in electric vehicles. *Energies*, 7(11):7499–7518, 2014.

[48] Petra Mesarić and Slavko Krajcar. Home demand side management integrated with electric vehicles and renewable energy sources. *Energy and Buildings*, 108:1–9, 2015.

[49] John S Vardakas, Nizar Zorba, and Christos V Verikoukis. Power demand control scenarios for smart grid applications with finite number of appliances. *Applied energy*, 162:83–98, 2016.

[50] Jamal Abushnaf, Alexander Rassau, and Włodzimierz Górnisiewicz. Impact on electricity use of introducing time-of-use pricing to a multi-user home energy management system. *International Transactions on Electrical Energy Systems*, 26(5):993–1005, 2016.

[51] Phani Chavali, Peng Yang, and Arye Nehorai. A distributed algorithm of appliance scheduling for home energy management system. *IEEE Transactions on Smart Grid*, 5(1):282–290, 2014.

[52] Mahmoud H Elkazaz, Ayman Hoballah, and Ahmed M Azmy. Artificial intelligent-based optimization of automated home energy management systems. *International Transactions on Electrical Energy Systems*, 26(9):2038–2056, 2016.

[53] Zheng Wen, Daniel O'Neill, and Hamid Maei. Optimal demand response using device-based reinforcement learning. *IEEE Transactions on Smart Grid*, 6(5):2312–2324, 2015.

[54] Abdorreza Rabiee, Mohammad Sadeghi, Jamshid Aghaeic, and Alireza Heidari. Optimal operation of microgrids through simultaneous scheduling of electrical vehicles and responsive loads considering wind and pv units uncertainties. *Renewable and Sustainable Energy Reviews*, 57:721–739, 2016.

[55] Sahar Rahim, Nadeem Javaid, Ashfaq Ahmad, Shahid Ahmed Khan, Zahoor Ali Khan, Nabil Alrajeh, and Umar Qasim. Exploiting heuristic algorithms to efficiently utilize energy management controllers with renewable energy sources. *Energy and Buildings*, 129:452–470, 2016.

[56] Muhammad Babar Rasheed, Nadeem Javaid, Ashfaq Ahmad, Zahoor Ali Khan, Umar Qasim, and Nabil Alrajeh. An efficient power scheduling scheme for residential load management in smart homes. *Applied Sciences*, 5(4):1134–1163, 2015.

[57] Ashfaq Ahmad, Nadeem Javaid, Nabil Alrajeh, Zahoor Ali Khan, Umar Qasim, and Abid Khan. A modified feature selection and artificial neural network-based day-ahead load forecasting model for a smart grid. *Applied Sciences*, 5(4):1756–1772, 2015.

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

[59] Asif Khan, Nadeem Javaid, Adnan Ahmad, Mariam Akbar, Zahoor Ali Khan, and Manzoor Ilahi. A priority-induced demand side management system to mitigate rebound peaks using multiple knapsack. *Journal of Ambient Intelligence and Humanized Computing*, pages 1–24, 2018.

[60] Adia Khalid, Nadeem Javaid, Abdul Mateen, Bilal Khalid, Zahoor Ali Khan, and Umar Qasim. Demand side management using hybrid bacterial foraging and genetic algorithm optimization techniques. In *Complex, Intelligent, and Software Intensive Systems (CISIS), 2016 10th International Conference on*, pages 494–502. IEEE, 2016.

[61] Yanyu Zhang, Peng Zeng, Shuhui Li, Chuanzhi Zang, and Hepeng Li. A novel multi-

objective optimization algorithm for home energy management system in smart grid. *Mathematical Problems in Engineering*, 2015, 2015.

[62] Zahra Baharlouei and Massoud Hashemi. Demand side management challenges in smart grid: A review. In *Smart Grid Conference (SGC), 2013*, pages 96–101. IEEE, 2013.

[63] Michael J Kuby, William F Fagan, Charles S ReVelle, and William L Graf. A multi-objective optimization model for dam removal: an example trading off salmon passage with hydropower and water storage in the willamette basin. *Advances in Water Resources*, 28(8):845–855, 2005.

[64] Mustafa Alparslan Zehir, Alp Batman, and Mustafa Bagriyanik. Review and comparison of demand response options for more effective use of renewable energy at consumer level. *Renewable and Sustainable Energy Reviews*, 56:631–642, 2016.

[65] A. Khalid, N. Javaid, M. Guizani, M. Alhussein, K. Aurangzeb, and M. Ilahi. Towards dynamic coordination among home appliances using multi-objective energy optimization for demand side management in smart buildings. *IEEE Access*, 6:19509–19529, 2018. ISSN 2169-3536. doi: 10.1109/ACCESS.2018.2791546.

[66] Lin Liu, Yang Liu, Lizhe Wang, Albert Zomaya, and Shiyan Hu. Economical and balanced energy usage in the smart home infrastructure: A tutorial and new results. *IEEE Transactions on Emerging Topics in Computing*, 3(4):556–570, 2015.

[67] Nikolaos G Paterakis, Ozan Erdinc, Anastasios G Bakirtzis, and João PS Catalão. Optimal household appliances scheduling under day-ahead pricing and load-shaping demand response strategies. *IEEE Transactions on Industrial Informatics*, 11(6):1509–1519, 2015.

[68] Pedram Samadi, Amir-Hamed Mohsenian-Rad, Robert Schober, Vincent WS Wong, and Juri Jatskevich. Optimal real-time pricing algorithm based on utility maximization for smart grid. In *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, pages 415–420. IEEE, 2010.

[69] Sereen Althaher, Pierluigi Mancarella, and Joseph Mutale. Automated demand response from home energy management system under dynamic pricing and power and comfort constraints. *IEEE Transactions on Smart Grid*, 6(4):1874–1883, 2015.

[70] Ziming Zhu, Jie Tang, Sangarapillai Lambotharan, Woon Hau Chin, and Zhong Fan. An integer linear programming and game theory based optimization for demand-side management in smart grid. In *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, pages 1205–1210. IEEE, 2011.

[71] Kai Man Tsui and Shing-Chow Chan. Demand response optimization for smart home scheduling under real-time pricing. *IEEE Transactions on Smart Grid*, 3(4):1812–1821, 2012.

[72] Chen Chen, Jianhui Wang, Yeonsook Heo, and Shalinee Kishore. Mpc-based appliance scheduling for residential building energy management controller. *IEEE Transactions on Smart Grid*, 4(3):1401–1410, 2013.

[73] Tanguy Hubert and Santiago Grijalva. Modeling for residential electricity optimization in dynamic pricing environments. *IEEE Transactions on Smart Grid*, 3(4):2224–2231, 2012.

[74] Tanguy Hubert and Santiago Grijalva. Modeling for residential electricity optimization in dynamic pricing environments. *IEEE Transactions on Smart Grid*, 3(4):2224–2231, 2012.

[75] Amjad Anvari-Moghaddam, Hassan Monsef, and Ashkan Rahimi-Kian. Optimal smart home energy management considering energy saving and a comfortable lifestyle. *IEEE Transactions on Smart Grid*, 6(1):324–332, 2015.

[76] E Wilson. Commercial and residential hourly load profiles for all tmy3 locations in the united states. *O. o. EE a. R. Energy, Ed., ed. US Department of Energy Open Data Catalog: US Department of Energy*, 2014.

[77] Time-of-use (tou) rate plans. https://www.sce.com/residential/rates/Time-Of-Use-Residential-Rate-Plans. Accessed: 2018-11-09.