OPTIMAL OPERATION AND ECONOMIC IMPACTS OF ENERGY STORAGE SYSTEM IN DISTRIBUTION NETWORK

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

DECEMBER, 2013

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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Dedication

To my Parents, brothers and sisters, for their endless love and support

ACKNOWLEDGMENTS

First and foremost, I would like to thank my advisor, Dr. Ibrahim M. El-Amin for his supervision, guidance, assistance and valuable comments throughout the progress of my research and the writing of this thesis. Without his support, advice and encouragement, this work would not have been possible.

I would also like to thank my thesis committee members, Dr. Muhammad Ali Abido and Dr. Ibrahim O. Habiballah for their support and advice.

I would also thank Dr. Shafiqur Rehman for his support.

Special thanks to all my friends for their support, interest, assistance and technical discussions during the course of my MS program at KFUPM.

Last but definitely not the least, my warmest acknowledgments to my parents and the rest of my family who have graciously extended their support and encouragement to me over the course of this work and for many years prior to that.

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LIST OF ABBREVIATIONS

CAES	Compressed air energy storage
ECRA	Electricity and Cogeneration Regulatory Authority
EPRI	Electric Power Research Institute
ERC	Energy Research Corporation
ESS	Energy Storage System
EVs	Electric Vehicles
LAB	Lead acid battery
NaS	Sodium sulphur battery
NPV	Net present Value
PSB	Polysulfide battery
SEC	Saudi Electric Company
SMES	Super-magnetic energy storage
VRB	Vanadium redox battery
WP	Wind Power
ZnBr	Zinc-bromide

ABSTRACT

Full Name	Muhammad Fahad Zia
Thesis Title	Optimal Operation and Economic Impacts of Energy Storage System in Distribution Network
Degree	Master of Science
Major Field	Electrical Engineering
Date of Degree	December 2013

A fundamental constraint in electric power system operations is the need to maintain equilibrium between supply and demand, instantaneously and all times. Energy storage systems present an opportunity to transcend the power balance paradigm by allowing energy to be stored and released at different times. The potential applications of grid-integrated energy storage systems cover the entire electric power delivery supply chain, from generation to end-use, and potential benefits range from improved frequency regulation and dynamic stability to superior utilization of renewable and distributed energy resources.

There are several promising technologies for both energy storage and power storage applications. Energy storage devices have gained importance in power system network

due to its longer term storage. Pumped hydro, Vanadium Redox battery and Sodium Sulphur battery are some of the viable energy storage technologies.

In this thesis, three research problems have been studied and analyzed. These research problems are distribution feeder deferment using ESS, optimal scheduling of ESS and optimal combined scheduling of ESS and wind power plant.

Firstly, an economic analysis has been performed to quantify the potential benefits of distribution feeder deferral planning using ESS. In this analysis, the net present value of feeder deferral has been calculated and simulated using different parameters such as annual load growth rate, feeder length, ESS round-trip efficiency and its power and energy capacities. Net present value is a function of several parameters which need to be carefully analyzed to achieve the maximum deferral benefit. The results show that distribution feeder deferral planning using energy storage systems is economical for long feeder length.

In subsequent problems, an optimal ESS scheduling algorithms with and without wind energy are developed and analyzed considering distribution feeder thermal limit, electricity price, load demand, maximum energy and power capacity of ESS and its charging and discharging efficiency. The developed algorithms have been implemented on different customer type's tariff rates such as residential, commercial and industrial customers. The results show that the developed optimal algorithms have proven to be economical for ESS scheduling with and without renewable sources. The effects of ESS parameters and distribution feeder thermal limit on the developed algorithm are also analyzed.

ABSTRACT (ARABIC)

الاسم الكامل	محمد فهد ضياء
عنوان الرسالة	التشغيل الأمثل والتأثيرات الاقتصادية لنظام تخزين الطاقة في شبكة التوزيع
الدرجة	الماجستير في العلوم
التخصص	الهندسة الكهربائية
تاريخ الدرجة العلمية	ديسمبر 2013 م

المحدد الرئيسي في تشغيل أنظمة القدرة الكهربائية هو الحاجة للمحافظة على التوازن بين قدرة التزويد والطلب لحظيا وفي جميع الأوقات . تقدم أنظمة تخزين الطاقة الفرصة لتجاوز نموذج توازن القدرة بالسماح للطاقة بالتخزين والإطلاق في أوقات مختلفة. التطبيقات الممكنة لأنظمة تخزين الطاقة المتكاملة مع الشبكة تغطي كامل سلسلة تزويد الطاقة الكهربائية من التوليد حتى الاستخدام النهائي. مدى الفوائد الممكنة من تحسين تنظيم التردد و استقرار ديناميكية النظام الى الاستخدام الأفضل لمصادر الطاقة المتجددة والموزعة .

هناك العديد من التكنولوجيا الواعدة فيما يخص تخزين الطاقة وتطبيقات تخزين القدرة.أجهزة تخزين الطاقة اكتسبت أهميتها في شبكات أنظمة الطاقة بناء على التخزين طويل المدى. من الأمثلة عليها : المضخات المائية , بطارية الفاناديوم المؤكسدة , بطارية سلفر صوديوم وبعض تكنولوجيا تخزين الطاقة القابلة للتطبيق.

في هذه الرسالة تم دراسة وتحليل ثلاث مشاكل بحثية. هذه المشاكل هي ارجاء تشييد خط التغذية الموزعة باستخدام انظمة تخزين الطاقة, الجدولة المثلى لأنظمة تخزين الطاقة و الجدولة المشتركة المثلى بين أنظمة تخزين الطاقة ومحطة القدرة الهوائية.

أولا, التحليل الاقتصادي نفذ لتحديد الفوائد الممكنة للتخطيط الارجائي للمغذي الموزع باستخدام أنظمة تخزين الطاقة. في هذا التحليل تم حساب ومحاكاة صافي القيمة الحالية باستخدام معايير مختلفة مثل معدل نمو الحمل السنوي, طول المغذي, وكفاءة الشحن لأنظمة تخزين الطاقة وسعة الطاقة والقدرة له. أن صافي القيمة الحالية هو اقتران لمعايير متعددة تحتاج الى الحذر في تحليلها لتحقيق أعلى فائدة مؤجلة. تظهر نتائج التخطيط الارجائي لمغذي التوزيع باستخدام أنظمة تخزين الطاقة جدواها الاقتصادية للمغذيات الطويلة.

في المسالة الثانية والثالثة تم تطوير الخوازميات المثلى لجدولة أنظمة مع تخزين الطاقة والجدولة المشتركة المثلى بين أنظمة تخزين الطاقة ومحطة القدرة الهوائية. وتحليلها اخذة بعين الاعتبار الحد الحراري للمغذي, سعر الكهرباء, طلب الحمل, السعة القصوى للطاقة والقدرة لأنظمة تخزين الطاقة وكفاءة الشحن والتفريغ. الخوازمية المطورة طبقت على معدلات تعرفة متنوعة : السكنية ,التجارية والصناعية. تظهر النتائج أن الخوازمية المثلى أثبتت الجدوى الاقتصادية لجدولة أنظمة تخزين الطاقة. تم أيضا دراسة وتحليل تأثير معايير أنظمة تخزين الطاقة والحد الحراري لمغذي التوزيع على الخوارزمية المطورة.

تظهر نتائج الدراسة الجدوى الاقتصادية لاستخدام أنظمة تخزين الطاقة مع و بدون الطاقة المتجددة. للمغذيات الطويلةالنتائج تظهر أن الخوارزميات المثلى المطورة أثبتت الجدوى الاقتصادية لجدولة أنظمة تخزين الطاقة مع مصادر الطاقة المتجددة وبدونها.

بالاضافة لذلك تم تحليل تأثير معايير أنظمة تخزين الطاقة و المحددة الحرارية لكيبل التوزيع على الخوارزميات المطورة.

CHAPTER 1

INTRODUCTION

1.1 Background

Electric power industry, over many years, has been depending heavily on fossil fuel based generation technologies. Though there is an abundance of fossil fuels available, yet it is a finite resource. It is fast depleting with the increase in consumption of electricity and changing lifestyle of people that is heavily dependent on artificial means than natural living. Thus the exhaustion of fossil fuels has a significant consequence upon generation of electricity.

The more grave concern is the emissions of harmful gases such as carbon dioxide from the fossil fuel generation units. Increased emissions have led to rise of global warming that is a serious threat to the human race. The climate change alarm with the rise in prices of fossil-fuels such as oil due to its fast depletion has made nations of the world support renewable sources of energy. Renewable sources such as the solar, wind, hydro, tides and geothermal heat are naturally replenished and free from emissions. In the last decade there has been a drastic increase in the penetration of renewable sources especially into the power grid.

The electric power industry has always operated on the principle of instantaneously supplying demand. Everything from generation planning to real-time control center operations have been dictated by the necessity to maintain the balance between generation and demand across the entire network at all times. Electricity unlike the other forms of energy cannot be economically stored, and has to be transmitted and utilized as it is being generated. It can be converted to another form of energy such as potential, kinetic or chemical. Until recently electricity was not stored in a major scale.

Energy storage systems present an opportunity to transcend the power balance paradigm by allowing energy to be stored and released at different times. Energy storage can be used to balance the variability of renewable generation and, properly deployed and integrated, can increase grid reliability and asset utilization [1, 2]. Energy storage systems can also provide direct benefits to end users through reduced rates, decreased outage costs and improved power quality. Until recently, the costs associated with implementing energy conversion and storage systems have outweighed their benefits and the investment in storage technology research and development was limited. Figure 1.1 shows the comparative estimates of total electric energy storage capacity worldwide in 2010. Since the pumped hydro energy storage has been used for decades and is quite mature with respect to technology now, its installation capacity is much more than other available energy storage systems. Pumped hydro energy storage occupies over 99% of total storage capacity. The technical maturity of different ESSs is shown in Figure 1.2. The dashed lines are meant to separate the mature, developed and developing ESS technologies.

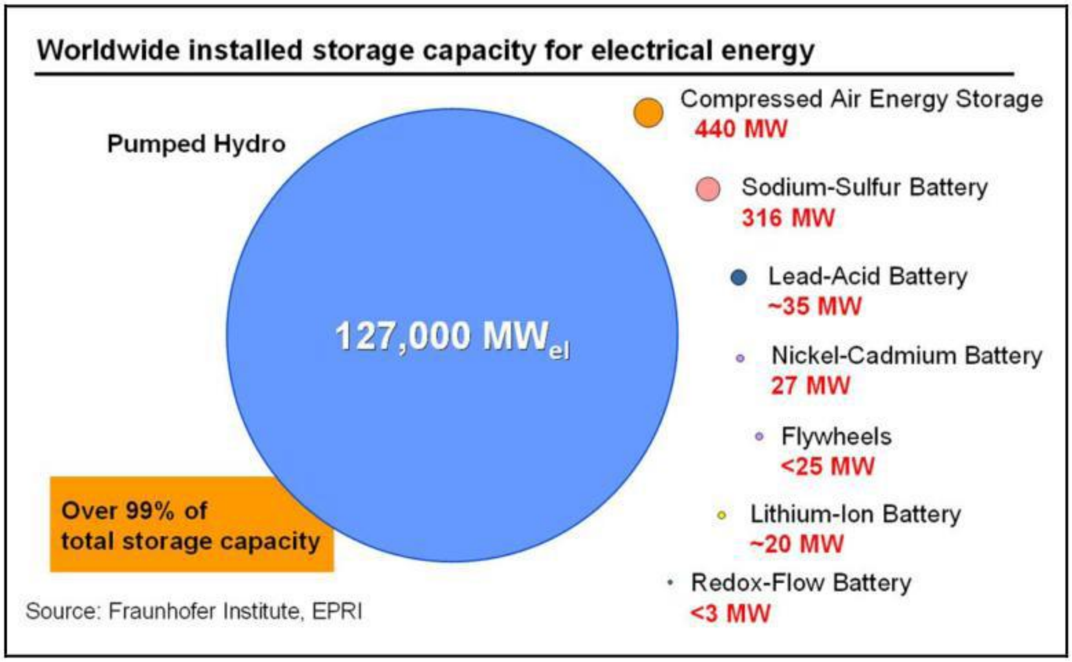


Figure 1.1 Worldwide Installed Storage Capacity for Electrical Energy [2]

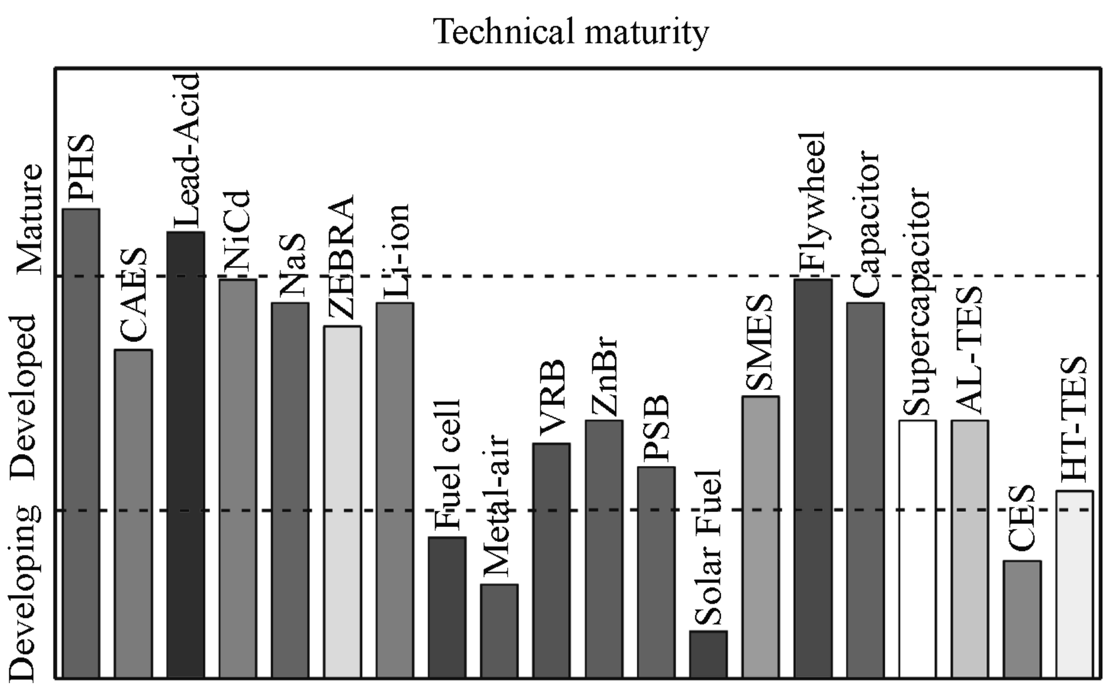


Figure 1.2 Technical Maturity of ESSs [3]

1.2 Industry Drivers

Despite technological and economic challenges, a recent influence of industry drivers has gained interest of utilities, regulators, researchers and private companies to rethink electric energy storage [4]. Recent economic, regulatory and technological trends have begun to make storage solutions economically feasible. The following trends and policies are a few of the many important industry drivers.

- **Economic:** Higher price differences between on-peak and off-peak power demands [4,5]
- **Technological:** Technological maturation of advanced storage technologies due to investments in R&D for consumer and transportation applications [4,5]
- **Regulatory:** A 2011 Federal Regulatory Energy Commission (FERC) mandate [6] that supports fast-ramping short term regulation resources, such as energy storage technologies.
- **Military**: Critical military installations are increasingly vulnerable to commercial electric grid outages, creating a need for long-duration emergency backup solutions.

1.3 Thesis Motivation

Energy storage systems transform electrical energy to another energy form to reserve excess or cheap energy for subsequent usage. When demand is higher than the available generation, this stored energy is converted back to electrical form and supplied to the grid. Depending on the type of the storage technology, the energy can be stored in thermal, mechanical, chemical, electromagnetic or electrostatic form within the device. Storage devices allow renewable energy sources, such as wind power, to provide a constant energy supply. Predictable power supply is one of the major difficulties in wide scale integration of renewable sources into the electricity grid. Using storage devices as buffers, the predictability can be increased to the level where renewable generation can be assumed to be dispatchable. To achieve the best performance from ESS, the storage systems should offer the following characteristics:

1) Energy storage operation should be optimized to achieve maximum energy price arbitrage in energy market.
2) ESSs should be used for economic benefits of power system by deferring the transmission and distribution system upgradation.

1.4 Thesis Objectives

The general objective of this research is to analyze economic impacts of ESS under different electric power system conditions. Following are the major issues that will be considered in this thesis:

1. Development of an economic model to quantify the potential benefits using ESSs to defer feeder installation.

2. Analysis of the effects of load growth rate, feeder length and ESS parameters on proposed feeder deferral economic model.

3. Development of an optimization model to maximize energy price arbitrage of ESS integrated with distribution feeder in electricity market.

4. Analysis of the effects of different ESS parameters on proposed optimal scheduling model.

5. Analysis of the effects of distribution feeder thermal limit on proposed optimal scheduling model.

6. Development of an optimization algorithm for optimal scheduling of ESS with wind power in electricity market.

1.5 Thesis Outline

In Chapter 1, introduction of thesis work is discussed in which the need of energy storage systems is explained in power industry nowadays.

Chapter 2 is about the literature review of ESS related to the thesis. The ESS research in its technology development and its contribution in electricity market and T&D deferral and its operation with wind power is presented.

Chapter 3 discusses the overview of energy storage systems. Energy storage system introduction and technology parameters are discussed. Energy storage system applications in electric system are stated. Different energy storage technologies working and their performance and effects in society and environment is discussed.

Chapter 4 presents the economic analysis of distribution feeder deferral using ESS. In this chapter, the economic model is developed that leads to the maximum economic benefit which can be provided by the ESSs. Sensitivity studies that reveal the effects of ESS parameters such as ESS power and energy capacity and round-trip efficiency combined with the feeder length as well as the feeder load growth rate are reported.

In Chapter 5, an optimization algorithm is developed for ESS scheduling on constrained distribution feeder considering electricity tariff rates, load demand, operation and maintenance cost of ESS, its maximum power and energy capacity and efficiency.

Chapter 6 presents an optimization algorithm developed for combined ESS and wind power scheduling on constrained distribution feeder considering electricity tariff rates, load demand, levelized cost of energy of wind power, operation and maintenance cost of ESS, its maximum power and energy capacity and efficiency.

Chapter 7 includes conclusion and future recommendations.

CHAPTER 2

Literature Review

Energy storage devices enhance predictability of renewable energy sources by smoothing out fluctuations in the difference between load and generation. Thus, systems with high penetration of renewable energy can benefit from storage devices. These devices can store energy during low demand and low price periods and whenever excess energy is available. The electrical energy is usually stored in another form of energy such as thermal, chemical, mechanical, electromagnetic or electrostatic. When demand is high or load is greater than the generation, the stored energy is converted back to electrical form and fed back into the system. Thus, storage devices can provide load generation balance and lead to stability in market prices. Storage devices can also provide a pseudo demand side management by acting as a load during low demand periods and as a source during high demand periods.

2.1 ESS Research and Applications

Over decades, a number of utilities and research organizations have done a lot of work on developing and evaluating new technologies of grid connected energy storage systems [7, 8]. This type of study can be traced back to as early as 1940's. The researchers such as Arlie Graham Sterling, JR. from MIT, had begun the potential energy storage devices study [9]. In Arlie's thesis, he dedicated to design a flywheel energy storage system for the grid peaking shaving application. He, as a pioneer, stated that the flywheel storage system was not economical and technically feasible. As time went by, The Sandia National Laboratories had started their energy storage system research [10]. One of the major topics in that series of study is the Energy Storage System. For example, they had a detailed technique report related to the Zinc/Bromine battery model development. In addition, they compared different technique's parameters with other flow batteries, even though the overall techniques were not mature at that time [11]. Since then, the U.S. Department of Energy as well as Electric Power Research Institute (EPRI) had been contracted Energy Research Corporation (ERC) to do the battery energy storage study. The technique of storage devices was improving gradually and hence more and more institutes were getting involved.

In the 1990s, some papers have been published dealing with the issues related to the battery design as well as battery early application cases [12-16]. As an example of energy storage design research, GE had reported its design example of a 5 MVA, 2.5 MWh battery energy storage system located in California [13]. It had all the details of design like ESS control system, filters, relays as well as various response curves under different operation conditions. Another GE's paper [14] provided more about the battery potential using cases, including back-up generation, power control, demand charge management as well as voltage support. Some notations such as power and energy applications of ESS as well as the distinctions between ESS and uninterruptable power supplies (UPS) were also presented. In the 1996, the University of Massachusetts Lowell's Bogdan, S. Borowy and Ziyad M. Salameh developed a methodology to determine the optimizing ESS and PV array size in the Wind/PV Hybrid System [15]. They calculated the average power outputs of both the wind turbine and the PV module. The idea was to operate the system by the purely renewable energy with the ESS back up. The ESS will supply power when the power output from the renewable sources is insufficient to supply the system load and charge when the generated renewable energy exceeds the load demand. Then, they introduced the term loss of power supply probability (LPSP) and used the algorithm to determine the number of ESS and PV panels. The objective is to minimize the PV/ESS combination cost. Their study was innovative at that time because they used the ESS to achieve the isolated operation and the approach is reasonable if the case study is ideal. However, the problem was oversimplified in their study since first, the cost function should consider multiple ESS and PV array's variables constraints and then second, they ignored the potential ESS economic benefit. Instead of optimization problem, the Dr. Salameh also published another paper in the year 2001 where he focused most on the ESS performance [16]. The seasonal load variation which was introduced in that paper, makes it more practical. Similar work have been done in [17].

For the last decade, the energy storage techniques have developed rapidly and many new application areas have been recognized [18-21]. The ESS becomes more attractive especially after the innovation of electric vehicles. In the late 2008, MIT electric vehicle team published a guide to understanding the battery specification [22] and hence improved the comprehension of the ESS's performance. With the proliferation of Smart Grid technologies and the mature electricity market, companies like NYISO and EOS have played a role in advancing the energy storage applications [23]. It can be predicted that the energy storage system applications and techniques will keep increasing through the years due to the improvements in their technology [24-27]. Now ESSs are used in transportation applications to reduce the overall use of hydrocarbons [24].

2.2 Distribution Feeder Deferral using ESS

Under the current economic condition of the electric power industry, utilities are forced to maximize the usage of the generation, transmission and distribution networks. Utilities may operate feeder up to or near thermal limits to avoid building new feeders. Such practice may endanger the network and can lead to power outages. On the other hand, building new lines is financially unacceptable and consumers may complain. Recently, some researchers proposed the concept of using ESS to defer the construction of new feeder.

The research on ESS distribution feeder deferral is not as much as the work on the ESS technology and its contusions is electricity market has done. But there are still some papers addressed this important topic. The feeder deferral issue is pointed out in the model; however, it did not do the economic analysis [28]. The feeder deferral problem is also discussed in [29]. The importance of deferral was introduced and different upgrade strategies were presented. The cost of upgrade in that paper was a function of the feeder length. Although the paper was using distribution generation to defer the feeder construction, similar approach can be addressed in ESS. It is also important to notice that Sandia National Laboratories had several reports focused on the deferral problem [30-32]. In those reports, the ESSs are used to supply the peak demand and both power and energy capacity constraint is considered in the reports.

2.3 Electricity Market: ESS and Wind Power plants

Electricity market has driven the power industry to exploit all possible economic and operational options that ensures the participation of ESS and renewables into electricity market. Electricity Market is the key to drive the economical use of ESS. The cost analysis has been performed where the present value calculation is used to determine the economic feasibility of using ESS/PV/Wind system. The discount rate, maintenance fee and life span effects of ESS on the cost has been considered. While load growth rate has not been considered [12]. There are number of papers which have discussed the electrical energy time shifting or energy arbitrage problem of ESS in Energy market [33, 34]. One early research on this problem was done by Kyung-Hee Jung from Korea [17]. In this paper, the optimal ESS installation and capacity for loading leveling is determined. In order to estimate the system load, the hourly load pattern for different substations at second side of main transformer is classified to determine the possibility of load factor improvement, and then used ESS to achieve the constant power operation as considered to be the optimal operation condition. It is interesting to see his approach to estimate the load curve in the real regional system and his study does present an interesting inside of ESS load shifting. However, this strategy to determine the optimal operation condition cannot be guaranteed to be proper since he did not consider the economic benefit.

As for the general market report, the [35, 36] gave the excellent guidance for the energy market economic analysis in the distribution system. Besides, [37] detailed the steps to calculate the power systems marginal cost curve and its potential applications. Similarly, [38] used actual measurement of the electricity price to predict the one in the future. The ESS market reports evaluated each ESS's applications market potential as well as the

ESS costs [39, 40]. For the issue of optimal charging/discharging method, the [28] considered it as a multi-step optimization problem to achieve the real-time control of ESS but it did not consider the rated charge/discharge power. Some papers used the dynamic programming to achieve the optimal ESS charge control, like [41-43]. This approach is elegant but may take a long time to find the optimal solution, also fail to study the multiple ESS's parameters effects on its economic performance.

Among renewable energies, wind power technology is quite mature now but the integration of wind energy into electrical grid is limited due to its intermittent nature and power system can't rely on it. ESS presents opportunity to provide constant power from wind power plants making a way for wind power plants to participate not only in energy market but also in ancillary services market [44-47].

Many researchers have proposed the optimum daily scheduling of wind-ESS plants using linear programming [48-50], but none have considered the operational cost of wind and ESS and feeder thermal limit effects in distribution system. Optimal scheduling of wind and pumped storage is proposed and solved using different scenarios generated by Monte Carlo simulation [51]. The combined operation of wind power plant and ESS has been studied in [52] for energy and regulation services. Optimal scheduling of ESS and wind plants was performed using dynamic programing in [53]. Wind power plant and ESS scheduling has also been studied using stochastic programming. Joint optimization of ESS and wind farm has been proposed in [54] but it is computationally challenging due to large number of scenarios marking it inefficient for large networks and systems. The following chapter is a summary of the various technologies of energy storage systems.

CHAPTER 3

Energy Storage Systems Overview

3.1 Introduction

Energy storage devices enhance predictability of renewable energy sources by smoothing out fluctuations in the difference between load and generation. Thus, systems with high penetration of renewable energy can benefit from storage devices. These devices can store energy during low demand and low price periods and whenever excess energy is available. The electrical energy is usually stored in another form such as thermal, chemical, mechanical, electromagnetic or electrostatic. When demand is high or load is greater than the generation, the stored energy is converted back to electrical form and fed back into the system. Thus, storage devices can provide peak shaving of the load demand and lead to stability in market prices. Storage devices can also provide a pseudo demand-side management by acting as a load during low demand periods and as a source during high demand periods.

In addition to supporting high penetration of renewable energy sources, storage solutions open many possibilities in the traditional power system. Storage allows loads to be supplied during power outages – thereby reducing downtime and improving system reliability. System stability and power quality can be improved by dampening power and frequency oscillations in the power system. Storage facilities can also provide ancillary services such as spinning reserve and reactive power compensation. Load following and leveling as well as energy management capabilities are also enhanced in the presence of energy storage devices. Storage devices along with installation of renewable energy sources can help defer expensive transmission and generation capacity expansion.

3.2 ESS Technology Parameters

The technologies used to store electrical energy are extremely diverse. Generally, following terms and parameters of ESS technologies are defined.

- **Energy Capacity**

  The quantity of stored energy that is retrievable as electric power.

- **Rated Power**

  Maximum rate at which electric energy can be continually stored or extracted from the storage system, usually given in kilowatts (kW) or megawatts (MW).

- **Discharge Time**

  The duration of time that the energy storage system can supply rated power.

- **Energy Density**

  Available energy capacity per unit mass, given in W-h/kg.

- **Power Density**

  Rated power per unit mass, given in W/kg.

- **Round-Trip Efficiency**

The overall efficiency of consuming and later releasing energy at the point of common coupling with power grid. Also known as AC-AC efficiency, round-trip efficiency accounts for all conversion and storage losses and can be broken into charging and discharging efficiencies. The round-trip efficiency of ESS can be expressed as:

$$\eta = \eta_{ch}\eta_{dch} \tag{3.1}$$

- **Cycle Life**

  The maximum number of cycles for which the system is rated. The actual operating lifespan of the battery is either the cycle life or the rated lifespan, whichever is reached first.

Additional parameters and performance indices can be found in [55].

3.3 ESS Technologies Overview

An extensive literature review has been performed to obtain information about the state-of-the art in storage device technologies. Several storage technologies have been analyzed and evaluated in various publications and journals. These technologies are: pumped hydro storage, flywheel storage, super-magnetic energy storage (SMES), compressed air energy storage (CAES), lead acid battery (LAB), sodium-sulphur battery (NaS), lithium ion battery (Li-ion), vanadium redox battery (VRB), zinc-bromide (ZnBr) battery, Polysulfide battery (PSB), fuell cells, super capacitors and Thermal Energy Storage.

3.3.1 Pumped Hydro Energy Storage

Pumped hydro energy storage is the most developed and most widely used energy storage technology. According to a study done by Electricity Storage Association, there are about 128 GW of electric energy storage worldwide, almost more than 99% of which is pumped hydro storage [2].

Traditional hydro generating stations are not storage facilities in the strictest sense but their output can be controlled to provide regulation support. Unlike a hydro generating station, a pumped hydro storage system allows two way water flow. During off–peak hours, the generator acts as a motor to store water in an elevated reservoir. During peak hours, the water is released to produce electricity.

Although large hydro stations have high generation efficiency, losses due to evaporation and leakage water reduces the overall efficiency for pumped hydro storage units. The overall efficiency of this technology is roughly 71% to 85% [3]. Very high energy and power capacities are two main features of pumped hydro storage. Large pumped hydro storage units can hold up to thousands of MWh energy. For example, a recently constructed unit in the Alps can store up to 8.5 GWh of energy and supply 1.06 GW of power [56]. Pumped hydro plants are capable of providing maximum ramp rate, approximately equivalent to their rated capacity, in less than 1 minute response time [57]. The Life time of pumped hydro storages is very long – some have been in operation for over 50 years [58].

Of the major difficulties with pumped hydro storage is its low energy density. Siting of these storage facilities require large areas preferably with different elevation levels. If geographical restrictions do not allow upper and lower reservoirs, underground reservoirs can be used as well. This option leads to higher cost of construction and longer lead time. Lack of suitable locations and impact on the environment are major drawbacks of pumped hydro storage.

3.3.2 Fly-Wheel Energy Storage

Fly-wheel storage devices store energy in the rotating mass of a rotor. Although conventional steel and titanium blades have proven to be viable options for grid integration, newer glass and carbon fiber reinforced plastics allow substantially higher rotating speeds. The amount of energy stored in a flywheel is a function of the rotating speed. As such, the newer materials have increased the energy capacity as well.

Fly-wheels are established modular storage devices. Unlike batteries, fly wheels are not sensitive to depth of charge. The efficiency of fly wheel is high, typically around 90-95%. The energy density of a fly-wheel is 10-30 Wh/kg. A typical flywheel has a life cycle of 20 years and tens of million cycles [58]. A 100 kW, 25 kWh scale-power Smart Energy Matrix unit comprised of Beacon Power flywheels has been built, installed and is currently operating on the California Independent System Operator grid in San Ramon, California [59].

One of the major draw backs of fly-wheel storage devices is its high self-discharge rates which can be between 1% and 10% per hour [58]. Fly-wheels are commercially used in the range of 1 kWh for 3 hours to 100 kWh for 30 seconds [60]. As such, fly-wheels are ideal for short term storage, including for the purpose of low-voltage ride through, but long term energy storage using fly-wheel storage devices is unlikely. Environmental impact of fly-wheel technology is similar to the impact of wind turbines. The rotation of the rotors create high pitch noise and affects migration pattern of birds.

3.3.3 Super Magnetic Energy Storage (SMES)

SMES devices store energy in the magnetic field of a cryogenically cooled superconductive coil. The AC power is converted and stored as DC energy in the magnetic field. The central storage system, i.e. the superconductive coil, is theoretically lossless – leading to a very high efficiency storage medium. Round trip efficiency of SMES devices are between 95% and 98% [60]. SMES devices are able to respond very quickly and can deliver large amounts of power for several seconds.

Energy storage capacity of SMES devices is very limited. As such, they are mainly suitable for power smoothing applications. Use of SMES in load-following or peak-shaving application alongside renewable energy sources is infeasible with the present technology. SMES devices have a life time of more than 20 years [3]. Due to the complexity of the technology, the production and installation of these devices is very expensive. SMES devices can be up to 1 MWh in energy storage capacity but the effect of magnetic field exposure on the surroundings is not completely known [57].

3.3.4 Compressed Air Energy Storage (CAES)

Compressed air energy storage devices store electrical energy by converting it into mechanical form. Air is compressed into a large container and, when energy needs to be discharged, the air is expanded to release the mechanical energy. Usually large salt caverns, abandoned mines and aquifers are used as the air container. CAES devices have been part of grid operation since 1970s [57].

The energy and power capacity of CAES devices depend primarily on the size of the container. Given a large mine can be located in the area, these devices can feature very high energy and power capacities. The compression process develops heat and, unless this heat is conserved, the cycle efficiency of CAES devices becomes low. The efficiency of CAES typically varies between 71% and 89% [3]. CAES have long storage periods, low capital cost and small self-discharge making it capable of providing large energy storage. The power rating of CAES is typically around 5-300 MW. The slow response rate is due to dependence on a mechanical system, CAES devices specific siting requirements make it an unviable option for reserve and regulation purposes in power systems. If aquifers are used as the air container, CAES systems may interfere with the eco-life near its vicinity. The cavern or mine based containers are susceptible to catastrophic raptures.

3.3.5 Lead Acid Battery (LAB)

Lead acid batteries, invented in 1859, have been used to store energy for many years. After pumped hydro storage, lead acid batteries are the most widely used storage devices. The modular and minimum siting restrictions have made these batteries a popular choice.

Lead acid batteries have relatively low capital cost. The response time for these batteries can be as low as 20 ms.

The life cycle of LAB devices are limited by the number of charge-discharge cycles. Typical cycle counts reached by lead acid batteries are around 500-1000 [3]. If depth of discharge is large, the life cycle of these batteries can be degraded. The use of lead has possible negative consequences to the nature. The efficiency of lead acid batteries is about 70-90% and have low capital cost.

3.3.6 Sodium Sulphur Battery (NAS)

First introduced in Japan in the 1980s, sodium sulphur batteries are high temperature batteries. Vacuum thermal insulation is usually used to improve efficiency and energy density. The cells inside the battery module are anchored using sand and the cell temperature is controlled by electric heaters. The electrolytes used in sodium sulphur battery is β–alumina with sodium and sulphur as –ve and +ve electrode active materials.

Recent improvements in sodium–sulphur battery technology have led to better performance and cost reduction. Sodium–sulphur batteries have a life cycle of 2500 cycles or more and efficiency of about 75-90% [3]. This technology features no self-discharge which contributes the high efficiency. Energy density of this battery technology is in the neighborhood of 150-240 Wh/kg. The energy density of sodium sulphur batteries is almost three times the traditional lead acid batteries. The shelf life of these batteries can be as high as 15 years [57]. The maintenance cost of sodium sulphur batteries is very low as well. The materials used in these batteries are abundant in nature and can be extracted at a very low cost. Therefore, costs are expected to be significantly lower for mass production [56]. Modular nature of this technology enables short construction interval and flexibility in future expansion.

Tokyo Electric Power Company (TEPCO) has a 48MWh NaS battery in operation since 1995 in its Tsunashima substation. This specific system is primarily used for load levelling [61]. There have been more than 20 projects worldwide involving sodium sulphur batteries as storage devices [56]. In North America, American Electric Power (AEP) has installed a 1.2 MW demonstration substation in Charleston, VA. This battery can supply power for up to 7 hour blocks for the overloaded substation. Another 6 MW substation is currently under construction [62].

3.3.7 Lithium ion (Li-ion) Battery

In Lithium ion battery, lithiated metal oxide (LiCoO2, LiMO2, LiNiO2 etc.) is cathode and graphitic carbon with a layering structure acts as anode [63, 64]. The electrolyte is made up of lithium salts (such as LiPF6) dissolved in organic carbonates. During battery charging, the lithium atoms in the cathode become ions and flow through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between the carbon layers as lithium atoms. During battery discharging, this process is reversed [3].

Lithium-ion battery storage devices are widely used in electronic devices to provide small amount of power at low voltages. The benefits of these devices include short access time, high energy density and very high efficiency almost 100%. But no large energy market is currently available for its utility scale use due to technical and high capital cost restrictions [56].

3.3.8 Vanadium Redox Battery (VRB)

Vanadium redox batteries are made up of two major sections: electrolyte tanks and charge/discharge stacks. Sulphuric acid solutions of vanadium are used for both cathode and anode electrolytes. These electrolytes are circulated in the stacks using a pump for charge and discharge operation.

VRB batteries feature low self–discharge, low construction costs along with high reliability and relatively high energy density [65]. Kashima–Kita, a private electric company in Japan, has implemented an 800 kWh rate battery in 1997. VRB batteries can reach an energy density of 10-30 Wh/kg and an overall efficiency of 75-85% [3]. The expected cycle lifetime of VRB batteries is more than 12000 cycles. VRB Power Systems Inc of USA has developed vanadium based battery systems that offer over 10,000 charge/discharge cycles. These batteries offer very low environmental effects [66].

In the United States, a 250 kW, 2 MWh VRB battery facility is in operation at Castle Valley, Utah. This unit is used as a load leveller. Another larger unit with 12 MWh is under construction in Sorne Hill, Ireland [66].

3.3.9 Zinc Bromide (ZnBr) Battery

Zinc bromide batteries use a bipolar electrode design in which the current travels directly through the plastic battery stack. The two half cells, anode and cathode, are separated by a micro–porous separator. Zinc is electroplated in the anode and bromine is evolved at the cathode.

Overall reaction: $ZnBr_2 \rightarrow Zn + Br_2$

Anode: $Zn^{2+} + 2e^{-} \rightarrow Zn$

Cathode: $2Br^{-} \rightarrow Br_2 + 2e^{-}$

A polybromide compound is usually used to minimize the self–discharge and improve system safety.

In general, zinc bromide batteries are suited for 50 kWh to 400 kWh applications. The lifetime of zinc bromide batteries is roughly 2500 cycles which is approximately 10 years (one cycle for 5 days/wk). The efficiency of zinc bromide batteries is in the range of 70% – 80% [67].

Unlike lead acid batteries, zinc bromide batteries can be fully discharged without adversely affecting the batteries life time. This deep discharge capability enables system designers to select batteries with lower rating and thus driving down the overall implementation costs. Replacement costs are also significantly lower for zinc bromide batteries since the stack and pumps account for roughly 20% of the overall storage system [68].

ZBB Energy Corporation is a major supplier of zinc bromide batteries. Their batteries are based on 50 kWh modules that consists three 60–cell, 2500 cm^2 battery stacks connected in parallel. These modules are designed to supply 150A discharge while maintaining 96V at the output terminal for 4 hours. The pre–commercial units have an anticipated cost of $400/kWh [67].

3.3.10 Polysulfide Bromide Battery (PSB)

Polysulfide Bromide battery is a regenerative fuel cell technology that provides a reversible electrochemical reaction between two salt solution electrolytes. It uses sodium bromide as the active material in the positive electrolyte and sodium polysulfide in the negative electrolyte. During charge, the electrolytes are pumped from separate storage tanks into half-cells on opposite sides of a polymer membrane. During discharge positive Na+ ions flow through the membrane and electrons flow in the external circuit of the battery creating a current. High-voltage is achieved by stacking cells electrically in series in bipolar modules. These cells are connected in parallel hydraulically and are fed by a pump and distribution system running to the electrolyte storage tanks [69].

Similarly to VRB batteries, the capability and power level of PSB batteries are independent of each other. The round-trip efficiency of this technology is about 75 %, the cycle life, 3000 cycles, and the energy density, 30 kWh/m^3, similar to the VRB system [64]. The current reference design of a PSB plant is for a power output of 50 MW. Regenesys Technologies is building a 120 MWh, 15 MW energy storage plant at Innogy's Little Barford Power Station in the UK. There is, however, a clear indication that this plant is a pilot or demo and, that future plants will probably have greater capacities [39].

3.3.11 Fuel Cell

The discovery of the fuel cell is generally attributed to Sir William R. Grove, who depicted the first useful fuel cell in his article *On the Gas Voltaic Battery - Voltaic Action of Phosphorus, Sulphur and Hydrocarbons* [70]. Fuel cell technology has inherent high efficiency almost twice that of a traditional internal combustion engine and low emissions. However, only a fuel cell using hydrogen as fuel can store excessive electrical energy by using the excessive electrical energy to produce hydrogen. Furthermore, the production-storage-usage of the conversion is very inefficient, such that it only makes sense for renewable energy that could otherwise be curtailed [71, 72]. Obviously, to make fuel cells helpful for renewable integration, this conversion efficiency needs to be improved.

The National Renewable Energy Laboratory (NREL) has an ongoing project, called the wind-to-hydrogen project, with the goal of improving system efficiency to produce hydrogen from renewable resources in quantities large enough and at costs low enough to compete with traditional energy sources such as coal, oil, and natural gas [73].

3.3.12 Super Capacitors

Super-capacitors are growing in popularity in the storage market as it has attractive claims. Their operation is similar to capacitors with one major difference being the usage of ionic conductor as electrolyte instead of insulating material, for the electrolyte made of conductors with a very large specific surface allows ion movement. Some of the major benefits in deploying these storage devices are improved power quality, enhanced reserve capacity, increase system reliability and stability, effective load management and rapid charge-discharge characteristics [74]. Some of the disadvantages are leakage issues, high maintenance and high capital costs.

3.3.13 Thermal Energy Storage

Thermal energy involves storing energy in a thermal reservoir such as molten salt, pressurized water etc. by either supplying heat from solar energy or extracting heat to maintain the reservoir at colder state.

Typically they are used in applications to offset temperature difference between day and night, such as heating at night, or producing ice during night, supplying chilled water systems etc. to cool the building in hot day time in HVAC/R applications [75]. Themis power station in France that uses molten salt to store heat is designed to store 40,000kWh of thermal energy, equivalent to almost 1 day of average sunlight [76].

3.4 Electric Vehicles (EVs)

EVs were first introduced in the mid-19th century. The high cost, low speed and their short range, as compared with internal combustion engines, led to their decline [77]. However, in the last two decades, an interest in the electric vehicles has developed due to the problems associated with internal combustion engine vehicles and its negative impact on the environment. The concept of vehicle-to-grid (V2G) has sparked this interest due to the potential support of EVs to the aging power grids.

Initially, the electric vehicles were considered as a load that only burdens the power system network [78], but the idea that EVs can be used to support the electrical grid system in a way that is beneficial for both the EV owner and the electricity power grid was first introduced in [79]. This leads to further development of the V2G concept later in [80, 81]. The V2G concept is divided into two types; unidirectional V2G and bidirectional V2G. Unidirectional V2G is also called load only V2G that performs EV load control and regular V2G, in which power is injected from grid to vehicle [82]. In bidirectional V2G, power can be transferred from vehicle-to-grid or the other way and most authors have considered V2G as a common terminology for bidirectional power flow. Since the introduction of the benefits of the electric vehicles, V2G basics have been fully defined and the potential benefits in different electricity market have been explored [80-81, 83].

CHAPTER 4

Economic Analysis of Distribution Feeder Deferral using ESS

In Distribution systems, load demand may exceed the feeder thermal limit during peak demand periods and causes system damages. This is avoided by load shading, resulting in financial losses to utilities and customers. This problem can be countered by using ESS. This chapter deals with the economic analysis of distribution feeder deferral using ESS. The scope of this chapter is to determine the conditions that lead to the maximum economic benefit of distribution feeder deferral which can be provided by the ESSs. Sensitivity studies that reveal the effects of ESS parameters such as ESS power and energy capacity, round-trip efficiency and feeder length, as well as the feeder load growth rate, are reported.

4.1 Distribution System Consideration

4.1.1 Feeder Thermal Limit

In the distribution system, the power is delivered from substation to the end user through a dedicated feeder. Each feeder has its recommend capacity limitation due to thermal effects. That affects substation equipment, cables and overhead conductors. It was assumed a typical 13.8 KV level class feeder that has the thermal limit of 10 MW in this thesis. Potential damages to the substation equipment can be caused if the feeder's load exceeds this value. To protect the system, a planned ESS operation will be implemented if the feeder load exceeds the thermal limit.

4.1.2 Distribution System Model

When modeling the distribution system, one must consider the following parameters:

a) Load Growth Rate, r_a

b) 24 hours Load Variation in time, $Pl(t)$

c) Feeder Length, l, and Capital Cost, C_f

d) Annual Load Variation

4.1.2.1 Load Growth Rate

The overall load demand monitored at the substation bus increases annually. The electricity demand is driven by various factors like the number of households served by the considered feeder, household income and the consumer confidence. The economic condition will drive the system load increase in the future. The load Growth rate r_a may be expresses as follows [84]:

$$r_a = \left(\frac{S_{max_t}}{S_{max_{t-1}}} - 1 \right) \times 100\ \% \tag{4.1}$$

where

S_{max_t}= Maximum feeder demand (MW) at the year t.

$S_{max_{t-1}}$= Maximum feeder demand (MW) at the year t-1.

4.1.2.2 24 hour Load Variation in Time

The feeder's load demand curve is time varying. For the most cases in Saudi Arabia, the power will peak during the early afternoon. Sometimes the load curve will also have multiples peaks. It should be realized that the peak demand is not allowed to go above the feeder thermal limit. If such a situation developed, a number of options including ESS may be implemented.

4.1.2.3 Feeder Length and Capital Cost

Giving the feeder length: l (mi), assuming the price of constructing feeder is $k_f = 2.25 \times 10^5\ SR/mile$ [85], the feeder capital cost C_f has the expression:

$$C_f = k_f l \tag{4.2}$$

4.1.2.4 Annual Load Variation

Similar to the daily load demand variation, the load curve will also vary throughout the year. The maximum peak demand usually happens during the summer. The spring and fall times will have lower demand. The winter depending on the geographies region will be in the middle range of the demand for most of the time.

4.2 ESS Capital cost

Capital cost of ESSs is very important factor to consider it for their installation and use in power industry. It is represented in terms of capital cost per unit power and capital cost per unit energy. The capital cost of ESS can be expressed as [34]:

$$C_e = C_p P_{max} + C_E E_{max} \tag{4.3}$$

where

C_p= Capital power cost of ESS (SR/KW)

C_E= Capital energy cost of ESS (SR/KWh)

P_{max} = ESS power capacity (MW)

E_{max} = ESS energy capacity

In order to establish an economic analysis of distribution feeder deferral, the capital power cost of ESS is assumed to be 1875 SR/KW and capital cost of ESS is considered to be 325 SR/KWh [3]. These are generic ESS capital costs.

4.3 Problem Definition

As the power demanded by the costumer's increases, its peak value reaches the point where the thermal stresses caused to distribution transformers, voltage regulators and conductors exceed the recommended levels and the life-span of the involved devices can be compromised.

Nearing such conditions can be avoided by using one of two methods:

1. Installation of additional feeders as shown in Figure 4.1 and eventual expansion of the involved substation.
2. Incorporation of storage devices such as pumped hydro energy storage, flow batteries or compressed air storage systems located near the areas of load growth.

The storage device will supply a portion of the feeder load during peak times, thereby keeping the feeder power within normal operating limits. The energy storage program can also include renewable energy sources such as wind farms. This method makes the feeder's installation deferral possible.

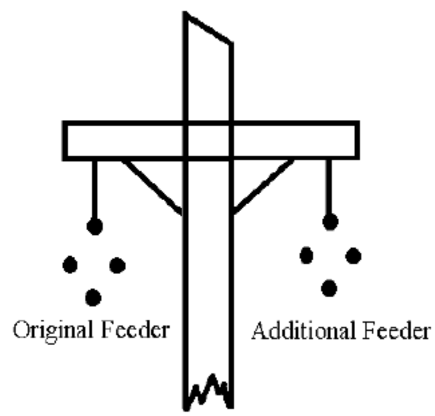


Figure 4.1 Additional Feeder Installation in the Distribution System

4.4 Problem Formulation

Knowing the present values of the cost of installation of the additional feeder with and without deferral, as well as the present value of the ESSs, it is possible to compute the Net Present Value at a given point in time. This is the benefit derived from feeder deferral. The cost of increasing capacity of substation is not considered. The detailed analysis and procedures are described below.

4.4.1 Distribution System Load History

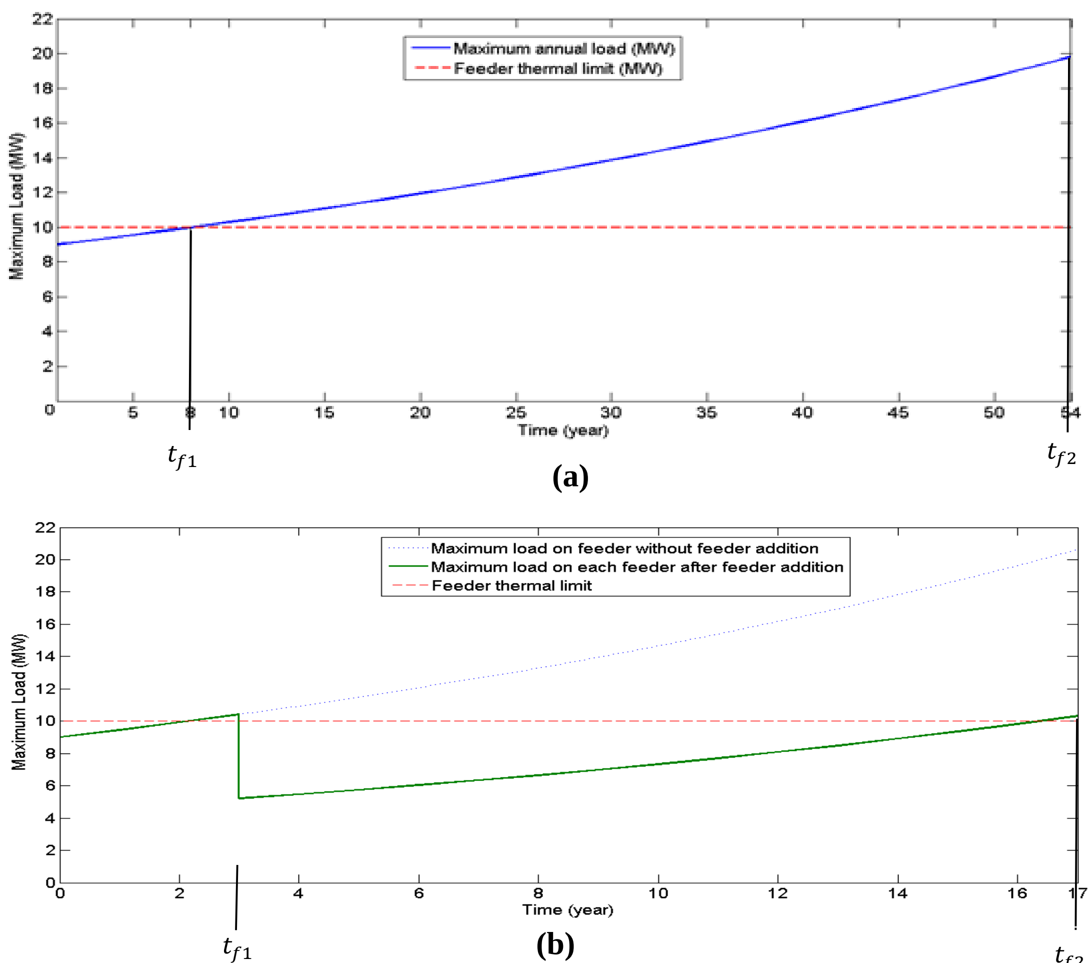
Figure 4.2 presents the system loading history of a radial distribution feeder of Dharan region supplying a load with the maximum power characterized by the annual load growth rates, r_a. The maximum thermal stress is correlated to the maximum power demand S_{max} (MW), whose analytical expression is [85]:

$$S_{max} = S_a e^{\ln\left(1+\frac{r_a}{100}\right)t} \tag{4.4}$$

where

S_a= Maximum real power demand (MW) at the year 0 (t=0).

t = Time (year).



(a)

(b)

Figure 4.2 Load History S_a = 9 MW (a) r_a = 1.5 % (b) r_a = 5 %

One will notice that at t = 0, S_a= 9 MW and after 8 years, at the time t_{f1}, S_{max}=ftl ≥10 MW. This is the critical level when the thermal stress will start causing excessive damage to the equipment.

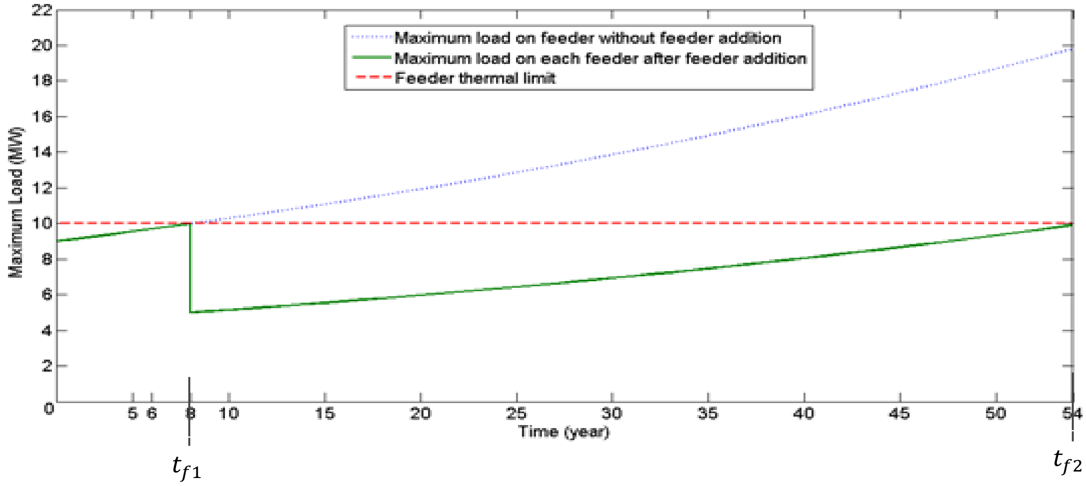
The two proposed mitigation methods will lower the new level S_{max}. Ideally, after adding an additional feeder, the feeders will be able to share the same amount of load so that the maximum demand can withstand the system may be doubled. However, in the year t_{f2}, S_{max}=2$*\,ftl \geq$ 20 MW, and the two feeders reach their power limit. Another (3rd) additional feeder must be ready to operate at the end of t_{f2}.

In reality, the two feeders will supply different customers, hence they never share the load equally. Therefore, the third additional feeder commission starting time may need to be moved to an earlier time. Assuming S_a=9 MW; r_a=1.5%/year and that the feeder thermal limit cannot exceed S_{max}=ftl=10 MW, the time t_{f1} is calculated using the following expression:

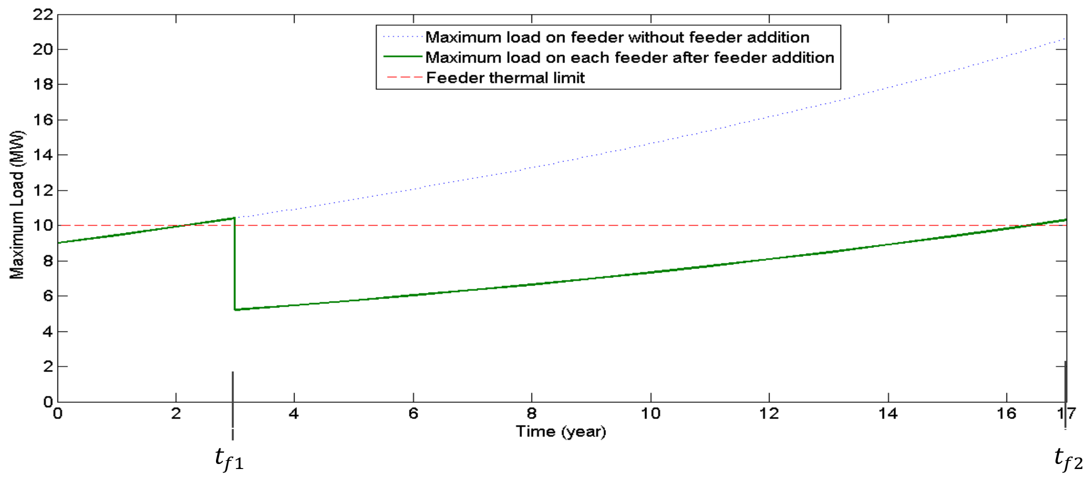
$$t_{f1} = \left\lceil \frac{\ln\left({ftl}/{S_a}\right)}{\ln\left(1 + {r_a}/{100}\right)} \right\rceil = \left\lceil \frac{\ln\left({10}/{9}\right)}{\ln(1 + 0.015)} \right\rceil = 8\ years \qquad (4.5)$$

4.4.2 Feeder Installation Model

An additional feeder construction in the year t_{f1} will upgrade the system. Therefore, at year t_{f1}**,** the two feeders will sustain a maximum demand of 10 MW with an total thermal limit of 20 MW. The new system maximum load evolution is presented in Figure 4.3.



(a)



(b)

Figure 4.3 Load History with an Additional Feeder Construction (a) r_a = 1.5 % (b) r_a = 5 %

From Figure 4.3, it is learned that the additional feeder doubles the maximum capacity of the supplying system. However, later at year t_{f2}, one of the two feeders will experience the demand limitation due to the load growth rate r_a and an additional feeder's construction is needed, for a total of three feeders.

Assuming the discount rate (d_r), the loan interest rate (i_r) and the capital cost of the feeder (C_f), the annual payment for the feeder (A_{Pf}) can be computed using the expression [78]:

$$A_{Pf} = C_f \frac{i_r(1+i_r)^{t_{Lf}}}{(1+i_r)^{t_{Lf}} - 1} \tag{4.6}$$

where

t_{Lf} = Loan time for the feeder construction investment.

Present value for the 1st additional feeder at the time t_{s1} is calculated from the following expression [84]:

$$PV_f = A_{Pf} \frac{(1+d)^{t_{Lf}} - 1}{d(1+d)^{t_{Lf}}} \tag{4.7}$$

where

PV_f= Total present value of the additional feeder (without deferral) at the time t_{f1}.

4.4.3 Energy Storage Model – Distributing Feeder Deferral Implementation

Instead of building a new feeder at t_{f1}, an ESS is installed to defer new feeder construction. The annual load growth rate is taken to be 1.5%. The concept is presented in Figure 4.4. This ignores the fact that an ESS's lifetime is limited to a certain number of cycles.

The ESS can be discharged at the rated power P_{max} during peak times, so that the critical time t_{f1} will be transferred to t'_{f1}. The present value of the deferred additional feeder as well as the ESS should be converted to a common timeline t_{f1} in order to compare the two investments. There are two terms in the total deferred present value expression in the year t_{f1}:

$$PV_f' = PV_{ess}' + PV_{fd}' \tag{4.8}$$

where

PV_{ess}' = ESS's present value at the time t_{f1}.

PV_{fd}' = Additional feeder's present value with deferral at the time t_{f1}.

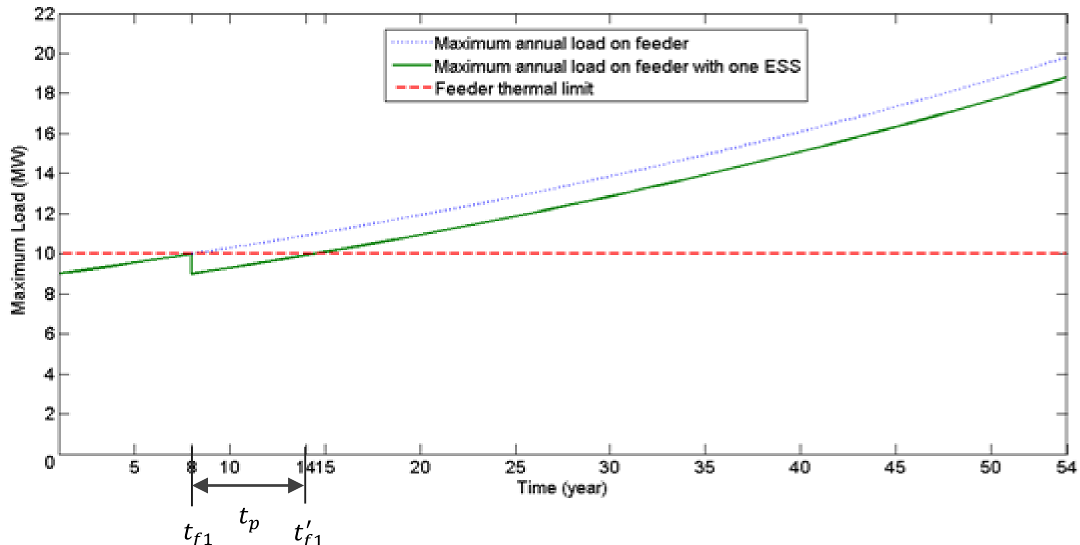


Figure 4.4 Load History with one ESS Installation for r_a = 1.5 %

The annual payment for the ESS is first calculated by [84]:

$$A_{Pe} = C_e \frac{i_r(1+i_r)^{t_{Le}}}{(1+i_r)^{t_{Le}} - 1} \tag{4.9}$$

where

C_e = the capital cost of the ESS.

A_{Pe} = the loan time of the ESS investment.

In Eq. (4.8), the first part (PV_{ess}') is the present value of ESS at the year t_{f1} with the equation:

$$PV'_{ess} = A_{Pe} \frac{(1+d)^{t_{Le}} - 1}{d(1+d)^{t_{Le}}} \tag{4.10}$$

The second part (PV'_f) of Eq. (4.8) is the present value of the additional feeder considering deferral, given by equation:

$$PV'_{fd} = PV_f \frac{1}{(1+d)^{t_p}} \tag{4.11}$$

where

t_p = the total feeder deferral time.

If only one ESS was installed to defer distribution feeder installation, then feeder installation deferral time is:

$$t_p = t_{ep1} = t'_{f1} - t_{f1} \tag{4.12}$$

where

t_{f1}= Additional feeder construction finish time (without deferral).

t'_{f1}= Additional feeder construction finish time (deferred).

In reality, in order to maximize the benefit of feeder deferral, more than one ESS may be installed at successive times. The expression for the total feeder deferral time has the expression:

$$t_p = \sum_{j=1}^{n} t_{ep_j} = t'_{f1} - t_{f1} \tag{4.13}$$

where

t_{ep_j} = the deferral time contributed by the jth ESS.

For the *j*th ESS, when $j \geq 2$, the present value of the *j*th ESS is:

$$PV'_{ess_j} = A_{Pe} \frac{(1+d)^{t_{Le}} - 1}{d(1+d)^{t_{Le}}} \frac{1}{(1+d)^{\left(\sum_{k=1}^{j-1} t_{ep_k}\right)}} \tag{4.14}$$

where

t_{ep_k}= the deferral time contributed by the *k*th BESS (k < *j*).

Then Eq. (4.8) will be rewritten as:

$$PV'_f = \sum_{j=1}^{n} PV'_{ess_j} + PV'_{fd} \tag{4.15}$$

where

PV'_{ess_j} = Additional ESS's present value at the time t_{f1} with deferral.

PV'_{fd} = Additional feeder's present value at the time t_{f1} with deferral.

Finally, the Net present Value (NPV) can be computed by substituting (4.7), (4.10), (4.14) and (4.15) in (4.16).

$$NPV = PV_f - PV'_f \tag{4.16}$$

where

PV_f= Total present value at the time t_{f1} (without deferral)

PV'_f= Total present value at the time t_{f1} (with deferral)

Equation (4.16) gives the net saving obtained by deferring the feeder construction (benefit).

An example is considered to illustrate the economic benefit by deferring the additional feeder construction. Two ESSs are installed to achieve the feeder deferral for 12 years. The Net Present Value (NPV) calculation parameters used in this example are summarized in Table 4.1. The VRB ESS parameters are used.

Table 4.1 Generic ESS Economic Data [3, 34, 85]

Load Growth Rate (r_a) (%/year)	Capital Cost (SR)		Loan Term (years)		Annual Interest rate (i_r)	Discount Rate (d_r) (%/year)	ESS Characteristics	
	13.8 kV Feeder (10 mi) (C_f)	ESS (C_e)	Feeder (t_{Lf})	ESS (t_{Le})			P_{max} (MW)	E_{max} (MWh)
1.5	22.5×10^6	3.5×10^6	20	10	6	10	1	5

Given the system load history shown in Figure 4.5, two ESSs (**N=2**) will be considered to install to achieve the maximum 12 years feeder deferral shown in Figure 4.5. The strategy that helps to determine the ESS commission starting time (t_{e_h}) and feeder deferral time is presented in the next section as a part of the simulation model developing process. It shows that ESSs will start operating in the years 8 and 14 respectively.

The first investment's total present value PV_f is the feeder upgrade investment without deferral. The second investment's total present value PV_f' has the similar feeder upgrade investment but with 12 years deferral plus the two ESSs investmen. The two investment's total present value can be subtracted to get the NPV which is the total deferral benefit at year t_{f1}. The feeder original upgrade time (t_{f1}= 8) is used as the common time. Each present value has to be referred to this common time in order to be compared.

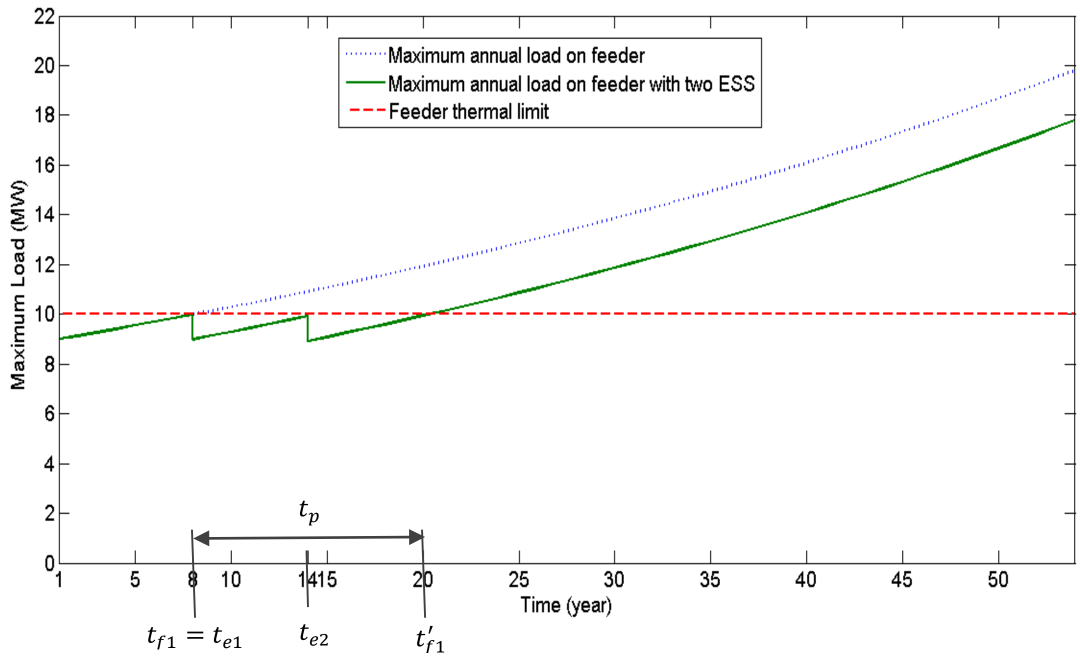


Figure 4.5 Load History with two ESS Installation

A flowchart diagram for evaluating the investments is shown in Figure 4.6.

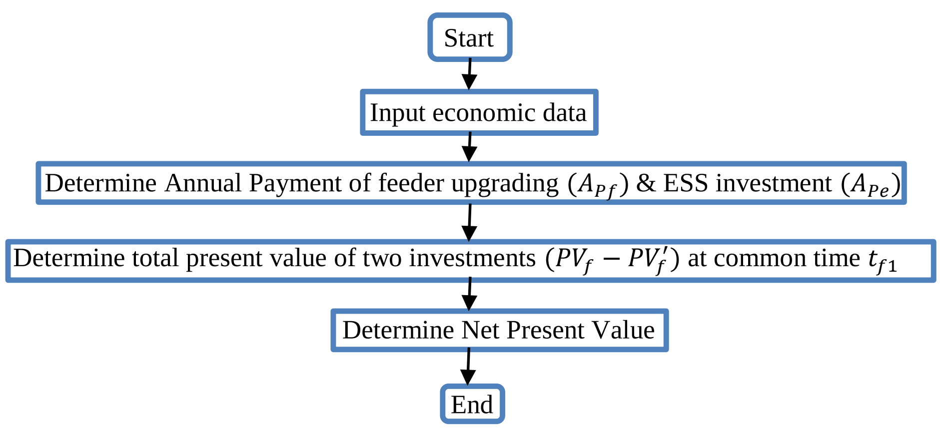


Figure 4.6 NPV calculation flowchart

The two investments' present values are summarized in Table 4.2. One is for feeder upgrade without deferral, the other is for feeder upgrade with two ESSs deferral.

Table 4.2 Economic Analysis Summary—Present Value (referred to the year t_{f1})

Case1: (Feeder Upgrade without deferral)		Case2: (Feeder Upgrade with 3 ESS deferral)	
Upgrade Feeder	$SR\ 16.69 \times 10^6$	ESS-1	$SR\ 2.93 \times 10^6$
		ESS-2	$SR\ 1.65 \times 10^6$
		Deferred Feeder	$SR\ 5.32 \times 10^6$
Total Present Value (PV_f)	$SR\ 16.69 \times 10^6$	Total Present Value (PV'_f)	$SR\ 9.90 \times 10^6$

Table 4.2 above summarized the present values of two different investment scenarios. Finally, (4.17) helps to compute this feeder deferral economic benefit:

$$NPV = PV_f - PV'_f = 16.69 \times 10^6 - 9.90 \times 10^6 = SR\ 6.79 \times 10^6 \qquad (4.17)$$

4.5 Model Development

Using the model developed in the section 4.4, the model can be proposed to calculate NPV considering following conditions:

- Feeder deferral time
- ESS commission starting time
- ESS Energy losses

- ESS Capital cost
- ESS O&M cost

The Net Present Value will be determined under these four constraints. A maximum value of NPV can be achieved. This method pivots around the feeder energy constraints and leads to the maximum deferral time.

4.5.1 Feeder Deferral Time

The total feeder deferral time has a limitation: the maximum load demand is continuously increasing. This means the energy that is available to charge under the thermal limit is decreasing while the total energy which is above the thermal limit is increasing. Considering the ESS efficiency, the total amount of energy available to charge should be sufficient to balance the energy which needs to be supplied. The mathematical expression is:

$$Pl_t(i) = Pl_0(i)\, e^{\ln\left(1+\frac{ra}{100}\right)t} \tag{4.18}$$

$$E_{ch} = \sum_i \begin{cases} ftl - Pl_t(i) & if\ Pl_t(i) < ftl \\ 0 & else \end{cases} \tag{4.19}$$

$$E_{dch} = \sum_i \begin{cases} Pl_t(i) - ftl & if\ Pl_t(i) > ftl \\ 0 & else \end{cases} \tag{4.20}$$

$$E_{ch}\eta \geq E_{dch} \tag{4.21}$$

where

$Pl_0(i)$ Load demand at year 0 during hour i

ftl Feeder thermal limit

E_{ch} Energy available for ESS to be charged in 24 hours

E_{dch} Energy to be supplied by ESS

The maximum feeder deferral time (t_p) can be determined when the (4.21) does not apply and the t'_{F1} will have the expression:

$$t'_{F1} = t_{F1} + t_p \tag{4.22}$$

4.5.2 ESS Operation Starting Time

The ESS's operation starting time should be carefully determined in order to optimize its use. The ESSs need to have two features in order to defer the feeder installation. These two conditions determine the ESS operation starting time. The first one requires that the total rated power of the ESSs should be able to supply all the power above the feeder's thermal limit. For instance, if there are h ESS installed, the total rated power of the ESSs will be hP_{max} MW. Assuming the load demand at the year t is $Pl_t(i)$, the maximum power above the thermal limit will be $(Pl_t(i) - ftl)$. The mathematical expression for this equation is:

$$hP_{max} - (Pl_t(i) - ftl) \geq 0 \tag{4.22}$$

The second condition on the ESSs insures that their total capacity should be large enough to supply the peak load energy which exceeds the thermal limit of the system. In the other words, when the h^{th} ESS is connected, the total capacity hE_{max} should be larger than the extra peak load energy needed to be supplied by the ESS, namely: E_{dch}. The mathematical expression of this second condition is:

$$hE_{max} \geq E_{dch} \tag{4.23}$$

Considering the load growth rate, the h^{th} ESSs operation starting time (t_{e_h}) can be found by considering both conditions as stated in Eq. (4.22) and (4.23). To maximize the benefit of using ESSs, the operation starting time should be decided when either of the two constraints does not hold. Therefore, the present value of the total ESSs will be minimized and the potential benefit will be maximized.

4.5.3 ESS Energy Losses

Electric energy will be lost during the charging/discharging process. These energy losses should be addressed in the case of deferring feeder construction. The main reason for this reconsideration is that ideally, if the ESS has 100% round-trip efficiency, all the charged energy can be used to discharge during the high demand. However, in reality, the efficiency of the ESS is less than 100%, which means the energy will be lost during charging/discharging process and therefore should be considered as the energy related operational cost. These energy losses due to ESS's inefficiency have to be accounted for financially in the simulation model. In that way, the daily money losses will be addressed in the present value calculation with the following mathematical expression:

$$C_{loss} = \sum_{t=t_{f1}}^{t'_{f1}} \lambda_{avg}\left(E_{dch}(1-\eta)\right)\frac{1}{(1+d)^{t-t_{f1}+1}} \tag{4.22}$$

where

C_{loss} Wasted cost during charging/discharging process due to BESS inefficiency.

λ_{avg} Average LMP in the region.

4.5.4 ESS Capital Cost

The ESS's capital cost is proportional to its capacity, which should be addressed in the ESS model present value calculation. Similarly, the feeder capital cost is proportional to the length of the feeder.

4.5.5 ESS O&M Cost

The annual ESS operation and maintenance cost is defined as:

$$C_{om} = \sum_{t=t_{f1}}^{t'_{f1}} \left(C_{omf}\, P_{max} + \; C_{omv}\, E_{dch_{annual}}\right) \frac{1}{(1+d)^{t-t_{f1}+1}} \tag{4.23}$$

Where C_{omf} and C_{omv} represent the fixed and variable O&M cost of ESS. The C_{omf} and C_{omv} values are 33.75 SR/KWh/year and 0 SR/KWh/year respectively [86].

Finally, the mathematical expression to compute NPV at year $t_{f1}$is:

$$NPV = \; PV_f - PV'_f - C_{loss} - C_{om} \tag{4.24}$$

The developed distribution feeder deferral simulation model is solved in Matlab using following flowchart.

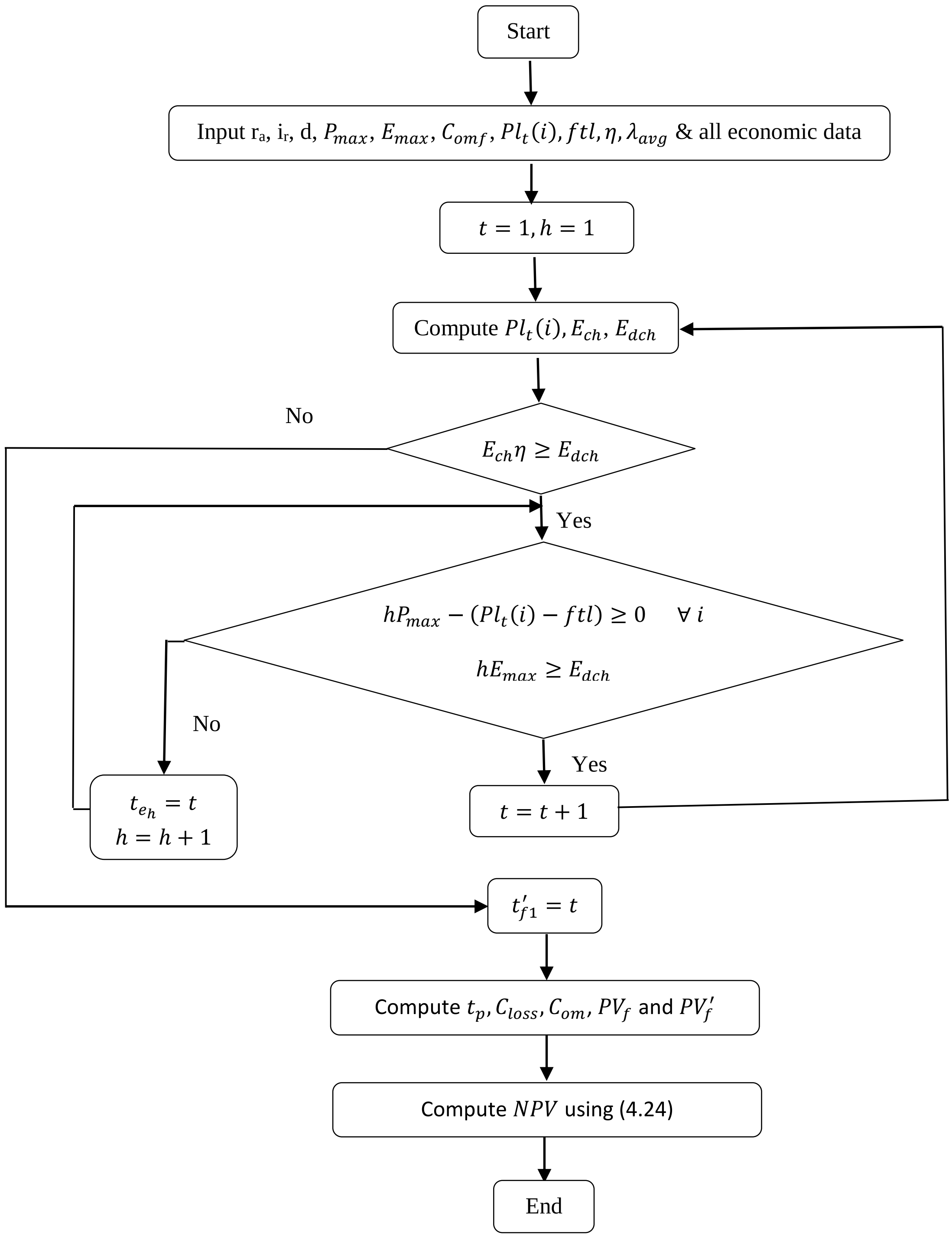


Figure 4.7 Flow chart for feeder deferral economic model using ESS

4.6 Model Implementation Example

The example to implement the model is shown in Table 4.1. The load profile is taken from a typical load demand of Eastern province region of Saudi Arabia.

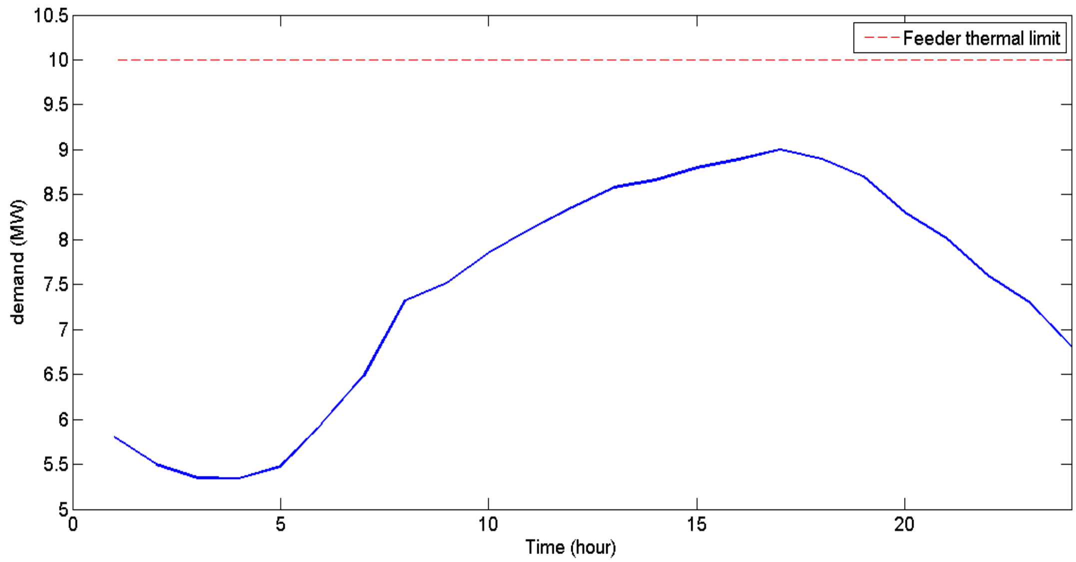


Figure 4.8 Hourly load demand at current year

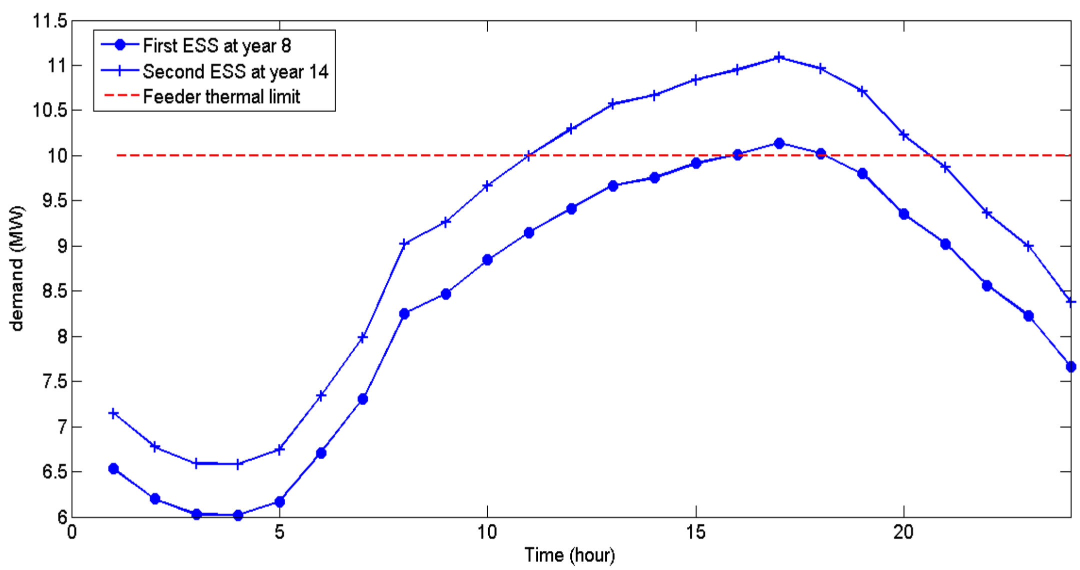


Figure 4.9 Hourly load demand at each ESS operation year

Figure 4.8 shows the hourly load curve at the year 0. The entire load profile is below the feeder limit (10 MW). However, under 1.5%/year load growth rate, the peak load will exceed the feeder thermal limit at year $t_{f1} = t_{e1} = 8$.

Figure 4.9 shows the hourly load curve under each ESS operation year. The first ESS is operated in the year **8** when the maximum load reaches the thermal limit of the existing feeder, This ESS has the capacity needed to supply the peak power demand till the year **14** when a new ESS starts operation.

The energy losses are calculated on daily basis. These losses have been taken into account in the present value calculation. Sensitivity studies are undertaken find the effect of a number of parameters on ESS operation.

4.7 Simulation Results

The following six parameters affect the economics of the ESS's application in feeder deferral:

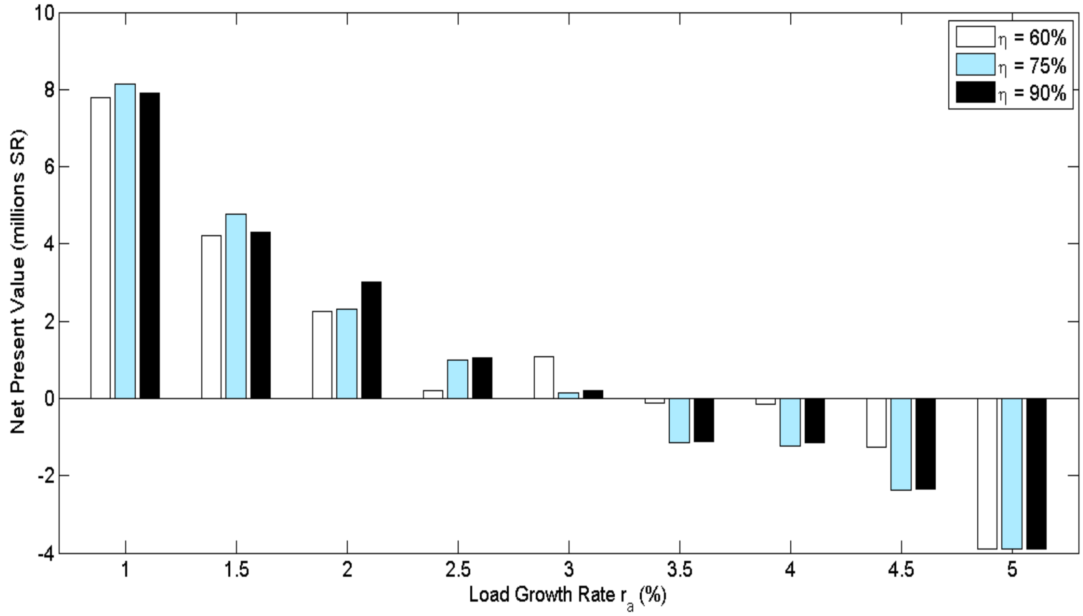
1. Feeder maximum load growth rate, r_a
2. Feeder length, l
3. ESS round-trip efficiency, η
4. ESS power capacity, P_{max}
5. ESS maximum Energy Capacity**,** E_{max}.
6. ESS Capital Cost

Multiple ESSs are used to achieve the maximum feeder deferral time t_p. The capital cost per unit energy of the ESS, \$/MWh, is a function of the round-trip efficiency η as well as the ESS's capacity E_{max}.

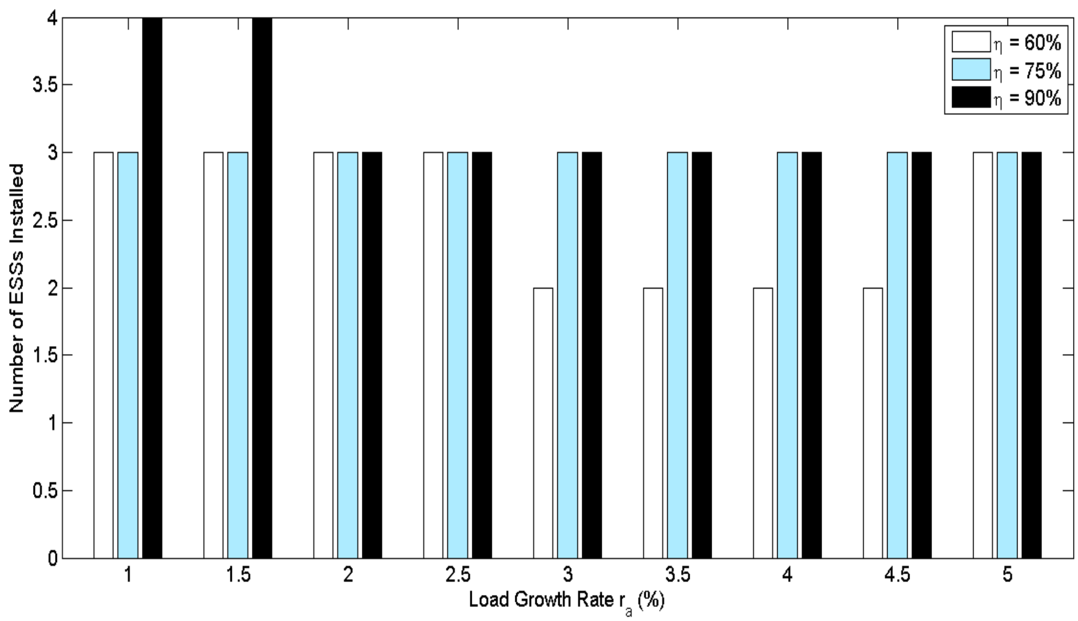
Both ESS round-trip efficiency and load growth rate effects on NPV are presented in Figure 4.10 (a). The ESS is assumed to have the base values. The charts show that the lower r_a will have higher NPV. The results shown in Figure 4.10 (a) illustrates the effect of energy lost while charging/discharging the ESS. Since the η is increasing, the NPV will increase because less energy will be lost. One will observe that for an ESS with high round-trip efficiency η, the NPV will be higher because the deferral time can be extended by using a higher η, which will increase the NPV.

From analyzing Figure 4.10 (a) & (b), it is clear that when number of installed ESSs are same for each case (r_a = 2%, 2.5% & 5%), NPV is higher in case of higher efficiency. When r_a is 1% and 1.5% the number of installed ESSs in case of 90% efficiency are more than those for ESSs having efficiency 60% and 75% . This is the reason that more capital cost is involved in calculation of NPV and NPV of 90% efficient ESS is less than that of 75%. If same number of ESSs are considered in each case, NPV will increase with increase in efficiency.

As load growth rate increases, deferral period of feeder installation decreases resulting in reduction of NPV. After load growth rate 3%, NPV goes to negative due to very small deferral time of new feeder construction.



(a)



(b)

Figure 4.10 (a) NPV of feeder deferral versus load growth rate with variation in efficiency of ESS (b) Number of installed ESSs versus load growth rate with variation in efficiency

Table 4.3 Charging and discharging energy required by ESS for annual load growth rates of 4.5% and 5%

Year	$r_a = 4.5\%$			$r_a = 5\%$		
	E_{dch} (MWh)	E_{ch} (MWh)	$max\ Pl_t$ (MW)	E_{dch} (MWh)	E_{ch} (MWh)	$max\ Pl_t$ (MW)
1	0	53.337	9.405	0	52.444	9.45
2	0	44.937	9.828	0	43.066	9.923
3	0.614	36.773	10.27	1.296	34.516	10.42
4	3.376	30.362	10.73	5.038	27.918	10.94
5	7.555	24.956	11.2	10.395	22.419	11.48
6	13.049	20.432	11.72	17.177	17.803	12.06
7	19.613	16.529	12.247	-	-	-

Table 4.4 Charging and discharging energy required by ESS for annual load growth rates of 6% and 8%

Year	$r_a = 6\%$			$r_a = 8\%$		
	E_{dch} (MWh)	E_{ch} (MWh)	$max\ Pl_t$ (MW)	E_{dch} (MWh)	E_{ch} (MWh)	$max\ Pl_t$ (MW)
1	0	50.658	9.54	0	47.085	9.72
2	0.112	39.409	10.112	1.718	33.420	10.5
3	3.283	30.538	10.719	8.8135	23.796	11.34
4	9.074	23.564	11.36	19.569	16.552	12.24
5	16.958	17.917	12.04	-	-	-

For ESS efficiency of 60% and load growth rate 4.5%, it is evident from table 4.3 that the new feeder will have to be installed at year 6 and maximum deferral period will be 3 years. For base case maximum energy capacity of ESS (5 MWh), 2 ESSs will be installed at years 3 and 5. Now for load growth rate 5%, new feeder will be constructed at year 6 and 3 ESSs will be installed at years 3, 4 and 5.

For ESS efficiency of 75% & 90% and load growth rate 4.5%, it is clear from table 4.3 that the new feeder will have to be installed at year 5 and maximum deferral period will be 4 years. For base case maximum energy capacity of ESS (5 MWh), 3 ESSs will be installed at years 3, 5 and 6. Now for load growth rate 5%, new feeder will be constructed at year 6 and 3 ESSs will be installed at years 3, 4 and 5.

For ESS efficiency of 60%, 75% & 90% and load growth rate 6%, it is clear from table 4.4 that the new feeder will have to be installed at year 5 and maximum deferral period will be 3 years. For base case maximum energy capacity of ESS (5 MWh), 2 ESSs will be installed at years 2 and 4. Now for load growth rate 8%, new feeder will be constructed at year 4 and 2 ESSs will be installed at years 2 and 3.

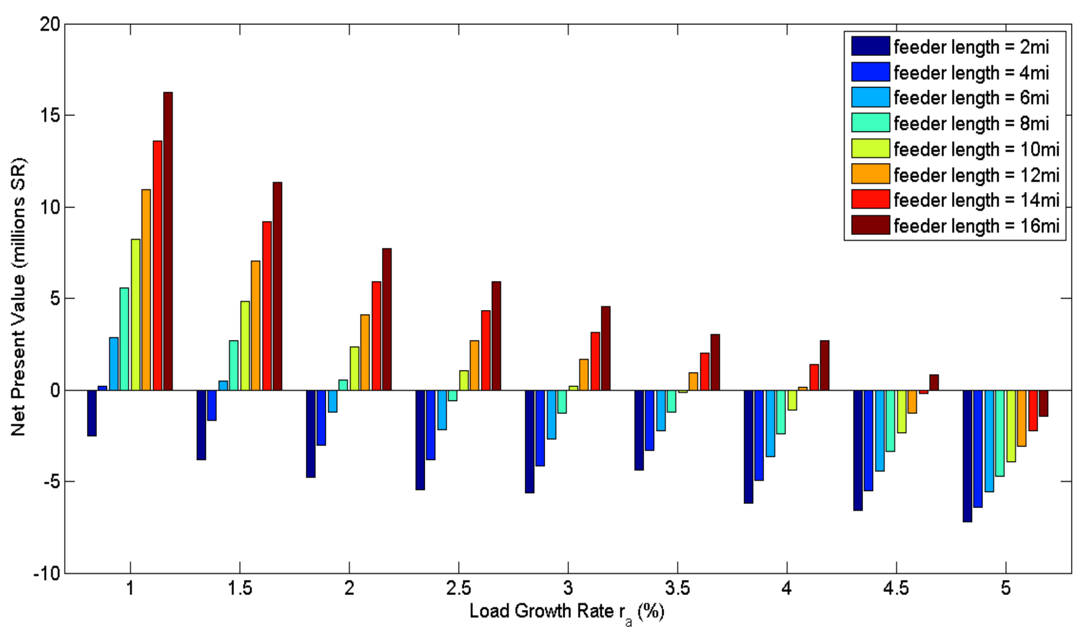
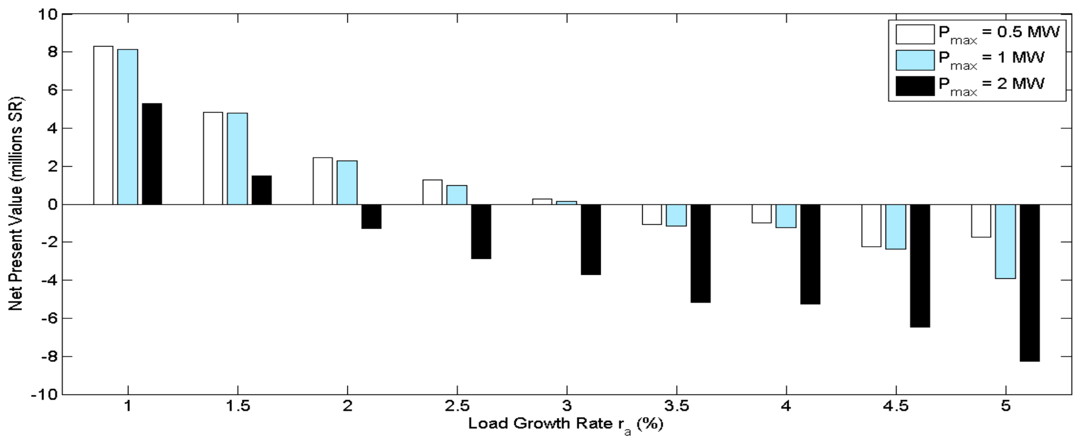


Figure 4.11 NPV of feeder deferral versus load growth rate with variation in feeder length

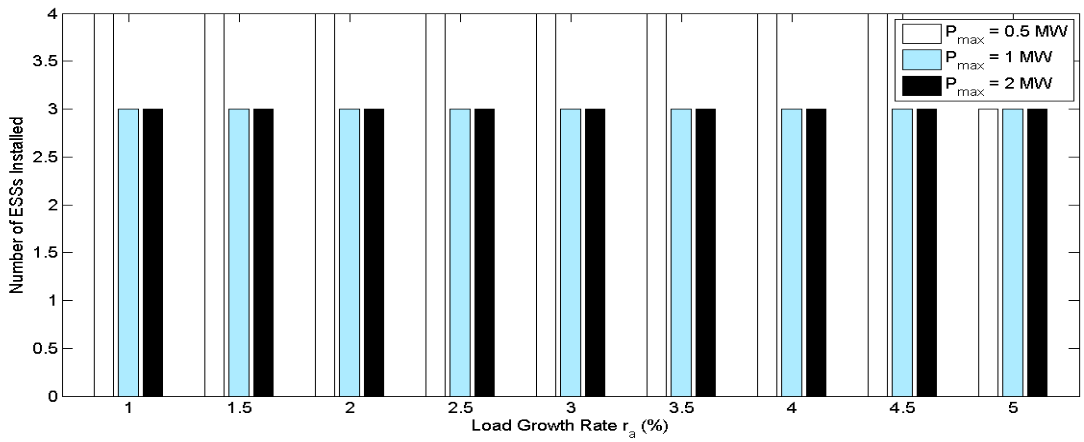
The effects of the feeder length on the NPV are presented in Figure 4.11. The ESS is assumed to have the characteristics of P_{max}= 1 MW and E_{max}=5 MWh with η=75%. The length of the distribution feeder is the main parameter in Figure 4.11 varying from 2 mile to 16 mile. The results of Figure 4.11 show that the NPV is highly dependent on the length of the feeder. Since the capital cost of feeder is proportional to its length, there will be a critical feeder length, which will separate between positive values and the negative values of the NPV. The impact of the feeder length is higher when r_a is low. For example, the NPV will increase by 2.27 million SR from l=8 mi to l=10 mi under the load increasing rate of 1.5%. Since the NPV increases as the length of the feeder increases, it is more economically to defer a long feeder than a short feeder.

The NPV versus the ESS maximum power capacity with the load increasing rate as a varying parameter is presented in Figure 4.12 (a). The maximum energy capacity, efficiency and feeder length are assumed to be of base case.

In general, the NPV will decrease if ESS is replaced with a higher power capacity one while keeping the same energy capacity. The reason lies in the fact that the capital cost of ESS is going up. However, one will notice that there are other factors to be accounted too for analysis. In case of low power capacity ESSs, they will need to be replaced more often during study period than the ESSs having higher power capacity as clear from Figures 4.12 (b) & (c). For example, for a load growth rate of 1.5%, the numbers of ESSs are 4, 3 and 3 with power capacity 0.5, 1 and 2 MW respectively and the capital costs 10.25, 10.5 and 16.125 million SR respectively. The present value of capital cost of 1 MW ESSs is little more than that of 0.5 MW ESSs due to each ESS's deferral period.



(a)



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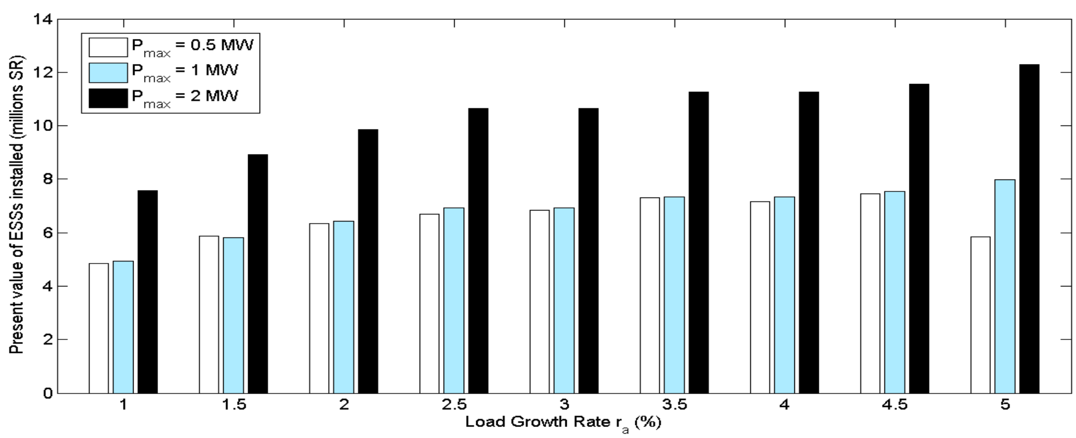


(c)

Figure 4.12 (a) NPV of feeder deferral versus load growth rate with variation in power capacity of ESS (b) Number of installed ESSs versus load growth rate with variation in ESS power capacity (c) Present value of installed ESSs versus load growth rate with variation in ESS power capacity

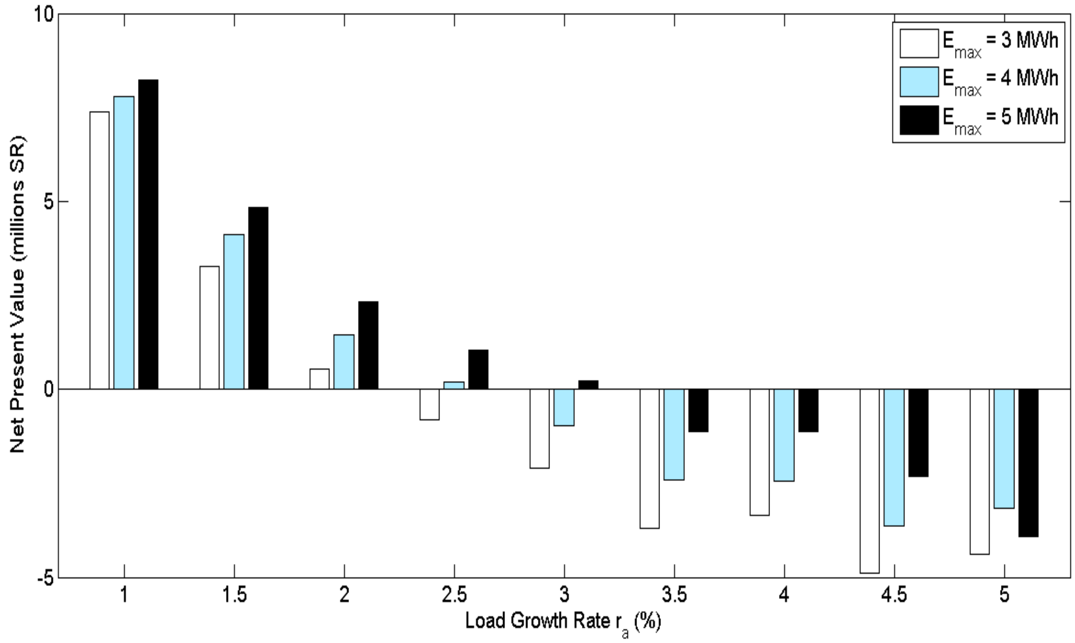


Figure 4.13 NPV of feeder deferral versus load growth rate with variation in power capacity of ESS

Similarly, the NPV as a function of ESS energy capacity with the annual load increasing rate variation is shown in Figure 4.13. In general, the NPV will decrease if ESS is replaced with a higher power capacity one while keeping the same energy capacity and same number of ESSs considered in each case. The reason lies in the fact that the capital cost of ESS increases. However from Figure 4.13, it is clear that the NPV is increasing with increase in energy capacity of ESS. The reason is that the capital cost of ESS does not increase significantly with increase in its energy capacity as the capital cost of energy capacity of ESS is small in comparison to its capital cost of power capacity. Besides, more ESSs are required in case of low energy capacity than those of high energy capacity.

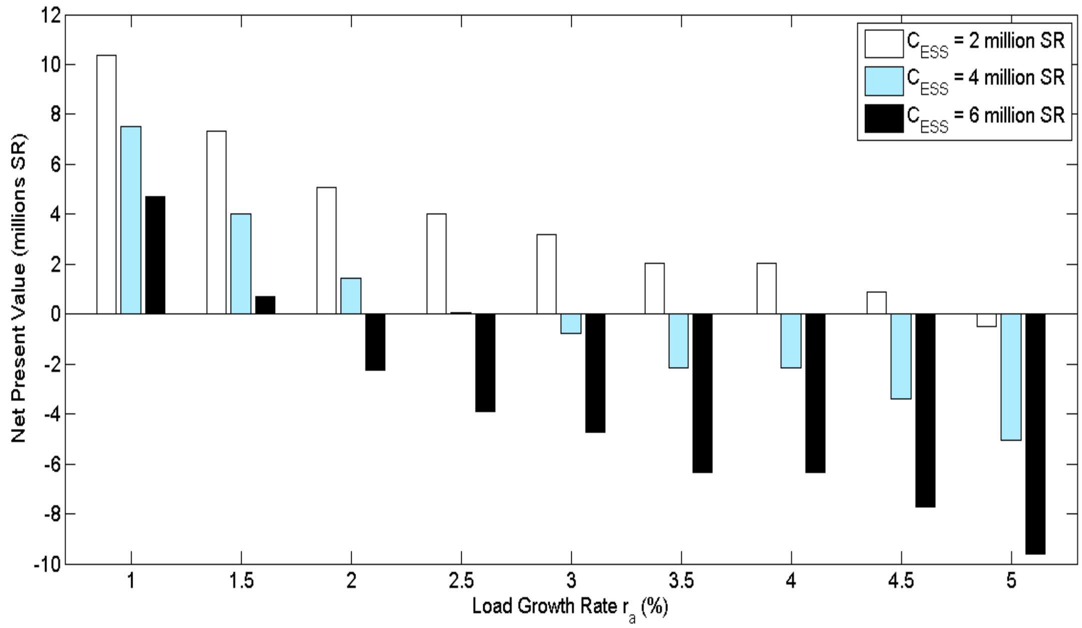


Figure 4.14 NPV of feeder deferral versus load growth rate with variation in ESS capital cost

Figure 4.14 shows the sensitivity analysis of NPV with respect to ESS capital cost. It is clear that NPV is decreasing with increase in ESS capital cost and annual load growth rate.

4.8 Conclusion

In this chapter, an economic analysis has been performed to quantify the potential benefits of distribution feeder deferral planning using ESS. In this analysis, the net present value of deferral has been calculated and simulated using different parameters like annual load growth rate, feeder length, ESS round-trip efficiency and its power and energy capacities. The results show that distribution feeder deferral planning using energy storage systems is economical for long feeder length.

CHAPTER 5

Modeling of Scheduling Optimal ESS

Energy storage for power systems has recently attracted significant interest and attention from researchers and the power industry. With fast response time and low operating cost, energy storage is viewed as an attractive resource to compensate for generation availability in the system. However, most energy storage technologies are not economically competitive compared to conventional generating resources. Finding the right conditions in the market to maximize energy storage's benefits is critical for the viability of storage technologies. This chapter discusses an optimization approach and guideline to obtain the optimal operation of ESS with distribution feeders to achieve maximum profit.

It is concluded from Chapter 4, that if feeder length is long and load growth rate is low, it is economical to defer feeder installation using ESS when load demand exceeds the thermal limit of the installed feeder. For example, if the feeder length is 10 mi and load growth rate is less than 3.2%, ESS will be installed otherwise additional feeder will be installed. Considering the case of feeder deferment using ESS to be economical, an optimal model is developed, in this chapter, to maximize daily profit of ESS based on energy price arbitrage and taking into account that load demand does not exceed feeder thermal limit.

5.1 System Description

The Energy storage system is represented in Figure 5.1. The distribution system consists of a distribution feeder, main grid and an energy storage device. It is assumed that ESS plant owner will either use it for its demand for electricity Pl or will sell it by having contracts with nearby electricity consumers represented by an aggregated load demand. The ESS is connected to the main grid by a distribution feeder with limited capacity.

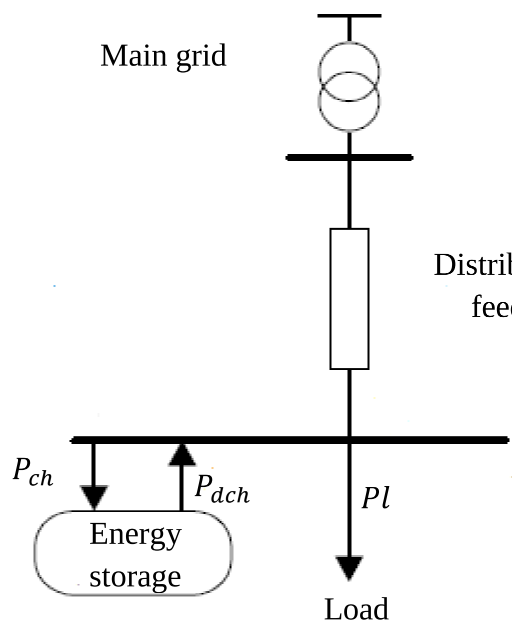


Figure 5.1 Energy Storage connected to the distribution feeder and main grid

5.2 Optimal Scheduling of Energy Storage: Problem Formulation

The optimization algorithm of Energy storage system developed by Hu [34] to achieve maximum profit of ESS in electricity market is modified and extended to consider distribution feeder thermal limit, hourly load demand and operational and maintenance cost of ESS. None of previous researchers have considered the feeder thermal limit in their optimization algorithms to maximize ESS profit [12-54]. In this thesis, feeder thermal limit is considered in developing an optimization algorithm to maximize ESS profit such that load demand does not exceed feeder thermal limit. The operation and maintenance costs of ESS are also included in algorithm to consider ESS operation more practically.

The modified optimization approach is formulated below:

Objective function:

$$Max\ Rev - C \tag{5.1}$$

$$Rev = \sum_{i=1}^{24} \left(P_{dch_i} - P_{ch_i}\right)\lambda_i \tag{5.2}$$

$$C = C_{omf_i} * P_{max} \quad \forall\, i \tag{5.3}$$

Feeder thermal limit constraint:

$$P_{ch_i} - P_{dch_i} + Pl_i \leq ftl \quad \forall\, i \tag{5.4}$$

ESS operating constraints:

$$0 \leq P_{dch_i} \leq P_{max} \quad \forall\, i \tag{5.5}$$

$$0 \leq P_{ch_i} \leq P_{max} \quad \forall\, i \tag{5.6}$$

$$E_{i+1} = E_i + P_{ch_i} * \eta_{ch} \quad \forall\, i \tag{5.7}$$

$$E_{i+1} = E_i - \frac{P_{dch_i}}{\eta_{dch}} \qquad \forall\, i \tag{5.8}$$

$$E_{min} \le E_i \le E_{max} \qquad \forall\, i \tag{5.9}$$

$$P_{dch_i} \,.\, P_{ch_i} = 0 \qquad \forall\, i \tag{5.10}$$

where

i = hour

Rev = Revenue (SR)

C = Cost (SR)

λ_i = Electricity price at hour i (SR/MWh)

P_{dch_i} = Discharging power of ESS at hour i (MW)

P_{ch_i} = Charging power of ESS at hour i (MW)

E_i = Energy of ESS at hour i (MWh)

η_{ch} = Charging Efficiency of ESS

η_{dch} = Discharging Efficiency of ESS

P_{max} = Maximum power capacity of ESS (MW)

E_{max} = Maximum energy capacity of ESS (MWh)

E_{min} = Minimum energy capacity of ESS (MWh)

C_{omf_i} = Fixed operation and maintenance cost of ESS at hour i (SR/MW)

Pl_i = Load demand at hour i (MW)

ftl = Feeder thermal limit (MW)

The purpose of this model is to charge ESS optimally during the period of low energy price and discharge ESS during the period of high price. Equation (5.2) represents the revenue generated by ESS. Equation (5.3) represents the operation and maintenance cost of ESS. Constraint (5.4) shows that the load and charge/discharge power of ESS remains within the feeder thermal limit. Constraints (5.5) and (5.6) ensure the charge/discharge power remain within the limits defined. Constraints (5.7) and (5.8) represent the energy balance equations of ESS. Constraint (5.9) ensures that the stored energy of ESS remains within the limits defined. Constraint (5.10) shows that ESS will either charge or discharge, but not both at a time.

Although, the objective function is linear but this optimization problem is nonlinear due to ESS constraint (5.10). This optimization problem can be converted into mixed integer linear formulation by using binary variable and additional constraints (5.10-5.12). The optimization algorithm becomes a mixed integer linear programming (MILP) by replacing constraint (5.10) with following constraints.

$$P_{ch_i} - M\alpha_i \leq 0 \qquad \forall\, i \tag{5.11}$$

$$P_{dch_i} - M(1 - \alpha_i) \leq 0 \quad \forall\, i \tag{5.12}$$

$$\alpha_i \in \{0,1\} \qquad \forall\, i \tag{5.13}$$

Where M is a large number and α is a binary variable.

5.3 Simulation Results of ISO-NE System

The developed optimal algorithm to maximize ESS profit is simulated on a system described in section 5.1. In this study, the system load and electricity prices are hourly averages. The ESS parameters and feeder thermal limit are given in Table 5.1. Figure 5.2 and 5.4 shows the energy price and load demand for each hour respectively taken from New England Independent System Operator (ISO-NE) [87]. The developed model is simulated using sequential quadratic programming algorithm in Matlab optimization toolbox, explained in Appendix B, and YALMIP optimization package [88-90].

Table 5.1 ESS parameters and feeder thermal limit

P_{max} (MW)	1
E_{max} (MWh)	5
E_{min} (MWh)	0
C_{omf} ($/MW-hour)	1
η_{ch}	0.87
η_{dch}	0.87
η	0.75
ftl (MVA)	10

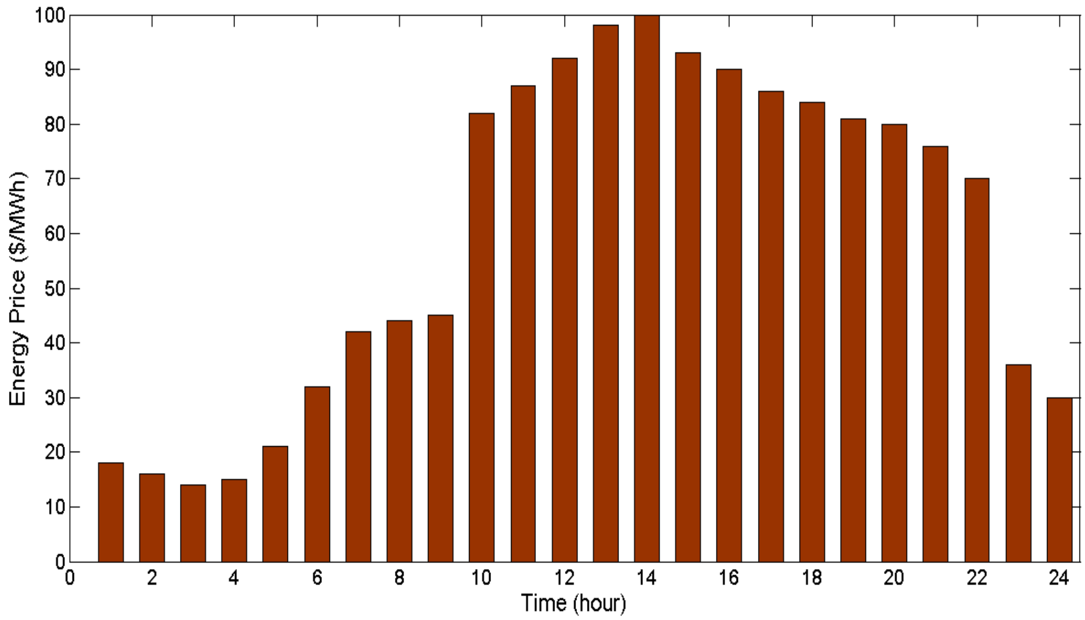
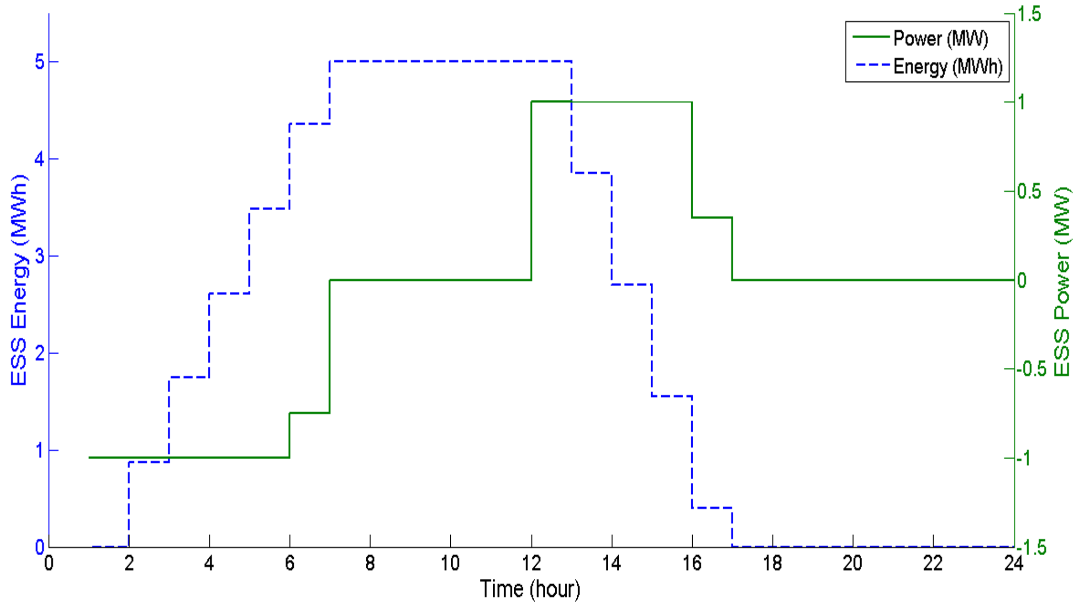


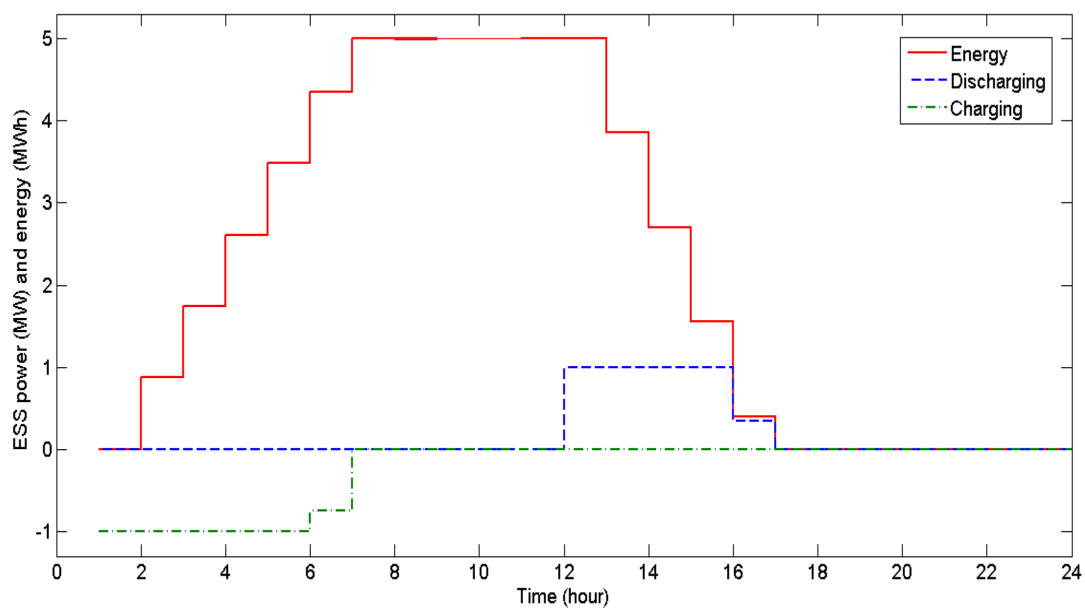
Figure 5.2 Electricity Price of ISO-NE during 2012 [87]

5.3.1 Charging Profiles

The charge/discharge power and energy profiles of ESS are shown in Figure 5.3. The ESS is charging during low price and low load period and it is discharging during high price and high load period to get maximum energy price arbitrage. Also, ESS optimal scheduling is ensuring that ESS will discharge during the period when load demand exceeds feeder thermal limit. It will save system from damages and outages. During this period, electric grid will only provide that much supply, which feeder can sustain while extra load demand will be countered by ESS. Hence developed optimization problem is ensuring that ESS is optimally scheduling its power and energy to achieve maximum profit and avoid outages. It is evident from Figure 5.3 (b) that ESS is charging or discharging at a time but both charging and discharging process of energy storage system is not happening at the same time.



(a)



(b)

Figure 5.3 (a) Optimal scheduling of ESS (b) Charging and Discharging profile of ESS

Figure 5.4 shows the load demand on distribution feeder before and after installation of ESS. It is evident from Fig. 5.4 that load demand exceeds the feeder thermal limit before installation of ESS, represented by solid blue line. This causes the load shedding and outages to protect the feeder from damages, resulting in financial losses to customers and utilities. The feeder thermal limit is represented by dotted brown line. After installation and optimal scheduling of ESS using developed optimization approach, load demand goes below the feeder thermal limit, ensuring system safety from damages and outages. The load demand on distribution feeder after ESS operation is shown by broken red line in Fig. 5.4. The profit of ESS after its optimal scheduling is $282 determined by using (5.1) to (5.3).

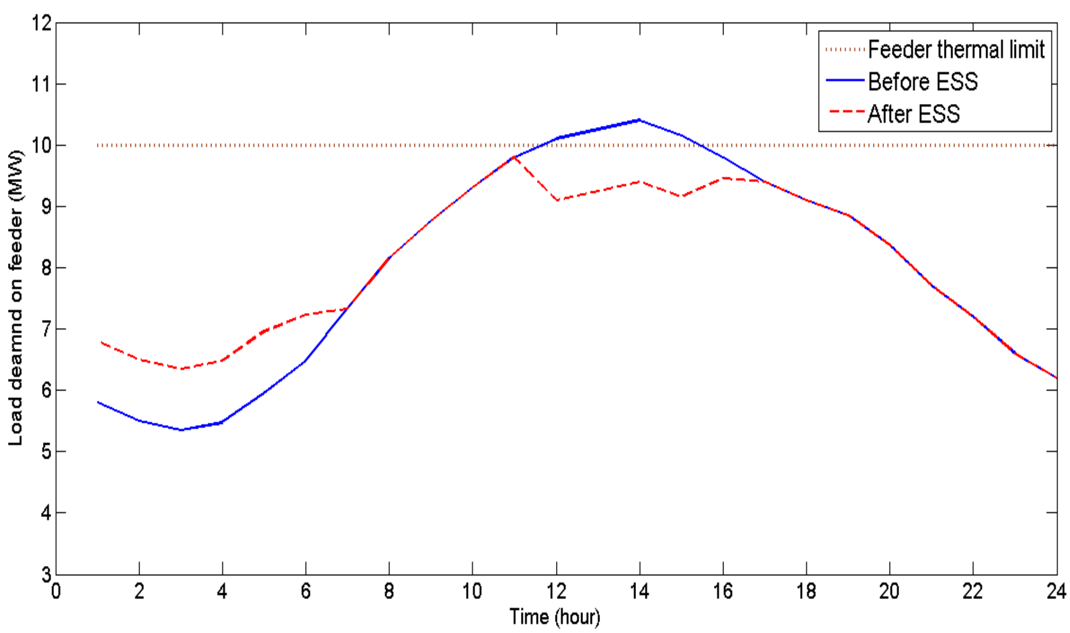


Figure 5.4 Load on distribution feeder with and without ESS

5.3.2 Monthly and Yearly Profits

The annual electricity price and load for year 2012 is taken form ISO-NE [87] and applied on developed algorithm to get monthly and annual profit from ESS optimal scheduling. Figure 5.5 shows the annual energy price data of ISO-NE. The annual load of ISO-NE for year 2012 is scaled to consider it as load demand on distribution feeder, which is shown in figure 5.6.

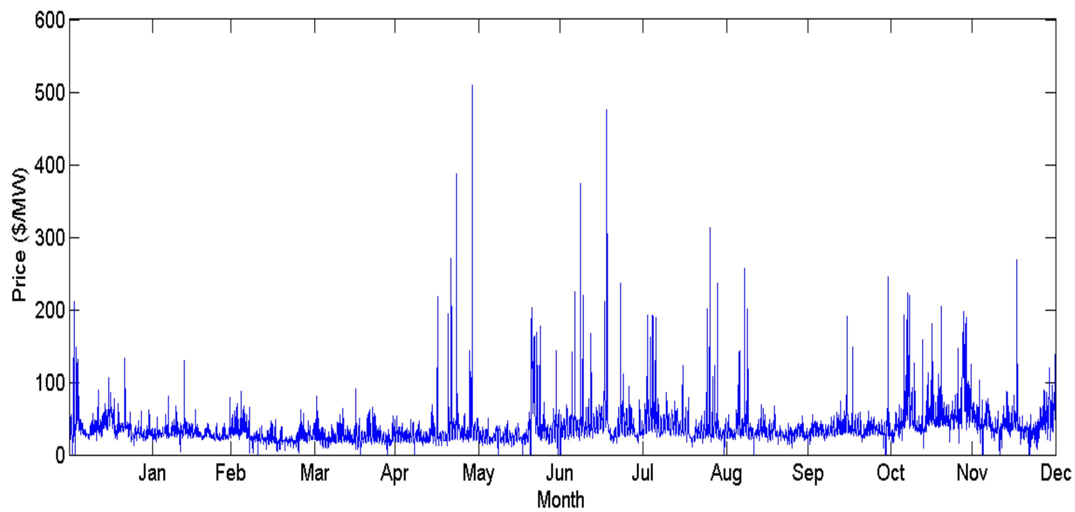


Figure 5.5 Annual energy price of ISO-NE in year 2012 [82]

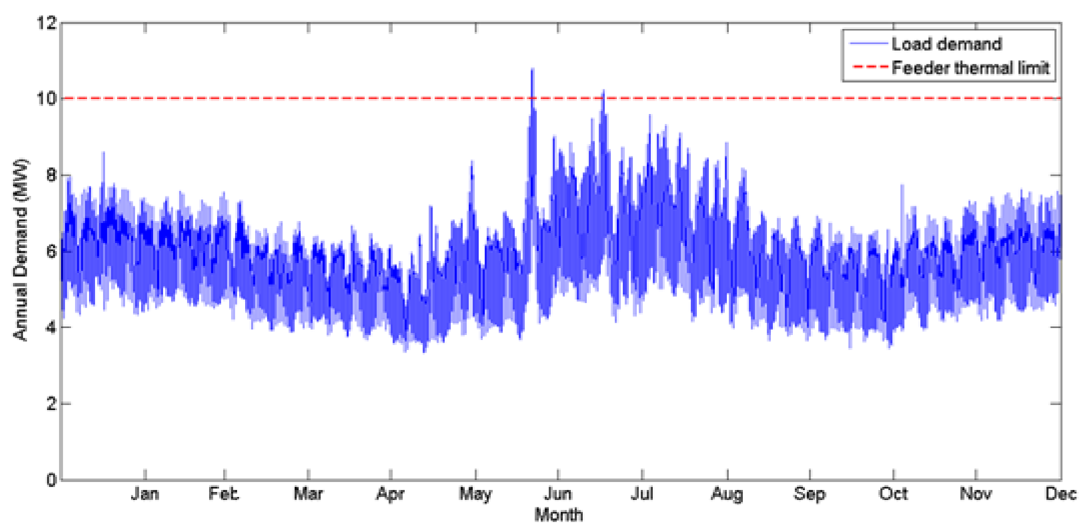


Figure 5.6 Annual load demand on distribution feeder

The maximum profit of ESS is calculated for the year 2012. Figures 5.7 and 5.8 show the daily profit of ESS during august 2012 and monthly profit for year 2012. The annual profit for year 2012 for ISO-NE system is $ 35,248 determined by using (5.1) to (5.3) for whole year.

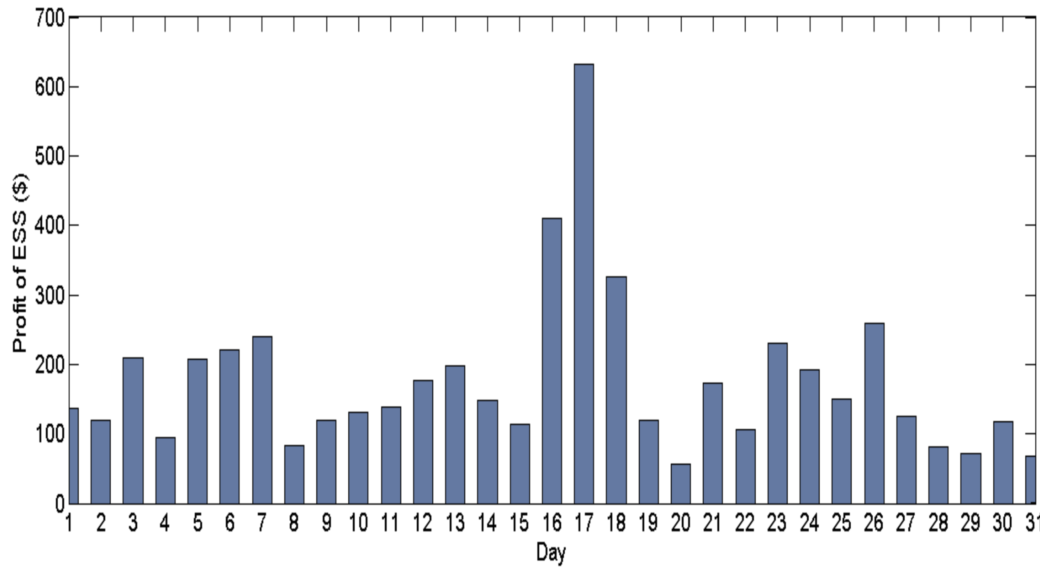


Figure 5.7 Daily ESS profit during august 2012

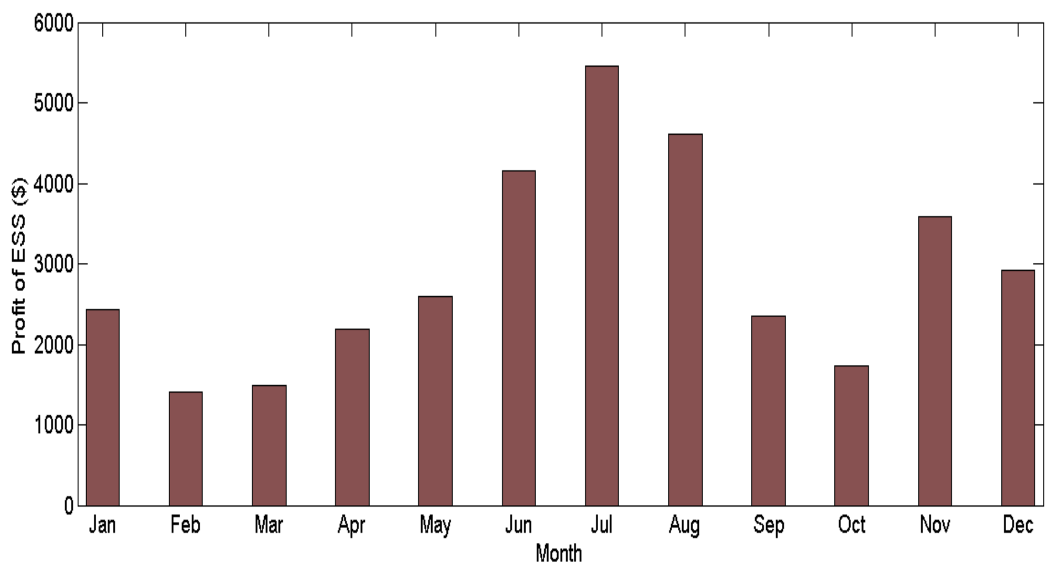


Figure 5.8 Monthly ESS profit for year 2012

5.4 Simulation Results of Saudi System

5.4.1 Simulation Data

The electricity system in Saudi Arabia is undergoing major changes. The recent creation of a separate national grid company is a step towards deregulation of the system. Serious efforts are undertaken to create a number of generation companies. The general objective is to institutionalize competitive operations within the system. However, at the time of writing this thesis, there is no electricity market in Saudi Arabia. The regulator and the Saudi Electric Company (SEC) operate a Time of Use Tariff (TOU). The time of use tariff for consumer sectors will be used in this thesis to represent the energy market.

The developed optimal algorithm to maximize ESS profit is simulated on a system described in section 5.1. In this study, the system load and electricity prices are hourly averages. The system load is modified load of eastern province of Saudi Arabia. Load forecasts are generated by adding an error to the actual load to match the load forecast errors observed in [91].

The electricity rates defined by Electricity and Cogeneration Regulation Authority (ECRA) Saudi Arabia for residential, commercial and industrial customers are shown in Table 5.2 ,5.3 & 5.4 [92].

Table 5.2 Electricity Tariff for residential customers [92]

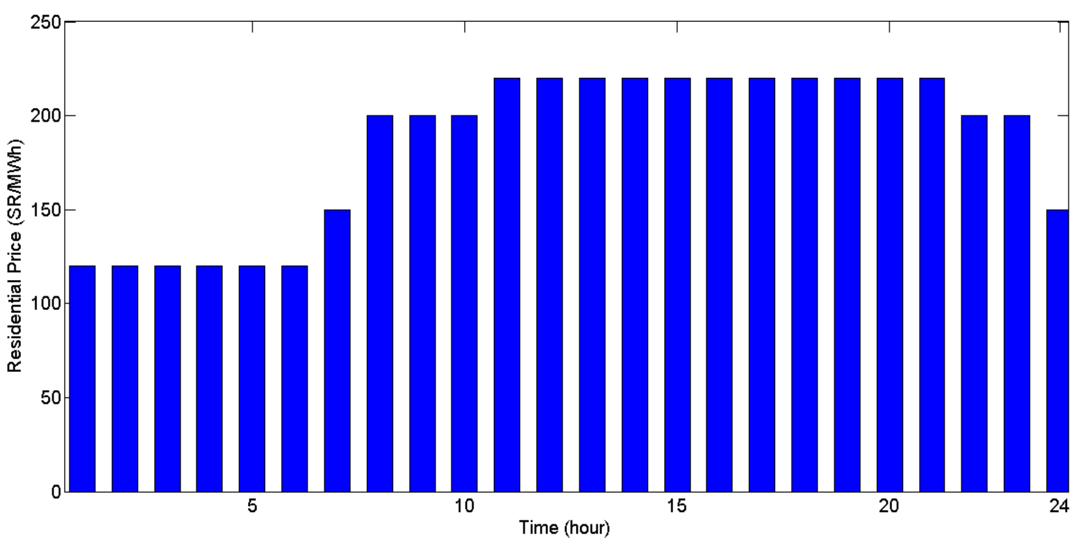
Consumption (KWh)	Tariff (hh/KWh)
1-2000	5
2001-4000	10
4001-6000	12
6001-7000	15
7001-8000	20
9001-10000	24
>10000	26

Table 5.3 Electricity Tariff for commercial customers [92]

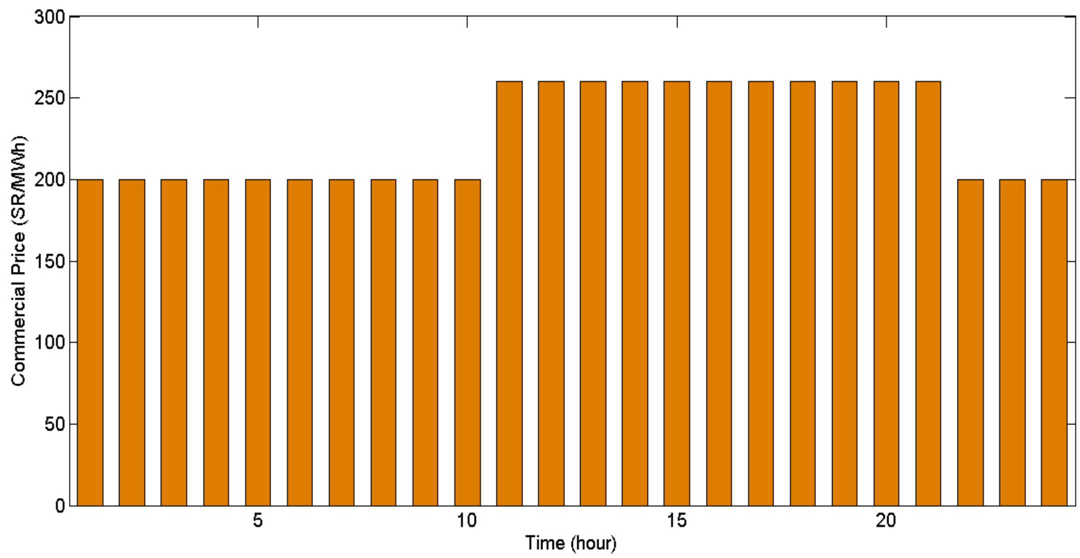
Consumption (KWh)	Tariff (hh/KWh)
1-4000	12
4001-8000	20
>8000	26

Table 5.4 Time of Use (TOU) Electricity Tariff for industrial customers [92]

Consumption Period	Consumption Hours	TOU Tariff (hh/KWh)
OCT - APR	all	14
MAY - SEP	**Off-Peak Hours** SAT – THU: 00:00 – 08:00 FRI: 00:00 – 09:00 21:00 – 00:00	10
	Peak Hours SAT – THU: 12:00 – 17:00	26
	Other Hours	15



(a) Residential tariff rates



(b) Commercial tariff rates

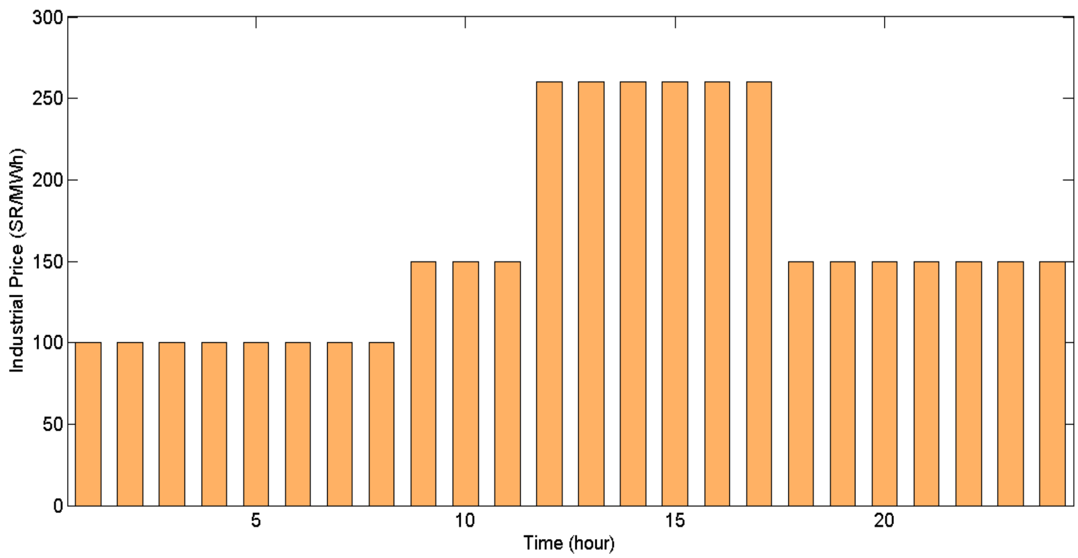


Figure 5.9 Hourly based Daily Electricity Price for (a) Residential customers (b) Commercial customers (c) Industrial customers

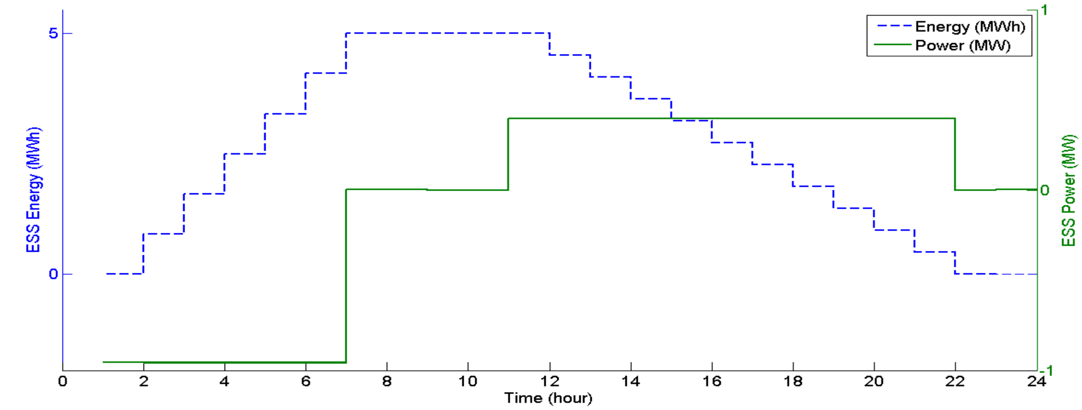
The ESS parameters and feeder thermal limit are given in Table 5.1. Figure 5.9 shows the hourly electricity price for residential, commercial and industrial customers taken from Electricity and Cogeneration Regulation Authority (ECRA) Saudi Arabia [92].

5.4.2 Charging Profiles

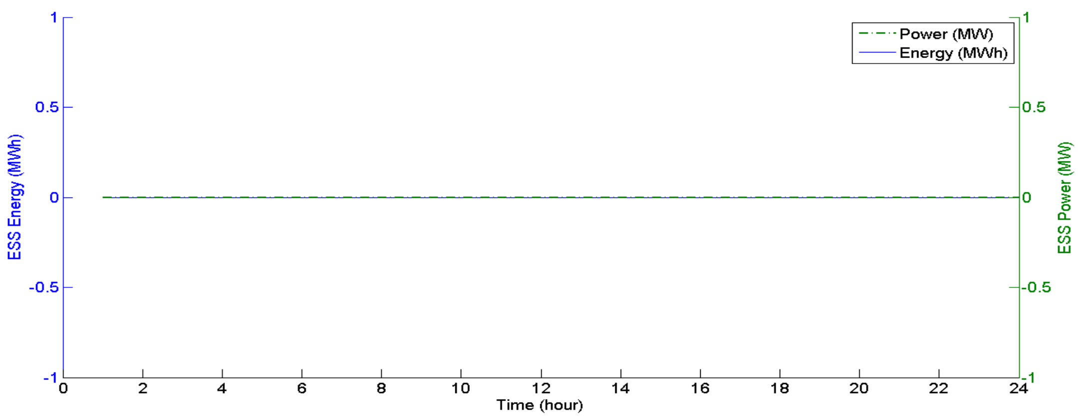
The charge/discharge profile of power and energy state of ESS for each hour are shown in Figure 5.10. Figure 5.10 (a) shows the energy and power profile of ESS for residential electricity tariff rates. Analyzing Figure 5.9 (a) and 5.10, the residential price is low, 120 SR/MWh, for first 6 hours, so ESS will charge during these hours. It will discharge to sell power during high price 220 SR/MWh.

Figure 5.10 (b) shows the energy and power profile of ESS for commercial electricity tariff rates. The price is low, 200 SR/MWh, but ESS will not charge during this price as maximum price is 260 SR/MWh. It will not make profit as if it purchases 1 MW for 1 hour at 200 SR/MWh, it can only sell 0.75 MW for an hour ($1MW*\eta = 1MWh*0.75 = 0.75$ MWh) at 260 SR/MWh resulting in a loss of 5 SR ($260*0.75-200*1 = -5$ SR). Hence ESS will not operate at commercial tariff rates.

Figure 5.10 (c) shows the energy and power profile of ESS for industrial electricity tariff rates. The price is low, 100 SR/MWh, so ESS will charge at this price rate and it will discharge to sell power during high price 260 SR/MWh. Hence ESS will operate at industrial. Figure 5.11 shows that ESS is either charging or discharging at a time.



(a)



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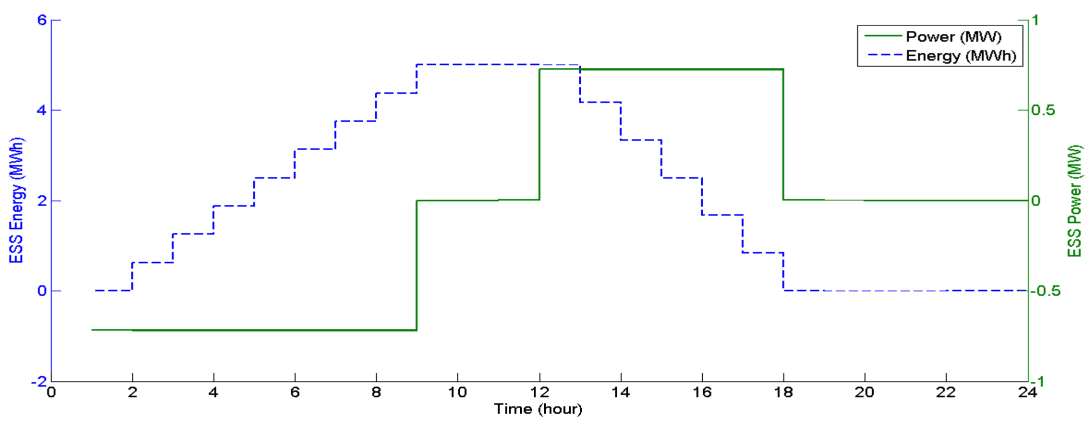


(c)

Figure 5.10 Optimal scheduling of power and energy of ESS for (a) Residential electricity tariff rates (b) Commercial electricity tariff rates (c) Industrial electricity tariff rates

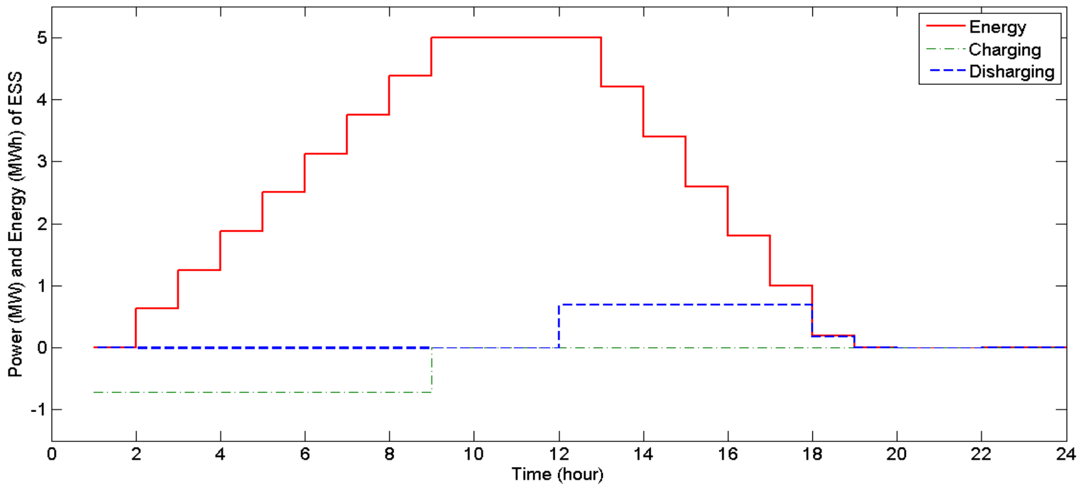
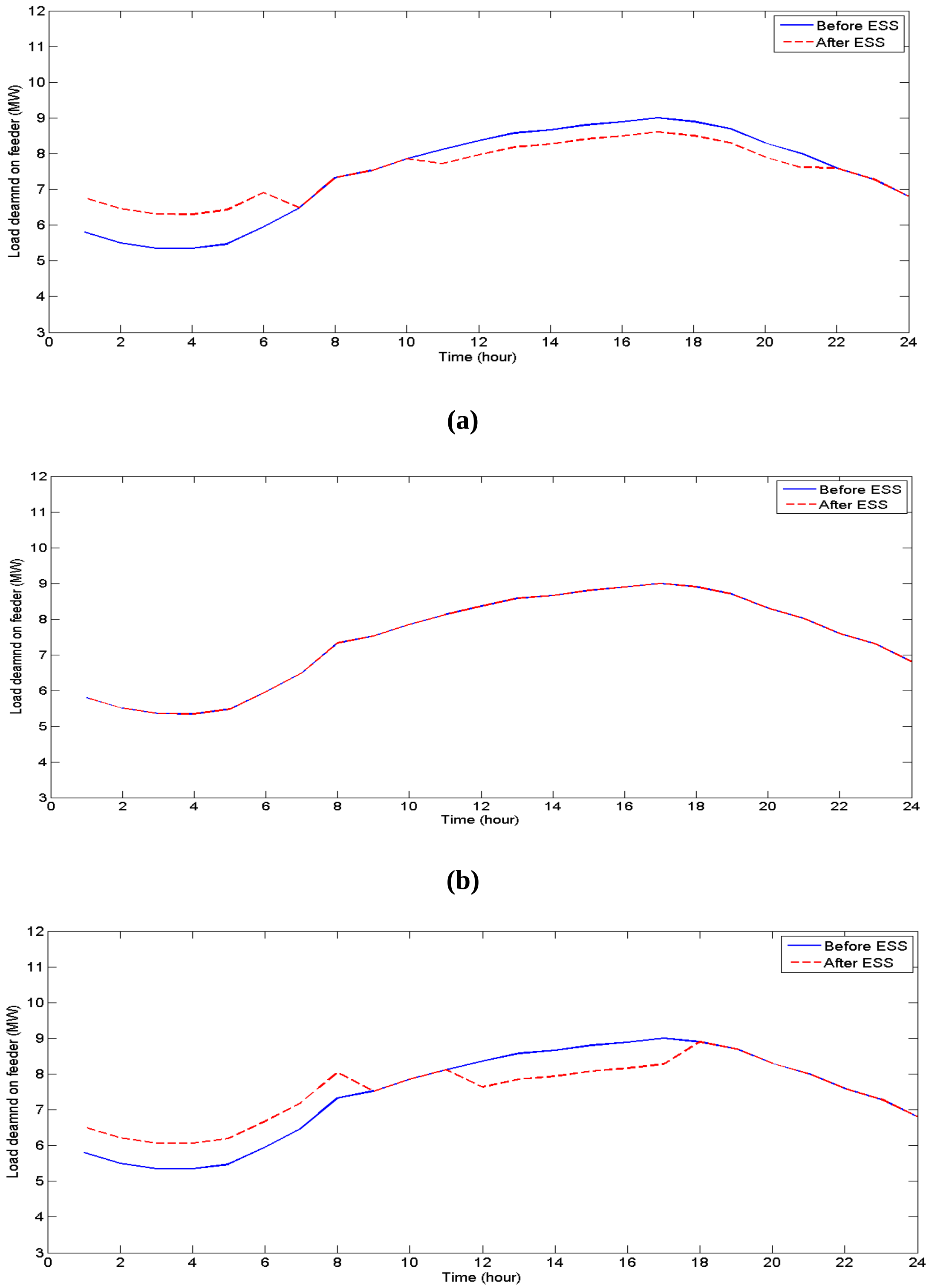


Figure 5.11 Charging and Discharging profile of ESS for Industrial customers

Figure 5.12 shows the load demand on distribution feeder with and without considering ESS for residential, commercial and industrial electricity tariff rates. In case of residential and industrial customers, ESS is charging during low load period and discharging during high load, so basically ESS is also performing load shifting operation in these cases. It is now obvious that as load demand is correlated with electricity price which means electricity price increases with increase in load demand, so load demand can be shifted from high price to low price period resulting in reduction of electricity bill of plant. Hence, an industrial plant can make use this ESS optimal scheduling algorithm to shift its load from high load to low load period. ESS will not operate at commercial electricity tariff rates as represented by Figure 5.12 (b).



(a)

(b)

(c)

Figure 5.12 Load demand on distribution feeder for (a) Residential electricity tariff rates (b) electricity tariff rates customers (c) Industrial electricity tariff rates

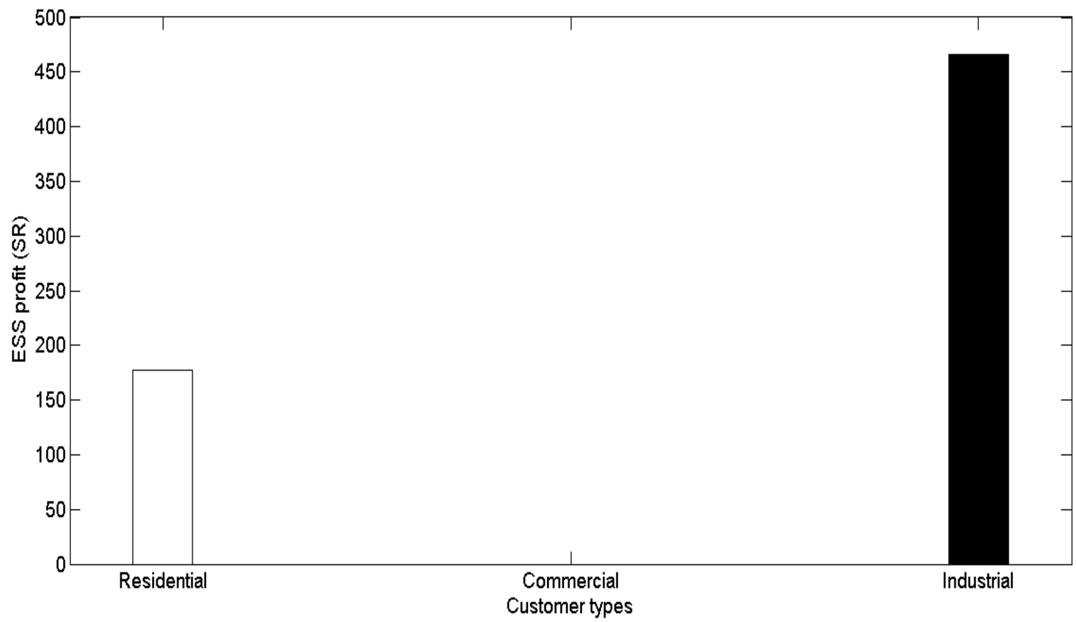


Figure 5.13 Hourly based Daily ESS profit for different customer's electricity tariff rates types

The hourly based daily ESS profits for residential, commercial and industrial electricity tariff rates are shown in Figure 5.13. The ESS profit in case of industrial customers is higher than those of residential and commercial customers. In Saudi Arabia, the residential and commercial customer's electricity tariff rates are independent of time while industrial customer's electricity rates depend on time and season. The ESS profit at industrial electricity rates is higher than that at residential electricity tariff rates due to larger difference between low and high prices of industrial electricity tariff rates as compared to residential electricity tariff rates. ESS profit is zero for commercial electricity tariff rates.

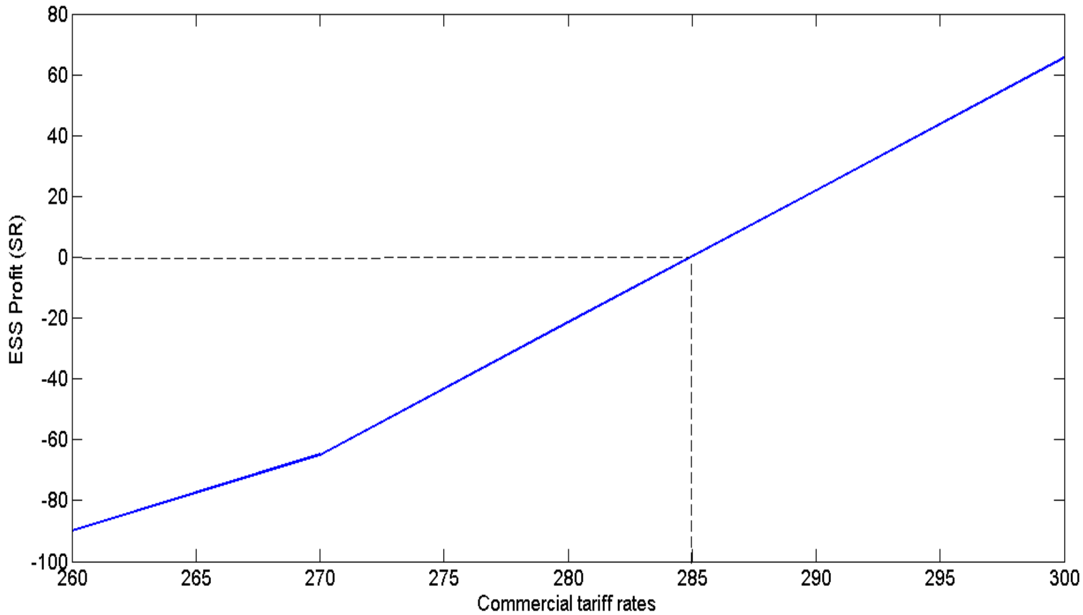


Figure 5.14 ESS profit with variation in commercial tariff rates for load demand more than 8 MW

ESS profit is not zero at commercial electricity tariff rates if the tariff rates are adjusted such that ESS starts marking profit at commercial electricity tariff rates. Figure 5.14 shows the ESS profit while varying commercial electricity tariff rates for load more than 8 MW. The ESS makes profit when commercial electricity tariff rates for load more than 8 MW are increased from 260 SR/MWh to 285 SR/MWh, increment of about 9.6% in 260 SR/MWh. If operation and maintenance cost of ESS is not considered, then commercial electricity tariff rates for load more than 8 MW are increased from 260 SR/MWh to 267 SR/MWh, increment of 3.5% in 260 SR/MWh

5.4.3 Monthly and yearly profits

The monthly and annual profits of ESS optimal scheduling are obtained after simulation using following different customer type's load demand.

- Mix residential, commercial and industrial substation
- Residential substation
- Industrial substation

5.4.3.1 Substation: Mix Residential, Commercial and Industrial

The annual hourly load demand of eastern province region of Saudi Arabia for mix residential, commercial and industrial sector has been adjusted and shown in Figure 5.15. The annual hourly electricity prices of industrial, residential, commercial customers are obtained using load demand and electric tariff rates for each customer type using Table 5.2, 5.3 and 5.4. The annual hourly electricity prices of each customer type are shown in Figure 5.16 (a), 5.17 ad 5.18. The annual hourly electricity prices of industrial customers during month of July is shown in Figure 5.16 (b).

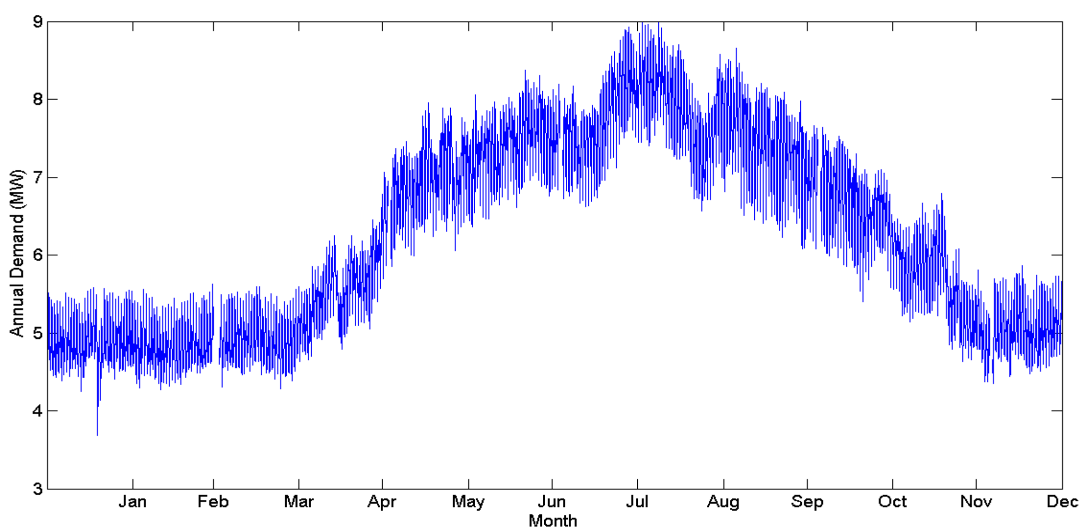
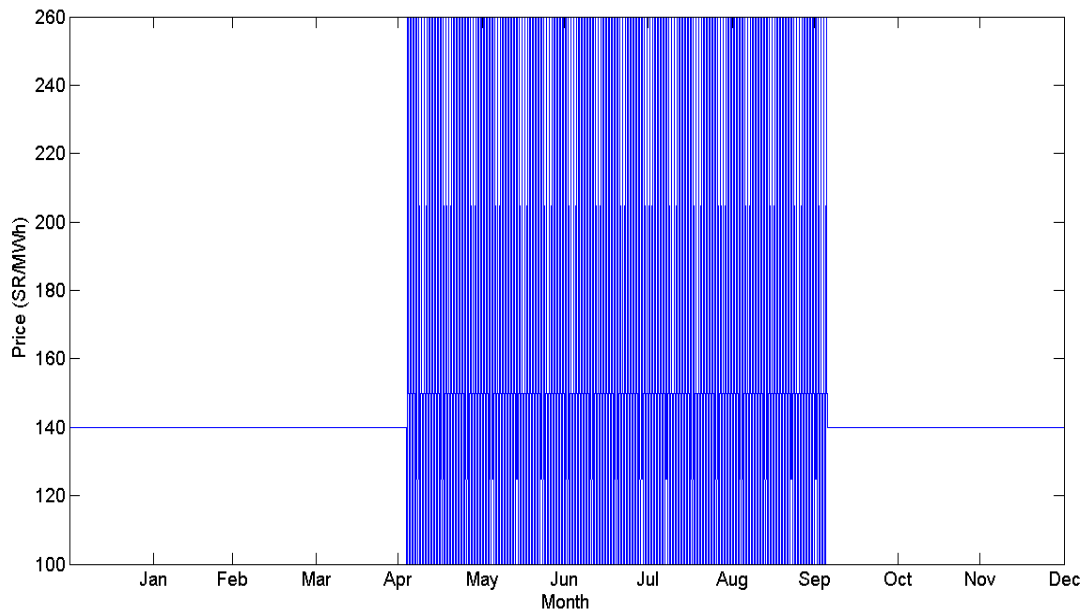
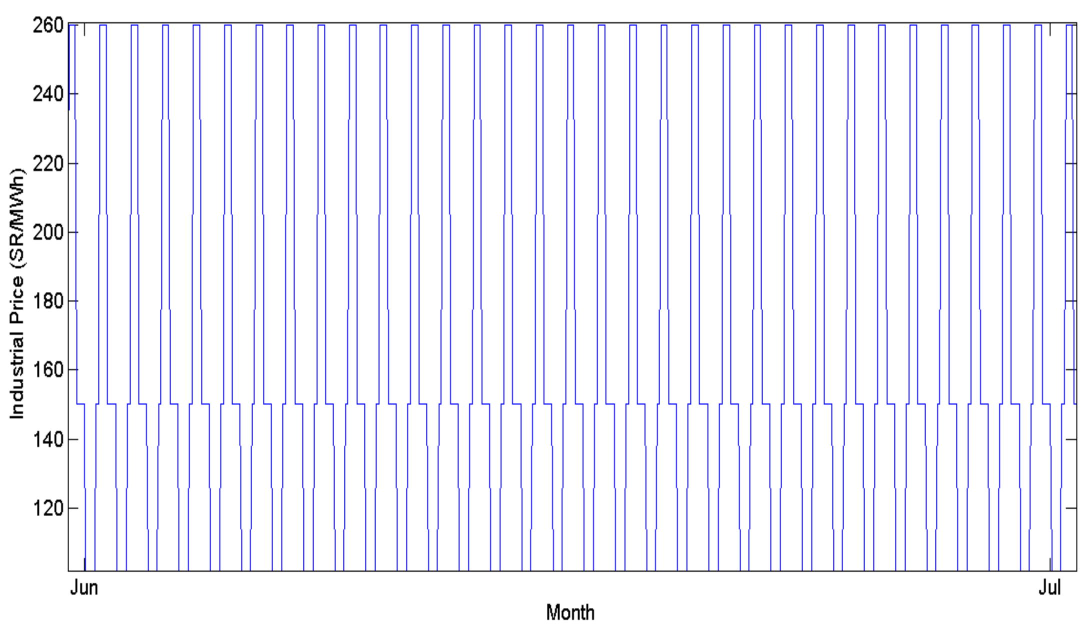


Figure 5.15 Annual hourly load demand on distribution feeder



(a)



(b)

Figure 5.16 (a) Annual hourly electricity price for industrial customers (b) Hourly electricity price for industrial customers during month of July

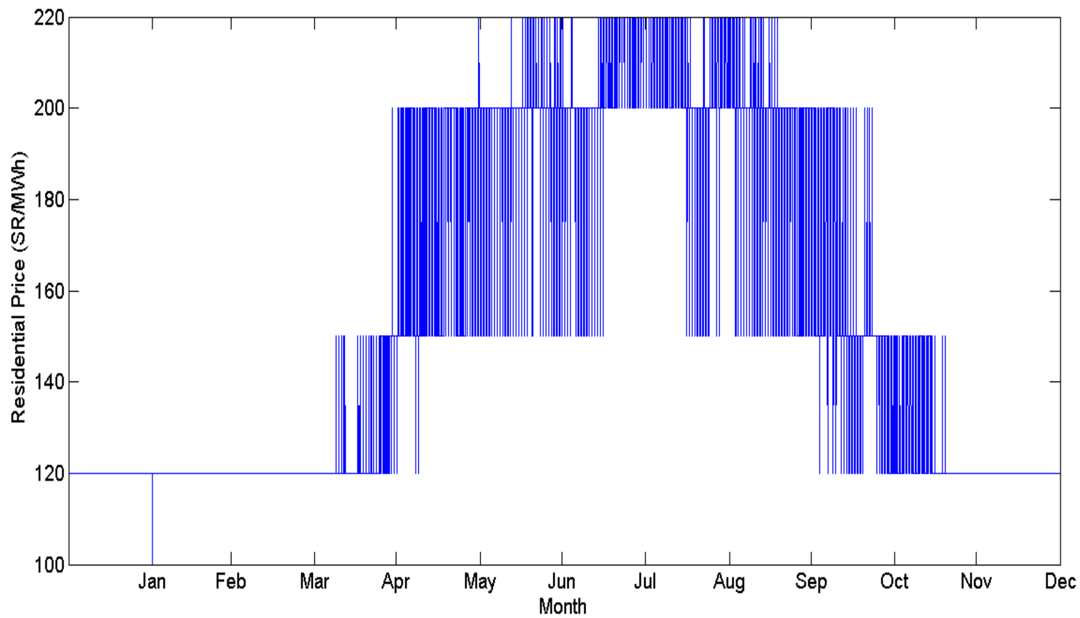


Figure 5.17 Annual hourly electricity price for residential customers

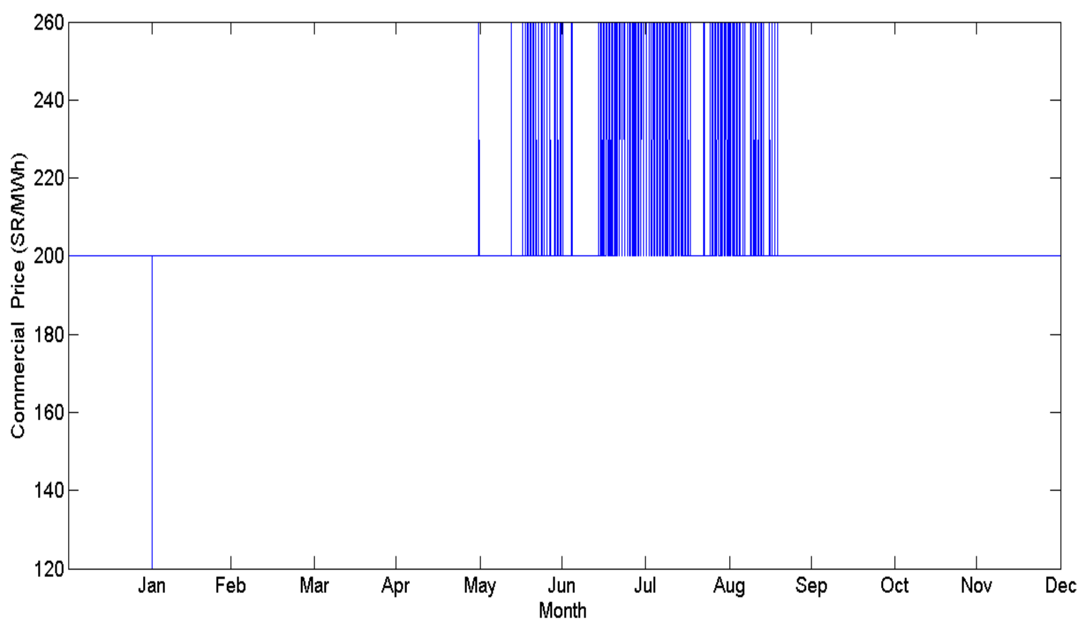
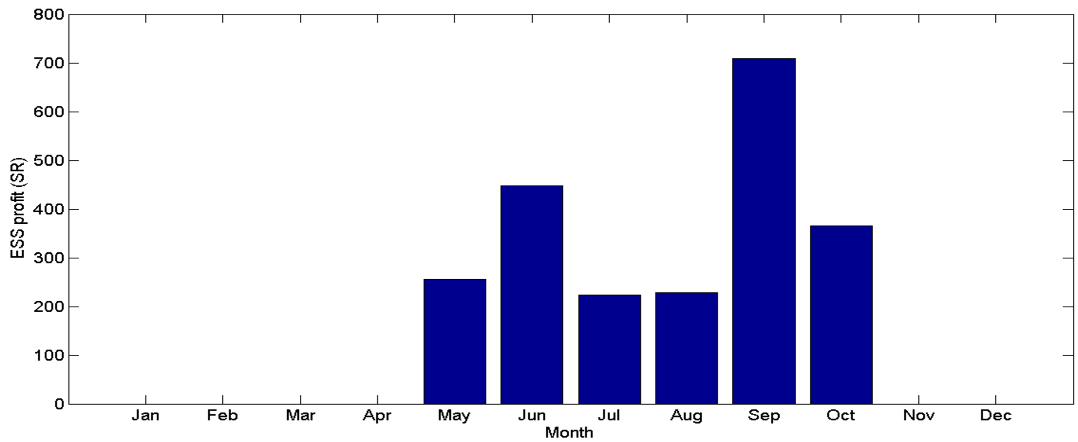


Figure 5.18 Annual hourly electricity price for commercial customers

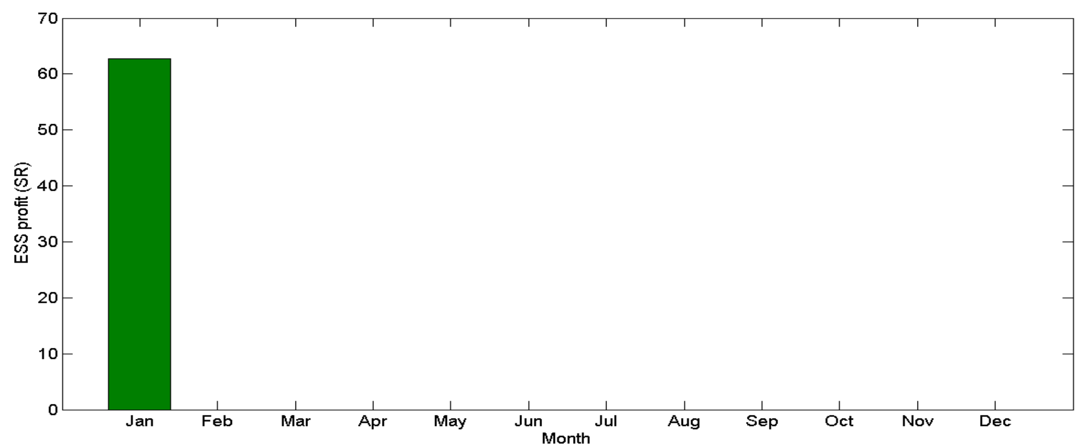
Figure 5.19 (a) shows the monthly profit of ESS considering residential tariff rates. The profit is low because there is considerable increment of tariff rates with respect to consumption. So, it is not preferable and economical to operate ESS at residential tariff rates.

Figure 5.19 (b) shows the monthly profit of ESS considering commercial tariff rates. The profit is very low due to not considerable increment of tariff rates with respect to consumption. It shows profit only during month of January. The reason is that hourly load varies from valley 3.69 MW to peak 5.7 MW and it is less than 4 MW for one day only during January. Commercial consumption tariff rates vary from 120 SR/MWh to 200 SR/MWh. But for all other months the load is greater than 4 MW and consumption rates vary from 200 SR/MWh to 260 SR/MWh. For example, if ESS buys 1 MW for 1 hour at 200 SR/MWh, it'll store only 0.87 MWh (1 MW*η_{ch}*1 hour= 0.87 MWh) and during discharge it can only sell 0.75 MW for an hour (0.87 MWh*η_{dch} = 0.75 MWh) and the profit comes out to be in negative (260*0.75-200*1 = -5 SR) due to which ESS will operate at commercial tariff rates from February to December. Hence it is not preferable to operate ESS at commercial tariff rates.

Figure 5.19 (c) shows the monthly profit of ESS considering industrial TOU tariff rates. The ESS will not operate from October to April due to flat tariff rates considering ESS efficiency and O&M cost, while it is economical to operate it from May to September period due to much variations in tariff rates during off peak and peak hours. Hence it is preferable to operate ESS at industrial tariff rates but only for May to September period.



(a)



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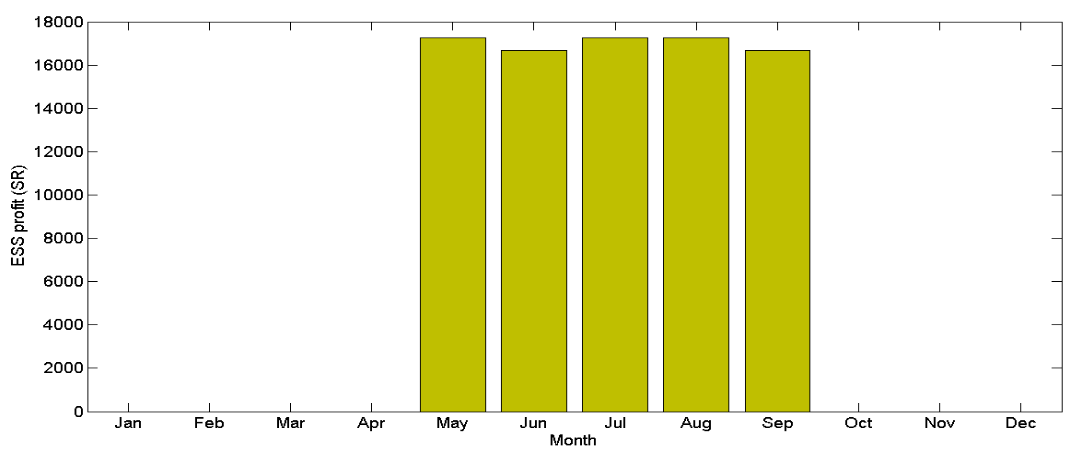


(c)

Figure 5.19 Monthly ESS profit for different customer types (a) Residential (b) Commercial (c) Industrial

The maximum energy price arbitrage or profits of ESS for residential, commercial and industrial customers are calculated for annual period using developed optimization approach for ESS. Figure 5.20 shows the monthly profits of ESS for residential, commercial and industrial customer's electricity tariff rates. From analyzing Figure 5.16, 5.17, 5.18 and 5.20 and electricity tariff rates of residential, commercial and industrial customers, it is clear that from January to April and October to December, the ESS profit is zero for constant tariff rates for industrial customers. While from November to April period, ESS profit is zero for residential customer. There is little deviation of load from its average during these months and these deviations lie within the constant electricity tariff rates due to which ESS will not operate for each day during these months.

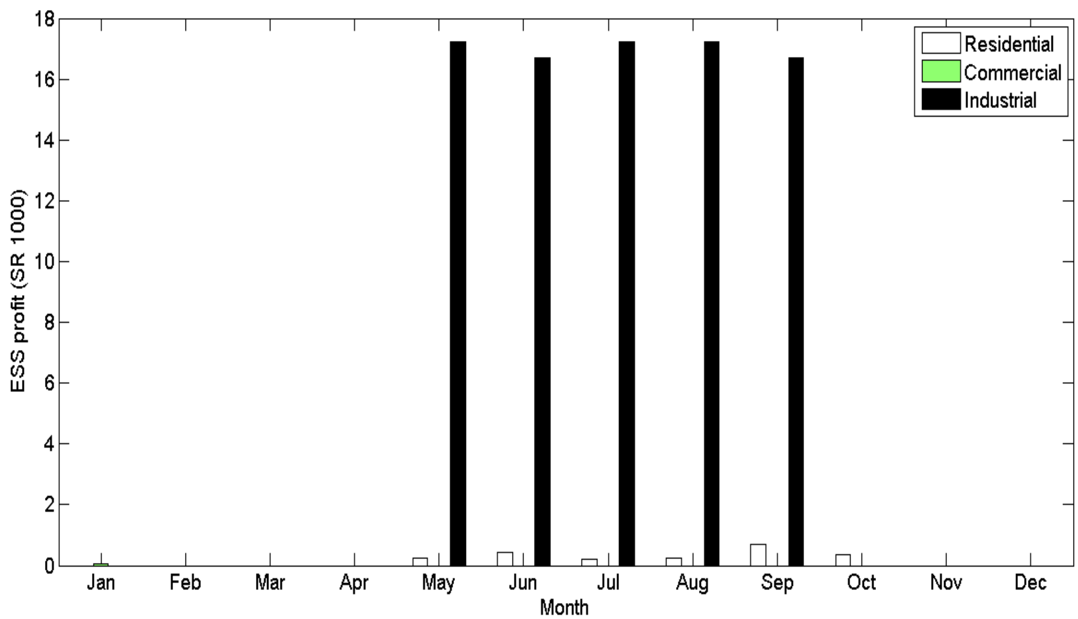


Figure 5.20 Monthly ESS profit

Now from May to September, there is much flexibility in electricity tariff rates especially in case of industrial customers, due to which ESS will operate each day during these months to get maximum profit. Hence ESS has maximum profit from May to September period, especially for industrial customers.

Figure 5.21 shows the annual profits of ESS for residential, commercial and industrial customer. The annual ESS profit of industrial customers is much greater than those of residential and commercial customers, clearly presenting that ESSs should be installed and operated at industrial sector. The reason of higher profit of ESS, in case of industrial customers, is the high deviation of electricity price between off peak and peak hours of days during May to September Period.

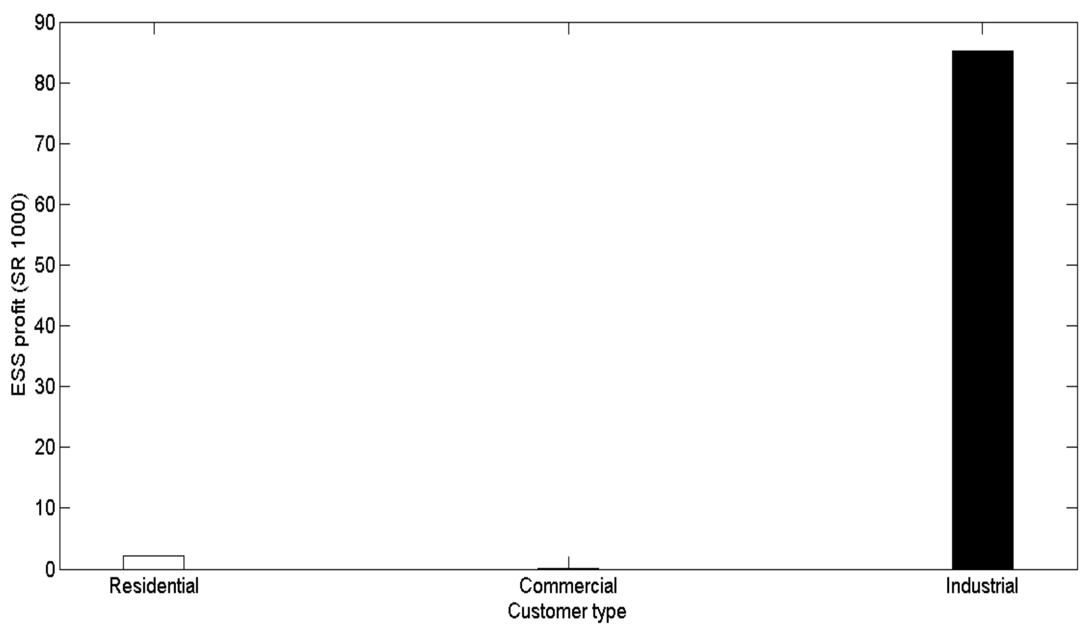


Figure 5.21 Annual ESS profit for different customer types

5.4.3.2 Residential and Industrial Substations

The effects of all residential sector and all industrial sector load demands and prices on developed optimal ESS scheduling algorithm are analyzed. The annual all residential and all industrial sector adjusted load demands are taken from eastern province region of Saudi Arabia respectively and are shown in Figure 5.22 and 5.23 respectively. The annual prices of all residential and all industrial sectors are obtained using Tables 5.2 and 5.4. These prices and demands are used in simulating and analyzing the performance of developed optimal ESS scheduling algorithm. The simulation results are shown in Figure 5.24 and 5.25.

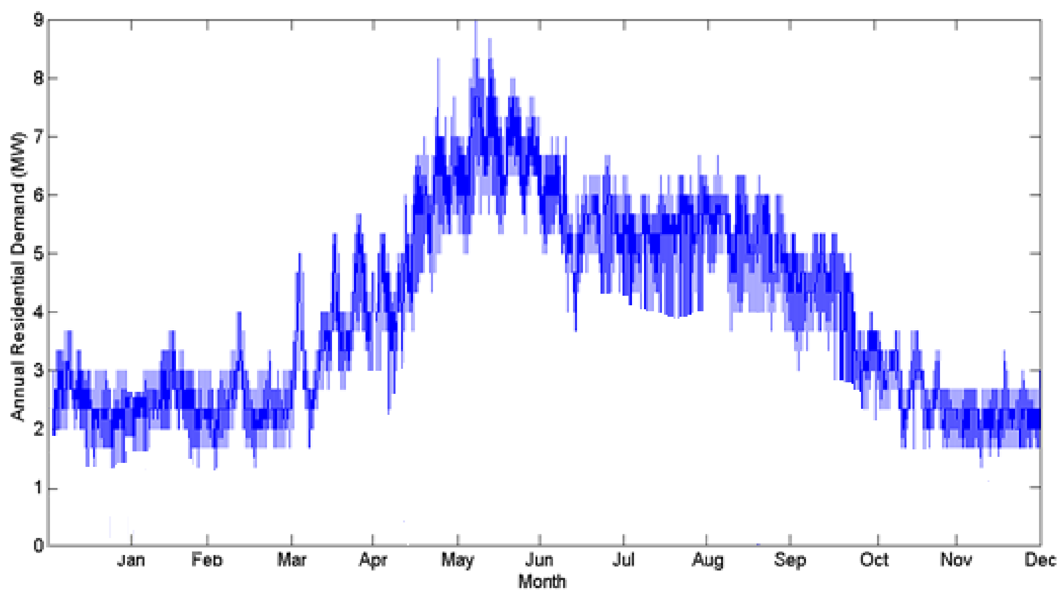


Figure 5.22 Annual load demand of all residential sector

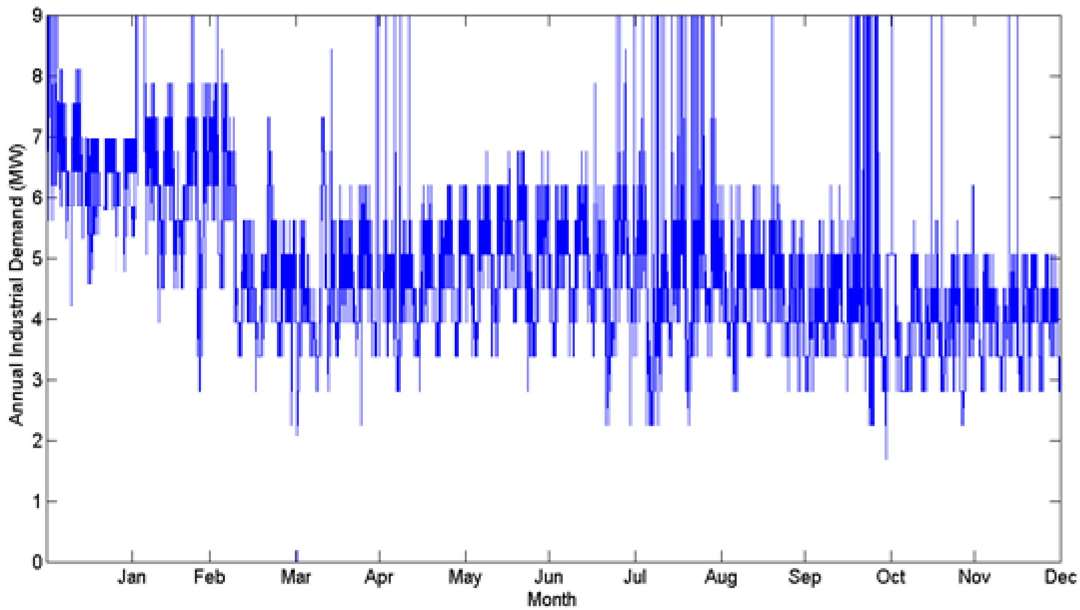


Figure 5.23 Annual demand of all industrial sector

The monthly and annual profits in case of all residential and all industrial sector are shown in Figure 5.24 and 5.25 respectively. From analyzing Figure 5.24, the ESS profit is zero at industrial tariff rates from October to April. It is due to the fact that the industrial electricity tariff rates are constant for October to April period, ESS will not operate during these months. While the ESS profit is much higher during May to September at industrial electricity tariff rates compared to residential electricity tariff rates due to large deviation between high and low energy price of industrial sector during this period. The electricity tariff rates of residential sector are much dependent on load demand while those of industrial sector are independent of load demand at any time due to which ESS profit will be greatly affected if there is not much variation in load at residential sector as obvious from Figure 5.22 and 5.24.

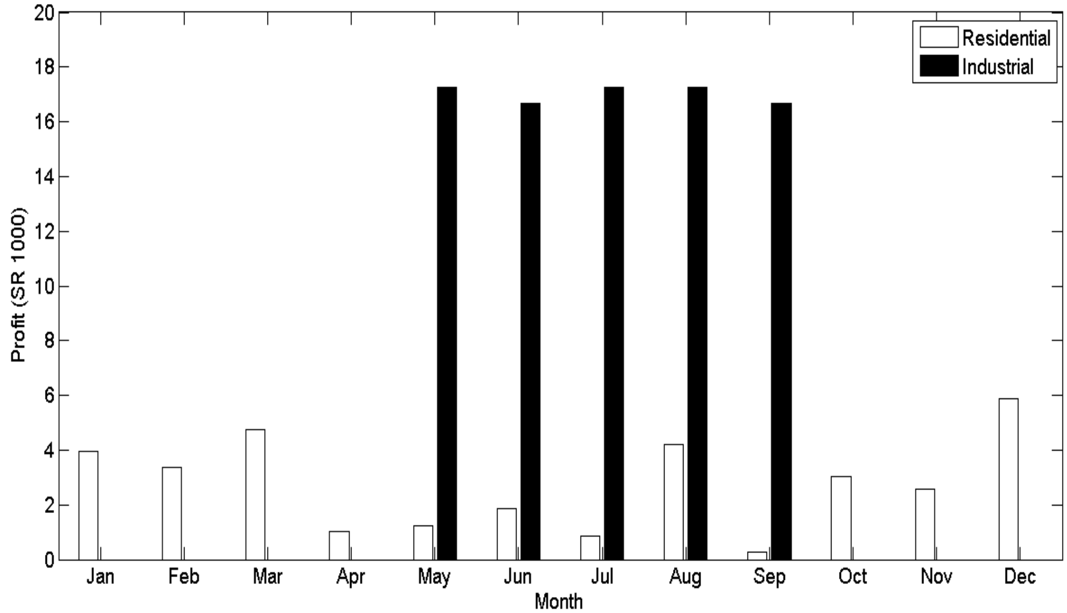


Figure 5.24 Monthly ESS profit in high residential and industrial sector

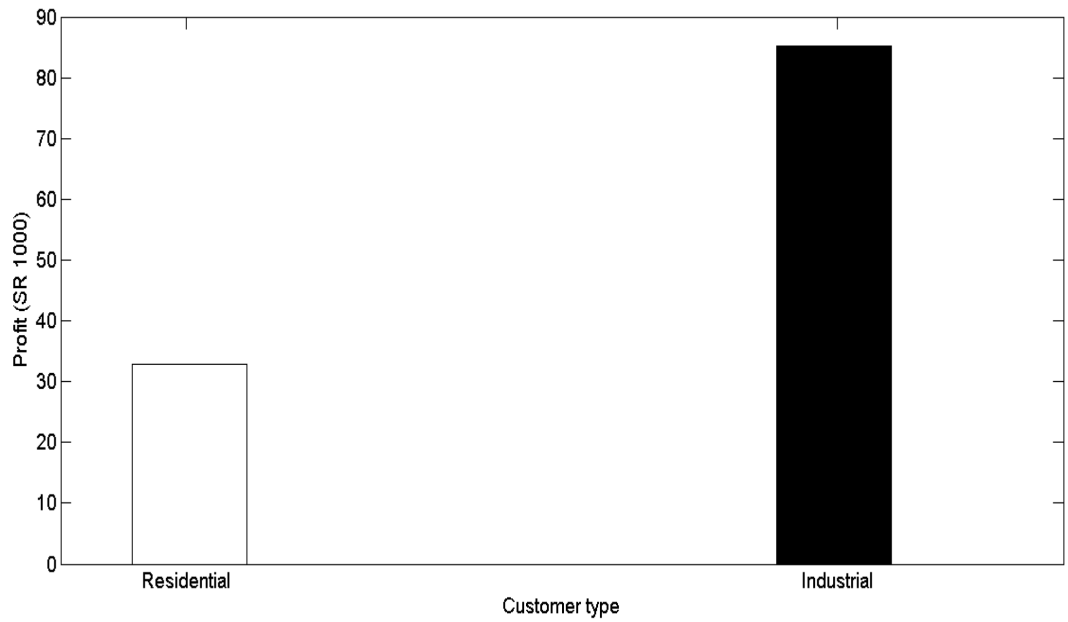


Figure 5.25 Annual ESS profit in high residential and industrial sector

5.4.4 Effect of ESS and feeder parameters on ESS Scheduling

The following parameters will affect the optimal scheduling of ESS:

1. ESS round-trip efficiency, η
2. ESS rated output/input power, P_{max}
3. ESS maximum Energy Capacity**,** E_{max}.
4. Feeder thermal limit, *ftl*

The effects of these parameters on ESS optimal operation algorithm, developed in Section 5.2, is studied by considering hourly electricity price of industrial customers and load demand shown in Figure 5.9 and 5.14 respectively.

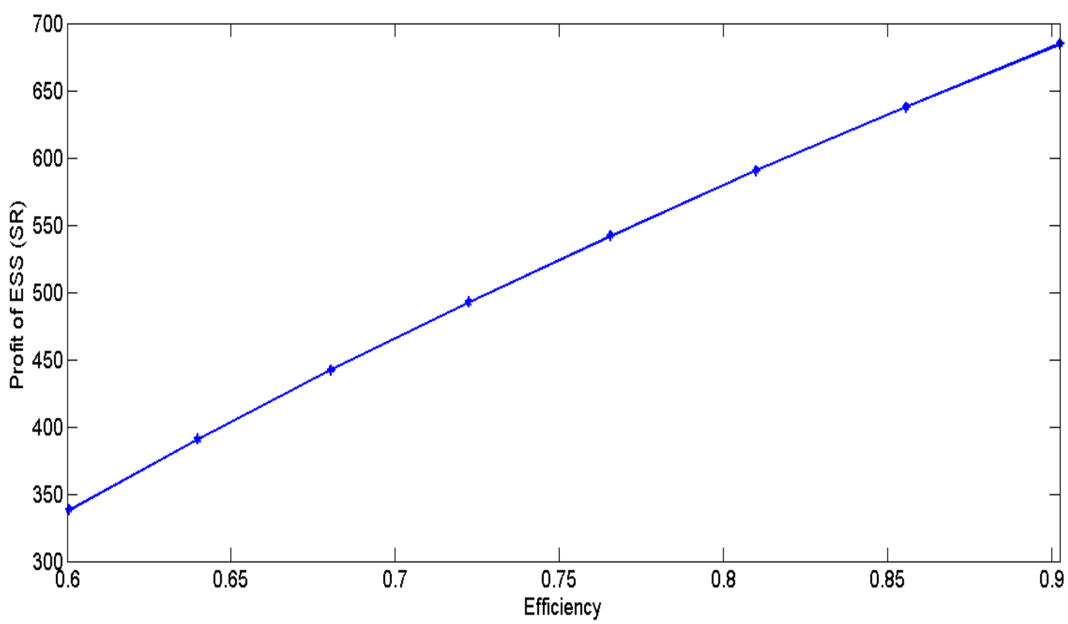


Figure 5.26 ESS profit with variation in its efficiency for E_{max} = 5 MWh and P_{max} = 1 MW

The ESS profit variation with change in its efficiency is shown in Figure 5.26. The maximum power and energy capacity of ESS is considered to be 1 MW and 5 MWh respectively. It is clear from Figure 5.26 that ESS profit linearly increases with increase in its efficiency.

Figure 5.27 shows that while keeping the maximum power capacity of ESS to be constant, the variations in its efficiency and maximum energy capacity affects its optimal profit. Results show that ESS profit increases with increase in both efficiency and maximum energy capacity. Hence ESS of higher energy capacity and efficiency will generate higher profit.

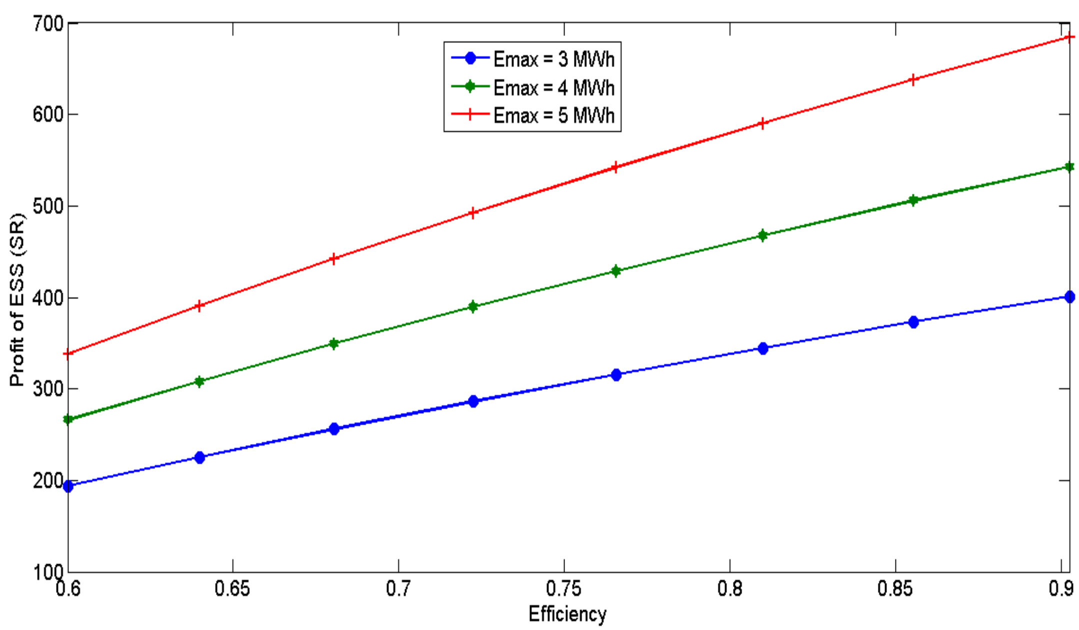


Figure 5.27 ESS profit with variation in its efficiency and maximum energy capacity for P_{max} = 1 MW

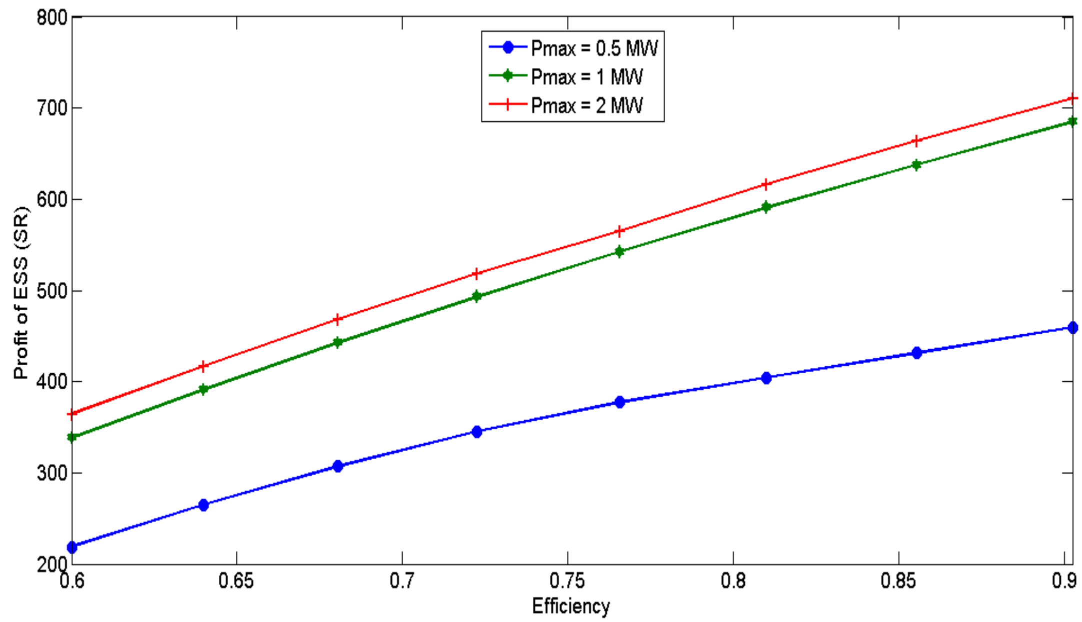


Figure 5.28 ESS profit with variation in its efficiency and maximum power capacity for E_{max} = 5 MWh

The ESS profit variation with change in its efficiency and maximum power capacity while keeping maximum energy capacity to be 5 MWh is shown in figure 5.28. ESS profit increases with increase in both efficiency and maximum power capacity.

Figure 5.29 and 5.30 show the effect of variation in maximum energy and power capacity of ESS on its profit while keeping its round-trip efficiency to be constant (η = 75%). The profit of ESS increases with increase in its maximum energy and power capacity until it reaches specific values of both of them, after which ESS profit remains same. It will help in determining the size of ESS in respects of its maximum energy and power capacity for its optimal operation and maximal profit.

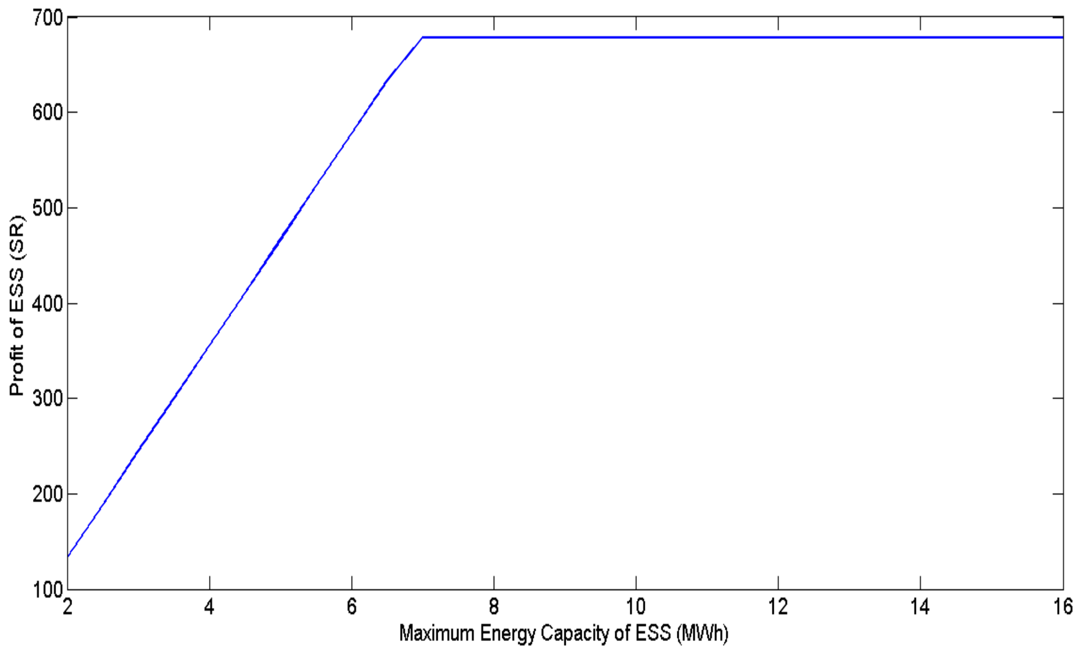


Figure 5.29 ESS profit with variation in its energy capacity for η = 0.75 and P_{max} = 1 MW

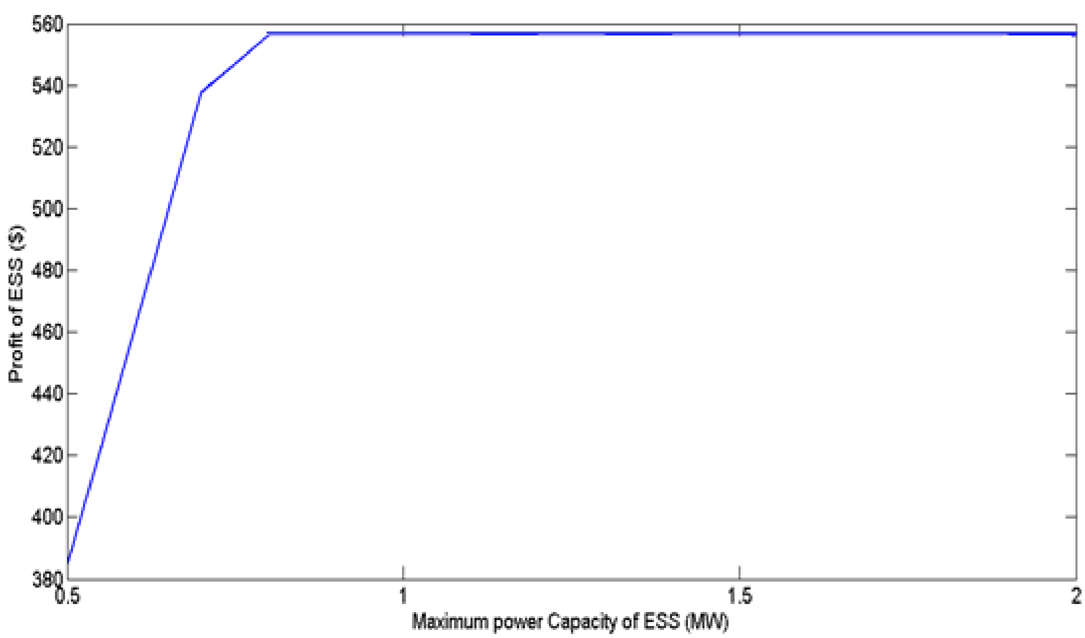


Figure 5.30 ESS profit with variation in its power capacity for η = 0.75 and E_{max} = 5 MWh

Figure 5.31 shows the effect of feeder thermal limit on ESS profit. When the load exceeds the feeder thermal limit, ESS will discharge to provide the additional load demand. If the feeder thermal limit is above than or equal to 8.6 MW, ESS profit will remain constant but if it becomes than less than 8.6 MW, ESS profit will start decreasing by scheduling its discharge power such that load can't exceed distribution feeder thermal limit.

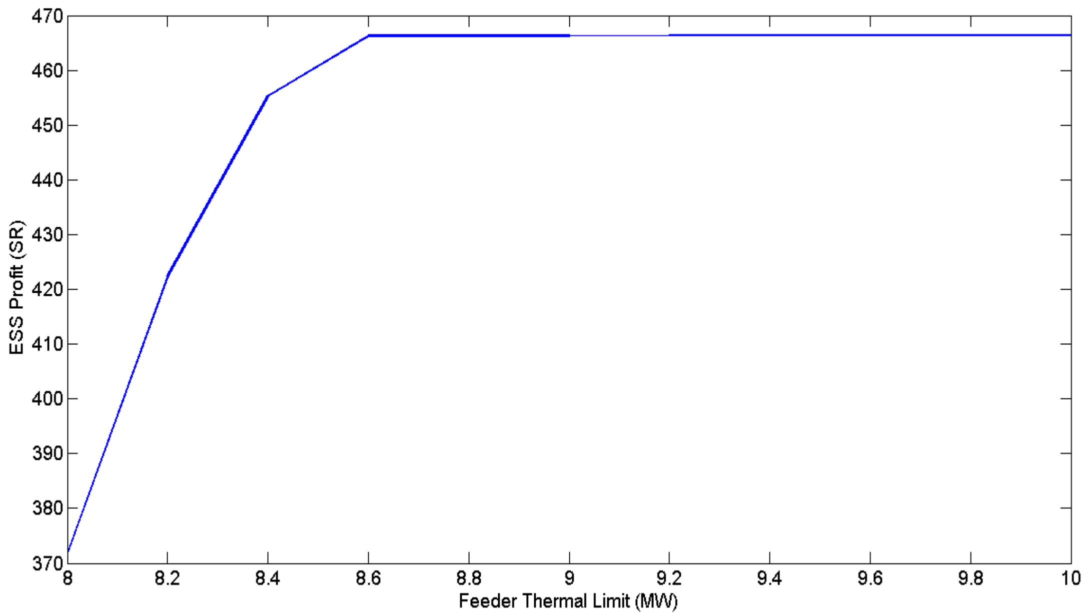


Figure 5.31 ESS profit with variation in feeder thermal limit for η = 0.75, P_{max} = 1 MW and E_{max} = 5 MWh

5.5 Conclusion

This chapter presents an optimal ESS scheduling algorithm considering distribution feeder thermal limit, electricity price, load demand, maximum energy and power capacity of ESS and its charging and discharging efficiency. The developed algorithm has been implemented for different customer types like residential, commercial and industrial customers. The results show that the developed optimal algorithm has proven to be economical for ESS scheduling. The effects of ESS parameters on its optimal operation are also analyzed.

CHAPTER 6

Modeling of Scheduling Optimal ESS with Wind Power Plant

The rising concerns over global warming, environmental pollution, and energy security have increased interest in developing renewable and environmentally friendly energy sources such as wind, solar, hydropower, geothermal, hydrogen, and biomass as the replacements for fossil fuels. This chapter discusses an optimization approach and guideline to obtain the optimal operation of ESS and wind power with distribution feeder to achieve maximum profit based on time of use electricity tariff rates of industrial customers which approach to competitive electricity market to some extent.

6.1 Wind Power

6.1.1 Introduction

Wind power for power systems has recently attracted significant interest and attention from researchers and the power industry. With low operating cost, wind power is viewed as an attractive resource to compensate for generation demand variability in the system. However, wind power generation is not economically competitive in electricity markets compared to conventional generating resources. Wind energy can provide suitable solutions to the global climate change and energy crisis. The utilization of wind power essentially eliminates emissions of CO_2 , SO_2 , NO_x and other harmful wastes as in traditional coal-fuel power plants or radioactive wastes in nuclear power plants. By further diversifying the energy supply, wind energy dramatically reduces the dependence on fossil fuels that are subject to price and supply instability, thus strengthening global energy security. During the recent three decades, tremendous growth in wind power has been seen all over the world. In 2012, the global annual installed wind generation capacity reached a record-breaking 44.5 GW, bringing the world total wind capacity to 282 GW. Figure 6.1 shows the cumulative global installed capacity from 1996 to 2012. As the most promising renewable, clean, and reliable energy source, wind power is highly expected to take a much higher portion in power generation in the coming decades.

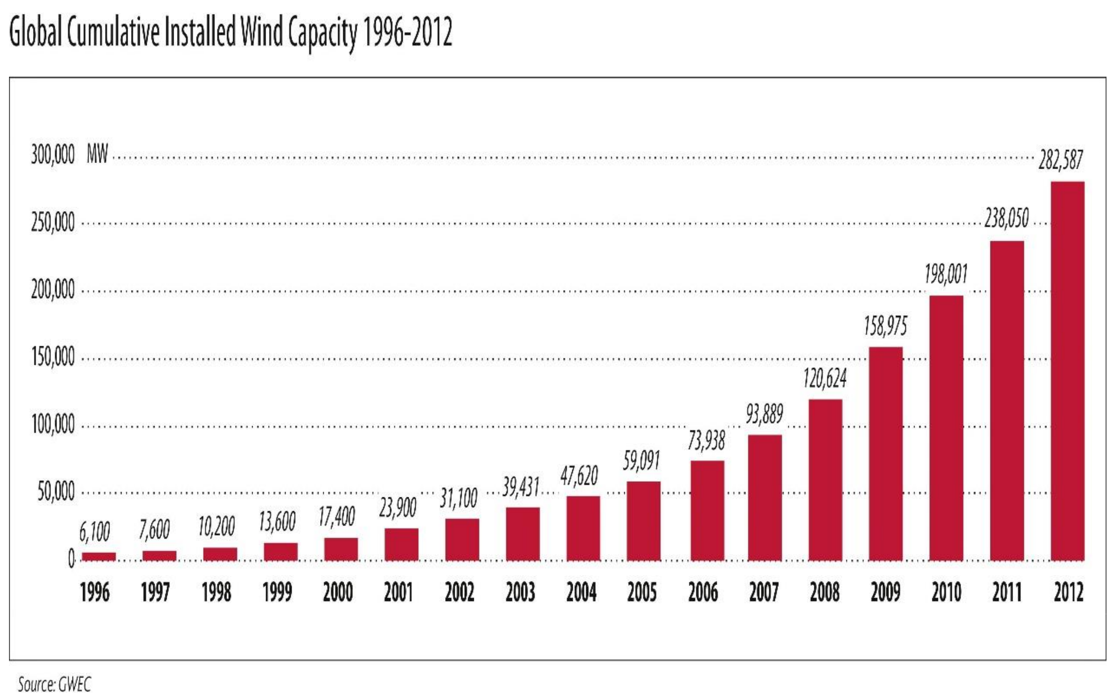


Figure 6.1 Global Installed wind capacity 1996-2012 [93]

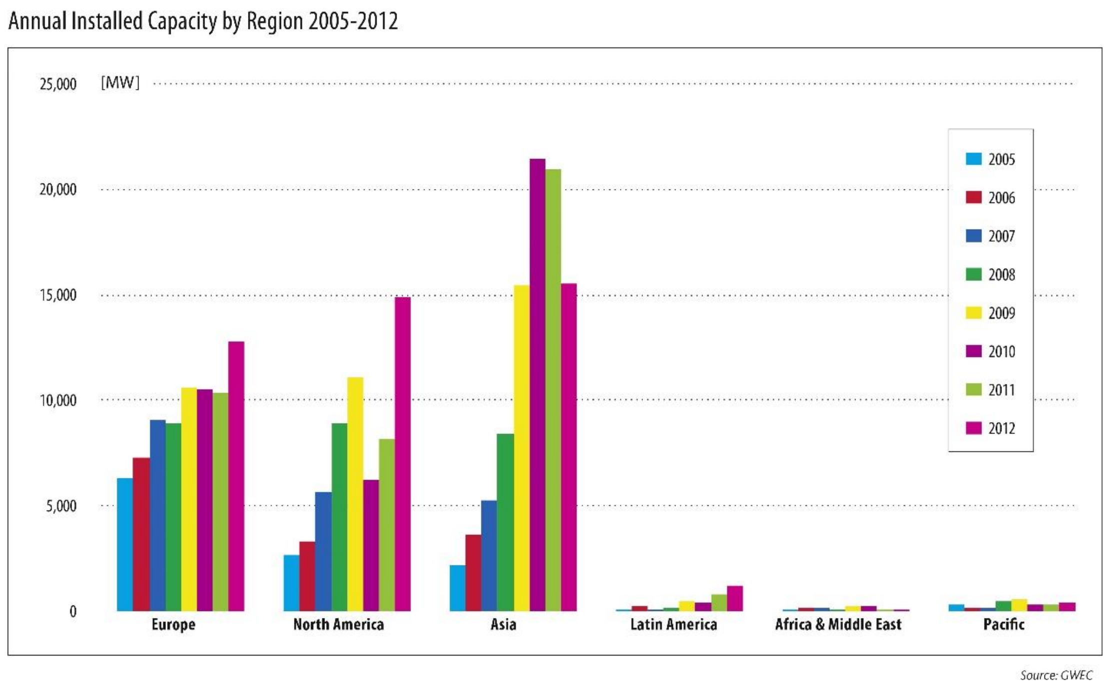


Figure 6.2 Annual installed wind capacity by region 2005-2012 [93]

Figure 6.2 shows the annual installed wind capacity by region from 2005 to 2012. Asia is leading the market of wind energy with North America a close second and Europe is not far behind. Africa & Middle East are far behind in wind energy market. In 2012, only 102 MW wind power capacity has installed in Africa & Middle East compared to 15.51 GW installed wind power capacity in Asia. The ambitious plans of the Saudi government of renewables, such as wind power, installation may begin to bear fruit during the next five years [85].

The introduction of wind power into the current electricity grid requires additional reserve generation in order to guarantee reliability of the grid [94]. Large scale integration of wind power in the electricity system presents some planning and operational difficulties, due mainly to the intermittent and difficult-to predict nature of wind, which is, therefore considered an unreliable energy source [95].

The energy generated from wind farms become more reliable if they are installed at different geographic locations because if they have been installed at same location and wind speed goes to zero, there will be no generation from wind farms. Now if these wind farms are installed at different locations and wind speed goes to zero in one location, there are chances that wind speed will be nonzero at other locations [73]. In order to operate wind farms at their best, there should be the availability of electricity generation from other traditional sources which are able to respond to changes in wind generation and balance generation levels with demand levels.

6.2 Wind Speed

The most important factor in wind power generation is wind speed. Wind speed depends on time as well as space and it is determined by many factors such as geographic and weather conditions. Since wind speed has random behavior so statistical methods are used to deal with measured wind speed data.

One of the major challenges in adopting wind power generation on a large scale is its dependability on Nature. Wind speeds vary continuously as a function of time and height. At very high altitudes, wind speed is not affected by the characteristics of earth's surface. But at lower heights, roughness due to urbanization and farming plays a major role in determining the speed at which the wind impacts the turbine rotors. In the wind industry, a roughness factor is used to indicate the terrain condition of the surrounding area.

The higher the height of the turbine, the lower is the impact of the roughness factor. In general, wind speed measurements are available from weather stations. The measuring height of these weather stations is rarely as high as the wind turbine. The following formula is used to determine the effective wind speed at the turbine height when the roughness factor and wind speed at another height is known [96].

$$v = v_{ref}\left(\ln\frac{h}{z_0} \Big/ \ln\frac{h_{ref}}{z_0} \right) \tag{6.1}$$

where

v_{ref} = Reference wind speed measured at known height [m/s]

h_{ref} = Height at which reference wind speed is measured [m]

z_0 = Roughness factor of the area

h = Wind turbine hub height [m]

v = Wind speed at turbine hub height [m/s]

Wind speed profiles usually demonstrate geographical and seasonal trends. Within these trends, wind speed may vary significantly. Figure 6.3 shows the hourly wind speed for 7 to 21 February 2011, scaled up to 80 m using (6.1) and measured wind speed at a height of 10 m above ground at KFUPM beach Dhahran location. The roughness factor, z_0, is taken to be 0.1 m [96].

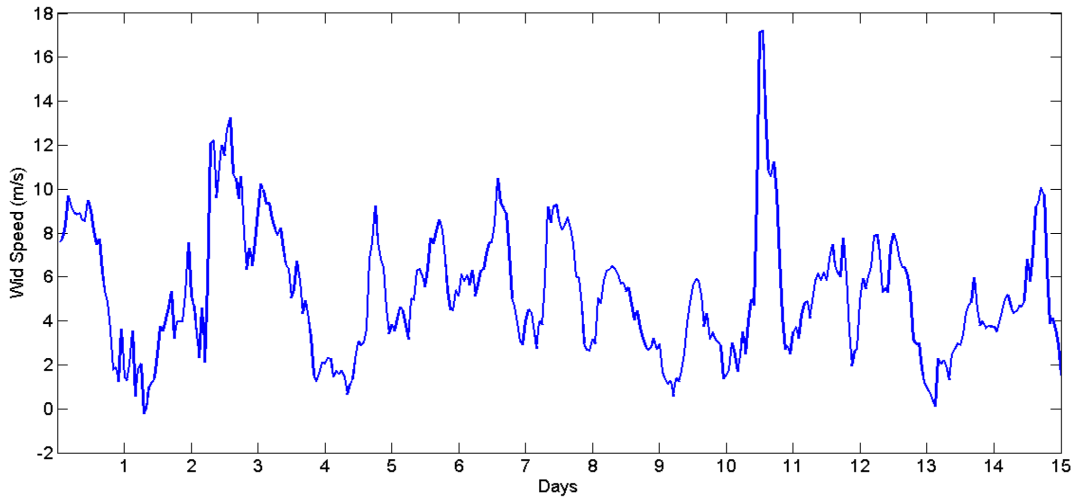


Figure 6.3 Wind speed variation over 15 days at height of 80 m

As seen from the plot above, the wind speeds are not in the turbine's rated speed range for most of the hours. The output of the wind turbine will be limited depending on the availability of wind.

6.2.1 Wind Speed Forecasting

In this thesis, hourly wind speed is forecasted using seasonal ARIMA model. Seasoal Autoregressive Integrated Moving Average (ARIMA) model is linear model that is able to represent time series. This study does not focus on ARIMA model building, further information about it can be found in [97].

In this thesis, wind speed is forecasted using seasonal ARIMA $(1,0,1) \times (1,0,1)_{24}$ model in Matlab, presented in (6.5). The estimated parameters of seasonal ARIMA model are shown in Table 6.1.

$$(1-\varphi_1 B^1)(1-\Phi_{24}B^{24})\, v_t = (1-\theta_1 B^1)(1-\Theta_{24}B^{24})e_t \qquad (6.2)$$

Table 6.1 Seasonal ARIMA model parameters and mean absolute percentage error (MAPE) for wind speed

φ_1	Φ_{24}	θ_1	Θ_{24}	MAPE
0.9924	-0.1384	-0.1821	-0.9352	4.612%

6.3 Wind Power Curve

Power generated by wind turbines depends heavily on wind speed [98]. The wind power can be predicted using wind speed prediction and wind power curve that describes the mathematical relation between wind power and wind speed. Wind power curve are different with respect to average wind speeds and turbines manufacturers. In this thesis, GE 1.5sle is used. The GE 1.5 MW sle and xle wind turbine power curves are shown in Figure 6.4. Each turbine has its own power curve and these curves are established relationships that can be used to go between predictions of wind speed and predictions of wind power.

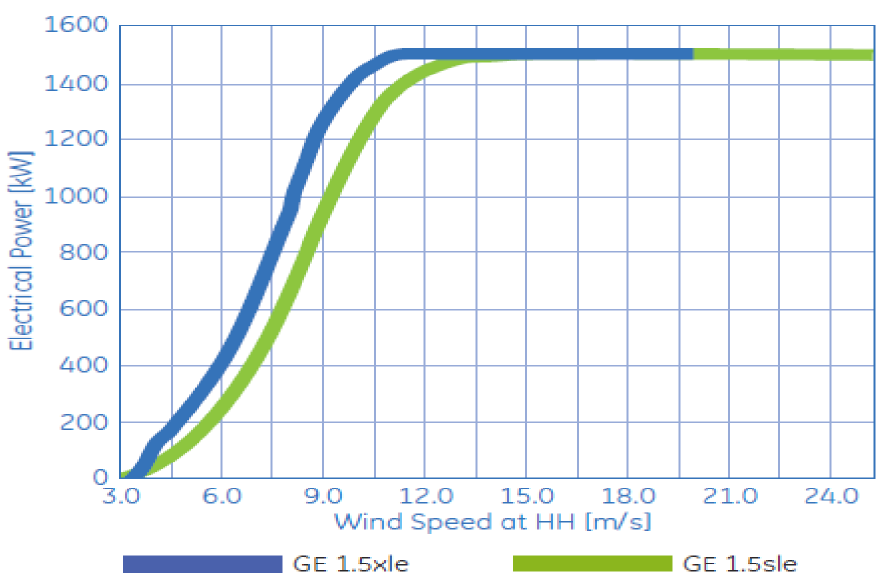


Figure 6.4 GE 1.5 MW wind power curve [99]

The power curve of a wind turbine used throughout this study is modeled in attempt to mimic the characteristics of a particular commercial GE sle 1.5 MW wind turbine.

Table 6.2 GE 1.5sle wind turbine technical data [99]

Rated power capacity (W_{max})	1.5 MW
Cut-in wind speed	3.5 m/s
Rated wind speed	14 m/s
Cut-out wind speed	25 m/s
Hub height	80 m

The wind turbine output is mathematically expressed as:

$$P_w(v_i) = \begin{cases} 0 & v_i \le 3.5 \\ \Psi(v_i) & 3.5 < v_i \le 25 \\ 0 & v_i > 25 \end{cases} \qquad (6.3)$$

and function $\Psi(v_i)$ is described as:

$$P_w(v_i) = \begin{cases} \Phi(v_i) & 3.5 < v_i < 14 \\ 1 & 14 \le v_i \le 25 \\ 0 & else \end{cases} \qquad (6.4)$$

where $\Phi(v_i)$ is a 5th degree polynomial function to be fitted by Matlab curve fitting toolbox to the power curve of GE 1.5sle wind turbine.

$$\Phi(v_i) = 0.1221v_i^5 - 5.334v_i^4 + 85.35v_i^3 - 612.3v_i^2 + 2091v_i - 2740 \qquad (6.5)$$

6.4 System Description

The Energy storage system and wind power plant are represented in Figure 6.5. The distribution system consists of a distribution feeder, main grid, energy storage device and wind power plant. The ESS and wind power plant are connected to the main grid by a distribution feeder with limited capacity.

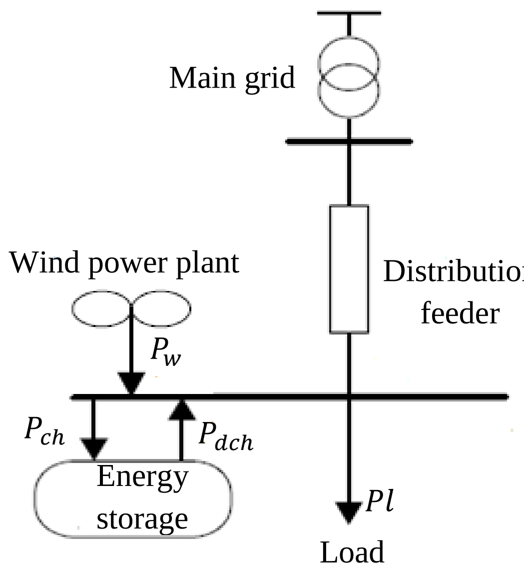


Figure 6.5 Energy Storage and wind power plant connected to the distribution feeder and main grid

6.5 Optimal Scheduling of ESS including Wind Power

The optimization algorithm of Energy storage system developed in Chap. 5 has been modified to consider also wind turbine to achieve maximum profit from ESS and wind turbine combination using electricity tariff rates, distribution feeder thermal limit, hourly load demand and operational and maintenance cost of ESS and technical parameters of both wind turbine and ESS. The developed optimal algorithm aims to optimize the combined scheduling of ESS and wind turbine.

The modified optimization approach is formulated below:

Objective function:

$$Max\ Rev - C \tag{6.6}$$

$$Rev = \sum_{i=1}^{24} \left(P_{dch_i} - P_{ch_i} + P_{w_i}\right)\lambda_i \quad \forall\ i \tag{6.7}$$

$$C = Com_{e_i} + C_{w_i} \quad \forall\ i \tag{6.8}$$

$$Com_{e_i} = C_{omf_i} * P_{max} \quad \forall\ i \tag{6.9}$$

$$C_{w_i} = LCOE_w * P_{w_i} \quad \forall\ i \tag{6.10}$$

Feeder thermal limit constraint:

$$P_{ch_i} - P_{dch_i} + Pl_i - P_{w_i} \le ftl \quad \forall\ i \tag{6.11}$$

Wind operating constraint:

$$0 \le P_{w_i} \le P_{w_i}^{f} \quad \forall\ i \tag{6.12}$$

ESS operating constraints:

$$0 \le P_{dch_i} \le P_{max} \qquad \forall\, i \tag{6.13}$$

$$0 \le P_{ch_i} \le P_{max} \qquad \forall\, i \tag{6.14}$$

$$E_{i+1} = E_i + P_{ch_i} * \eta_{ch} \qquad \forall\, i \tag{6.15}$$

$$E_{i+1} = E_i - \frac{P_{dch_i}}{\eta_{dch}} \qquad \forall\, i \tag{6.16}$$

$$E_{min} \le E_i \le E_{max} \qquad \forall\, i \tag{6.17}$$

$$P_{dch_i} \,.\, P_{ch_i} = 0 \qquad \forall\, i \tag{6.18}$$

where

i = hour

Rev = Revenue (SR)

C = Cost (SR)

λ_i = Electricity price at hour i (SR/MWh)

$P^f_{w_i}$ = Forecasted wind power (MW)

P_{dch_i} = Discharging power of ESS at hour i (MW)

P_{ch_i} = Charging power of ESS at hour i (MW)

E_i = Energy of ESS at hour i (MWh)

η_{ch} = Charging Efficiency of ESS

η_{dch} = Discharging Efficiency of ESS

P_{max} = Maximum power capacity of ESS (MW)

E_{max} = Maximum energy capacity of ESS (MWh)

E_{min} = Minimum energy capacity of ESS (MWh)

Com_i = Operation and maintenance cost of ESS at hour i (SR)

C_{omf_i} = Fixed operation and maintenance cost of ESS at hour i (SR/MW)

Pl_i = Load demand at hour i (MW)

ftl = Feeder thermal limit (MW)

C_{w_i} = Production cost of Wind power at hour i (SR)

$LCOE_w$ = Levelized cost of wind energy (SR/MWh)

The purpose of this model is to schedule combined ESS and wind turbine power optimally using electricity tariff rates. Equation (6.7) and (6.8) represent the revenue and cost of ESS and wind power plant respectively. Equation (6.9) and (6.10) represent the operation and maintenance cost of ESS and wind power production cost of wind turbine respectively. Constraint (6.11) shows that the load, charge/discharge power of ESS and wind power remain within the feeder thermal limit. Equation (6.12) ensures that the scheduled wind power remains within the limits of forecasted wind power. Constraints (6.13) and (6.14) ensure the charge/discharge power remain within the limits defined. Constraint (6.15) and (6.16) represent the energy balance equations of ESS. Constraint (6.17) ensures the stored energy of ESS remains within the limits defined. Constraint (6.18) shows that ESS will either charge or discharge, but not both at a time.

Although, the objective function is linear but this optimization problem is nonlinear due to constraint (6.18). However, this optimization problem can be converted into mixed integer linear formulation by using binary variable and additional constraints. The optimization algorithm becomes a mixed integer linear programming (MILP) problem by replacing constraint (6.18) with constraints (5.11) – (5.13).

6.6 Simulation Results

The developed optimal algorithm to maximize ESS and wind power plant profit is simulated on a system described in section 6.2. The simulations are performed for 24/7 period. The Levelized cost of wind energy (LCOE) is hypothetically assumed to be 100 SR/MWh, which considers the investment, O&M and production cost of wind energy. In this study, the system load, electricity prices and wind speed are hourly averages. The system load is adjusted load of eastern province region of Saudi Arabia. The hourly electricity tariff rates are taken from ECRA [92].

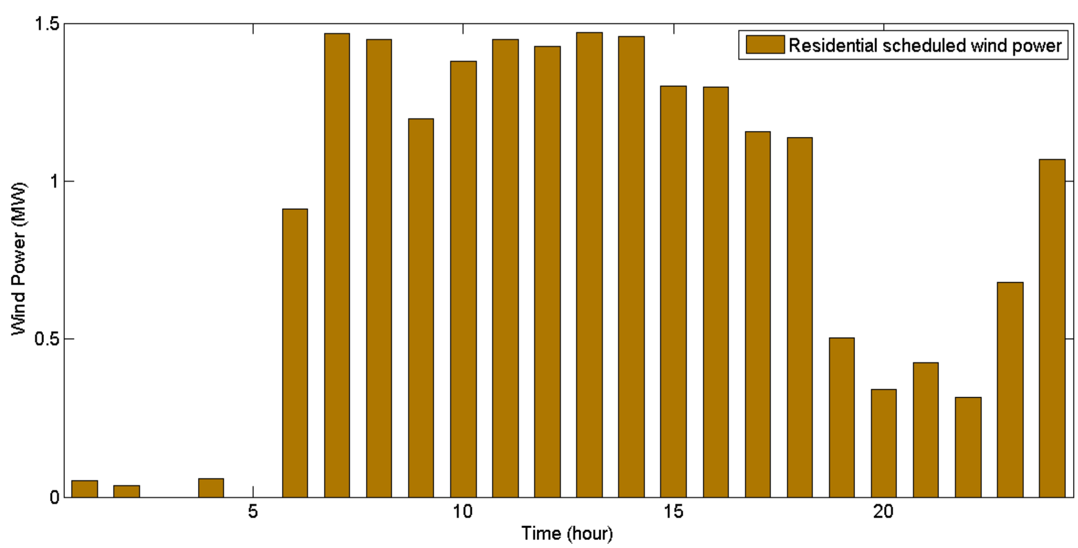
Hourly measured Wind speed data of Dhahran region at 10 m height is used to calculate the wind speed at hub height, 80 m, using Eq. (6.1). Wind speed is forecasted using seasonal ARIMA $(1,0,1)\times(1,0,1)_{24}$ model. Hourly actual and forecasted wind power is calculated using Eq. (6.2) to (6.4). Load forecasts are generated by adding an error to the actual load to match the load forecast errors observed in [91]. Profits are calculated based on actual values of load, price and wind power.

The ESS parameters and feeder thermal limit are given in Table 5.1. Figure 5.2 shows the hourly electricity price for residential, commercial and industrial customers taken from

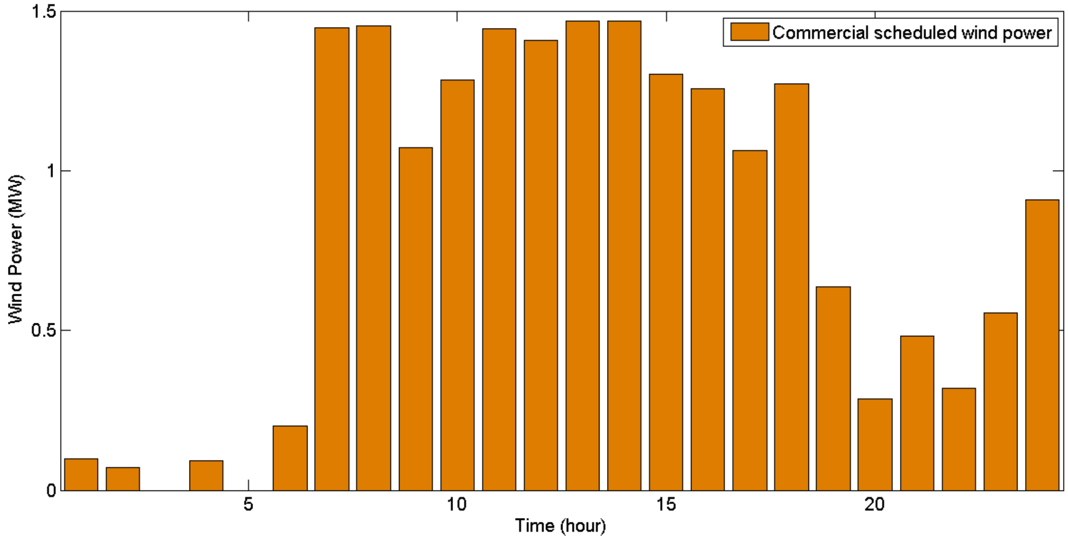
Electricity and Cogeneration Regulation Authority (ECRA) Saudi Arabia [92]. The electricity rates of ECRA for residential, commercial and industrial customers are shown in Table 5.2 ,5.3 & 5.4 respectively.

6.6.1 ESS and wind power scheduling profiles

The wind power plant scheduling profiles at residential, commercial and industrial tariff rates are shown in Figure 6.6. The scheduled wind power is zero for first 9 hours in case of industrial customers. It is due to the fact that LCOE of wind power plant is 100 SR/MWh and industrial tariff rates for first 9 hours are also 100 SR/MWh, so wind power plant will not produce wind energy for industrial customers during these hours.



(a)



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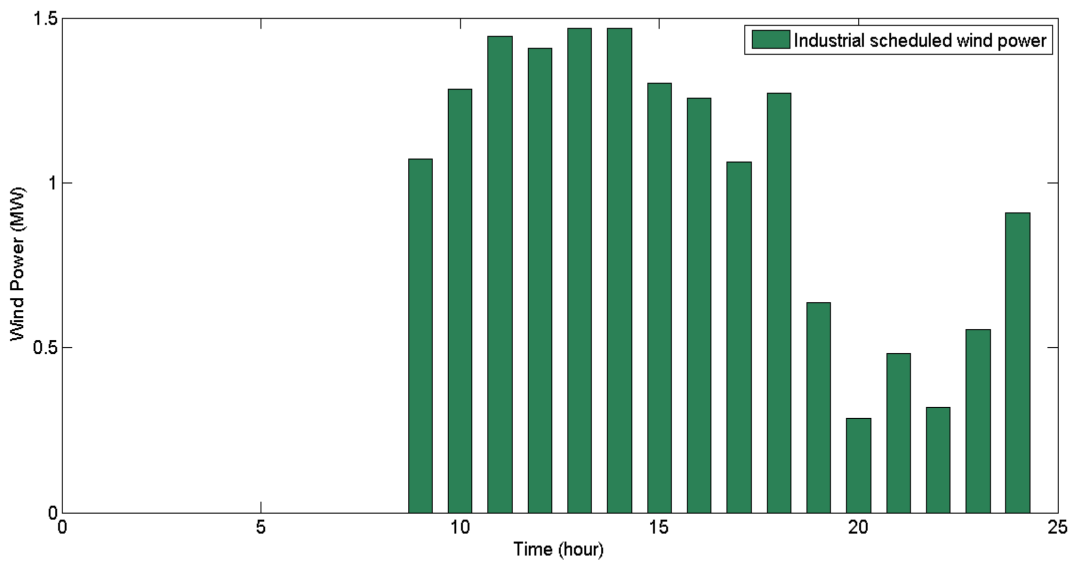
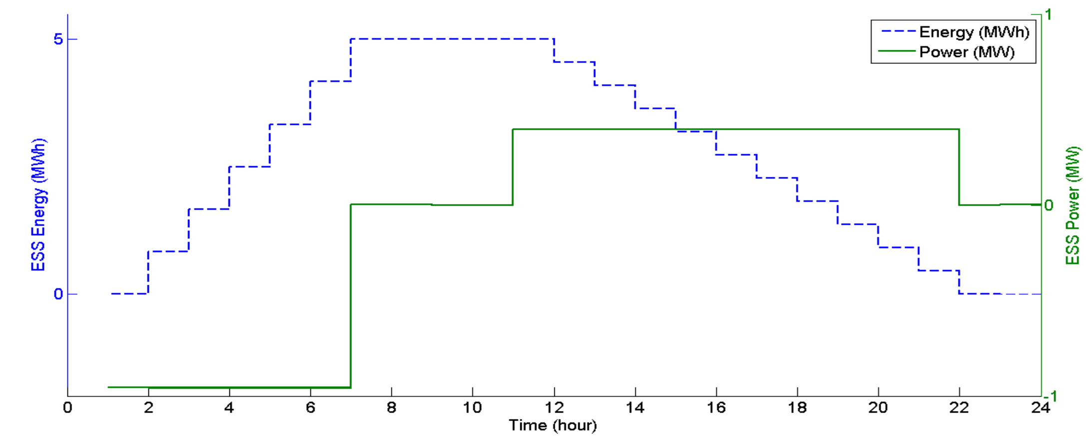
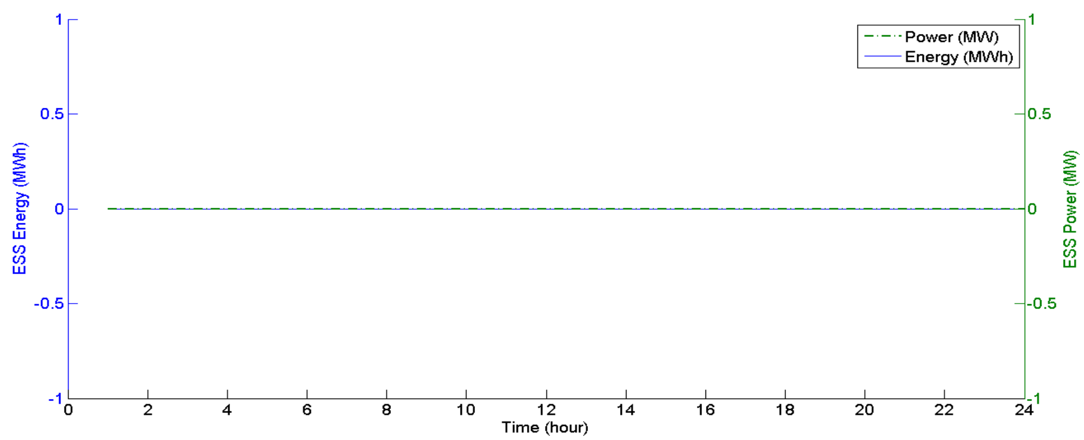


(c)

Figure 6.6 Hourly scheduled wind power for (a) Residential electricity tariff rates (b) Commercial electricity tariff rates (c) Industrial electricity tariff rates



(a)



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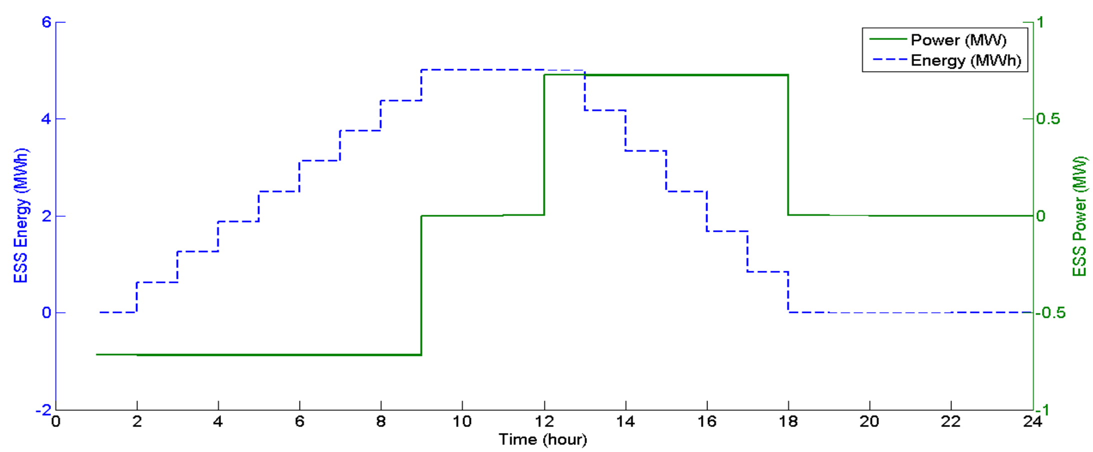


(c)

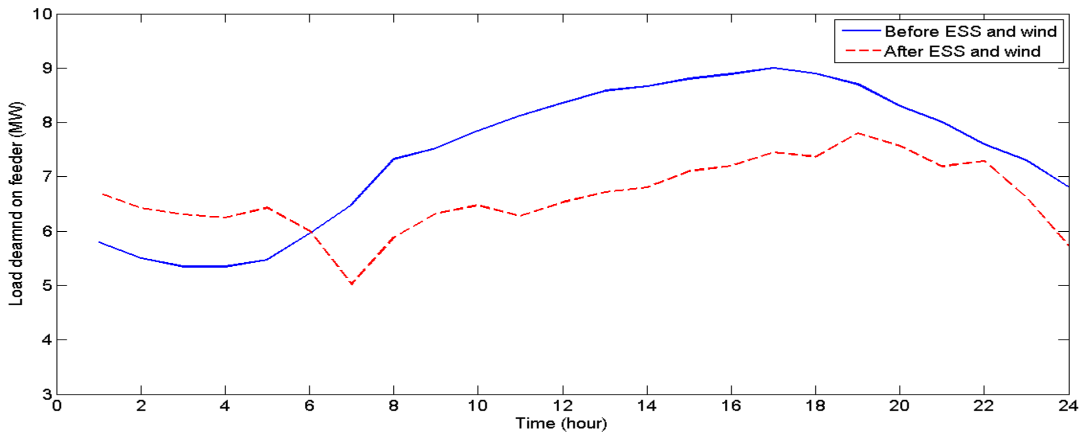
Figure 6.7 Optimal scheduling of power and energy of ESS for (a) Residential customers (b) Commercial customers (c) Industrial Customers

The charge/discharge power profile and energy state of ESS for each hour are shown in Figure 6.7. It is obvious after comparing it with electricity price, shown in Chapter 5, that the ESS is charging during low price period and it is discharging during high price period to get maximum energy price arbitrage. Figure 6.7 (a) shows the energy and power profile of ESS for residential electricity tariff rates. The price is lower 120 SR/MWh for 6 hours so ESS will charge during these hours and it will discharge to sell power during high price 220 SR/MWh.

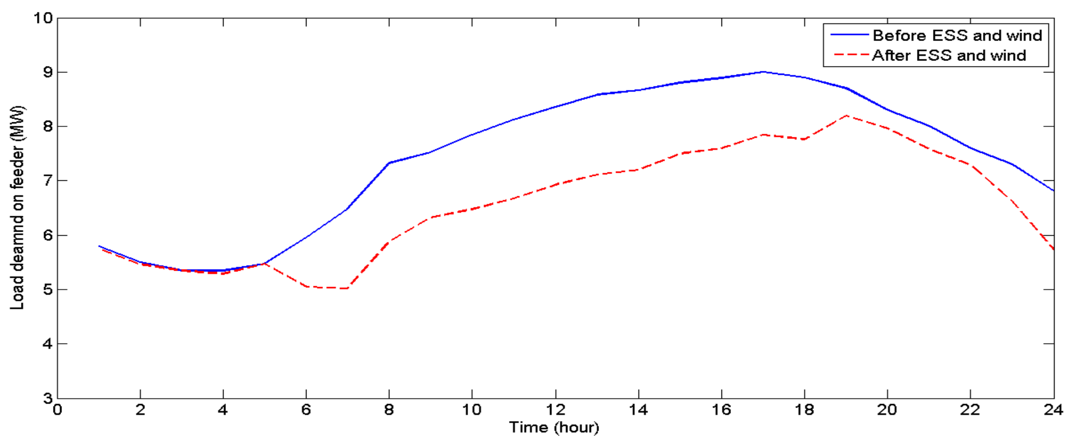
Figure 6.7 (b) shows the energy and power profile of ESS for commercial electricity tariff rates. The price is lower 200 SR/MWh but ESS will not charge during this price as maximum price is 260 SR/MWh and considering efficiency it will not make profit as if it buys 1 MW for 1 hour at 200 SR/MWh, it can only sell 0.75 MW for an hour (1MW*η = 1MWh*0.75 = 0.75 MWh) at 260 SR/MWh making loss of 5 SR (260*0.75-200*1 = -5 SR). Hence ESS will not operate at commercial tariff rates.

Figure 6.7 (c) shows the energy and power profile of ESS for industrial electricity tariff rates. The price is lower 100 SR/MWh so ESS will charge at this price rate and it will discharge to sell power during high price 260 SR/MWh. Hence ESS will operate at industrial.

The load demand on distribution feeder with and without considering ESS and wind power plant is shown in Figure 6.8.



(a)



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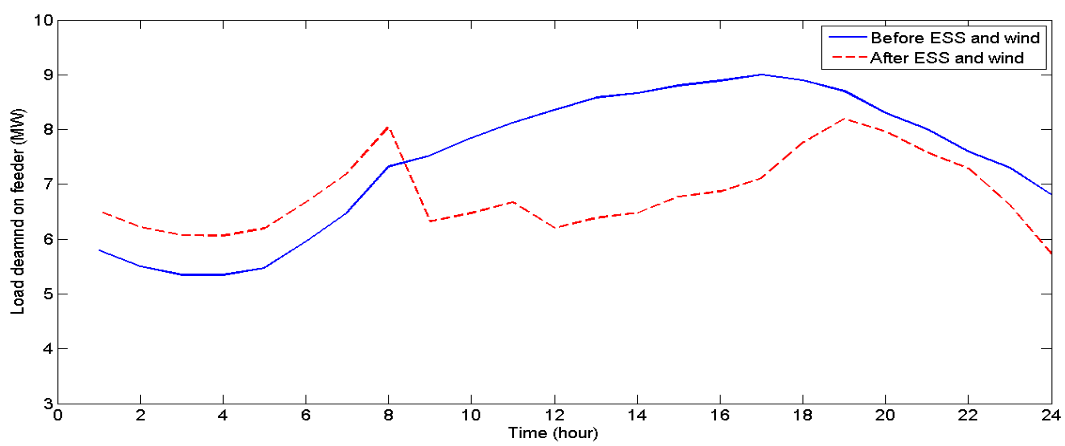

(c)

Figure 6.8 Load demand on distribution feeder for (a) Residential customers (b) Commercial customers (c) Industrial customers

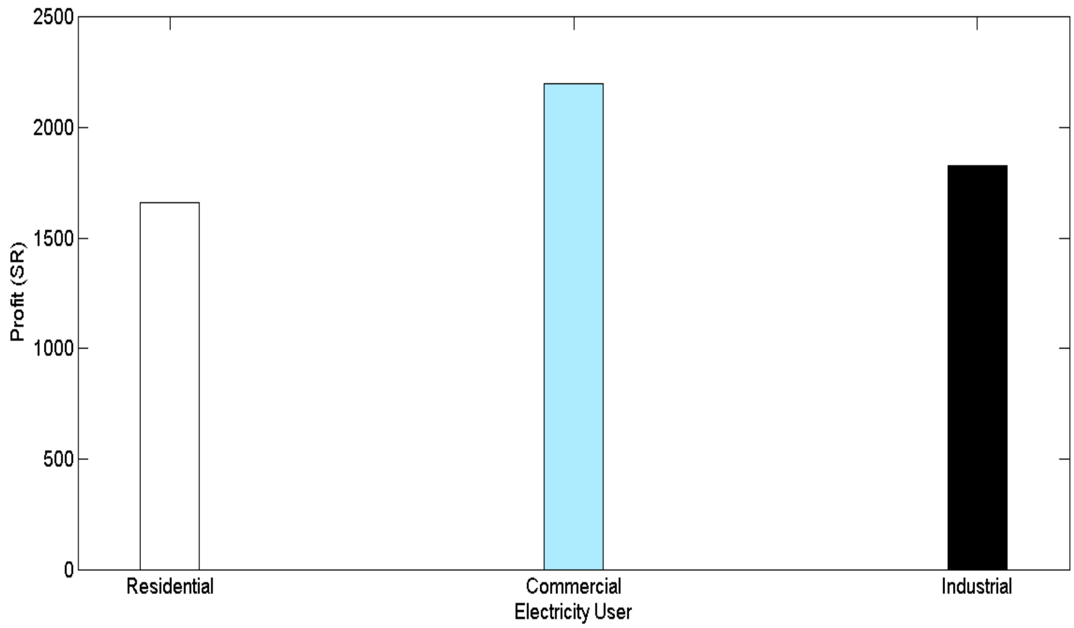

Figure 6.9 Profit from ESS and wind turbine combination

The hourly based daily ESS and wind turbine profits for residential, commercial and industrial customers are shown in Figure 6.8. These profits are calculated based on actual values of wind power and load demand. The optimal profit in case of commercial customers is higher than those of residential and industrial customers due to higher commercial electricity tariff rates obvious from section 5.3.

6.6.2 Monthly and yearly profits

The monthly and annual profits of ESS optimal scheduling are obtained after simulation using following different customer type's load demand.

- Mix residential, commercial and industrial substation
- Residential substation

- Industrial substation

6.6.2.1 Substation: Mix Residential, Commercial and Industrial

The annual hourly load demand of eastern province region of Saudi Arabia for mix residential, commercial and industrial sector has been modified and given in Section 5.3. The annual hourly electricity prices of industrial, residential, commercial customers are obtained using load demand and electric tariff rates for each customer type provided in Chapter 5. The annual hourly electricity prices of each customer type are also shown in Chapter 5.

The combined profits of ESS and wind power plant for residential, commercial and industrial customers are obtained for annual period using developed optimization approach for combined ESS and wind power plant. Figure 6.10 shows the monthly profits for residential, commercial and industrial customer's electricity tariff rates. The profit at commercial electricity tariff rates are higher than that at residential and industrial electricity tariff rates due to the reason that commercial electricity tariff rates remain greater than or equal to 200 SR/MWh for almost all year. ESS will not operate at commercial electricity tariff rates and the reasons are described in Section 5.3.2. The ESS will also operate at commercial electricity tariff rates if these rates are increased to 285 SR/MWh for load greater than 8 MW.

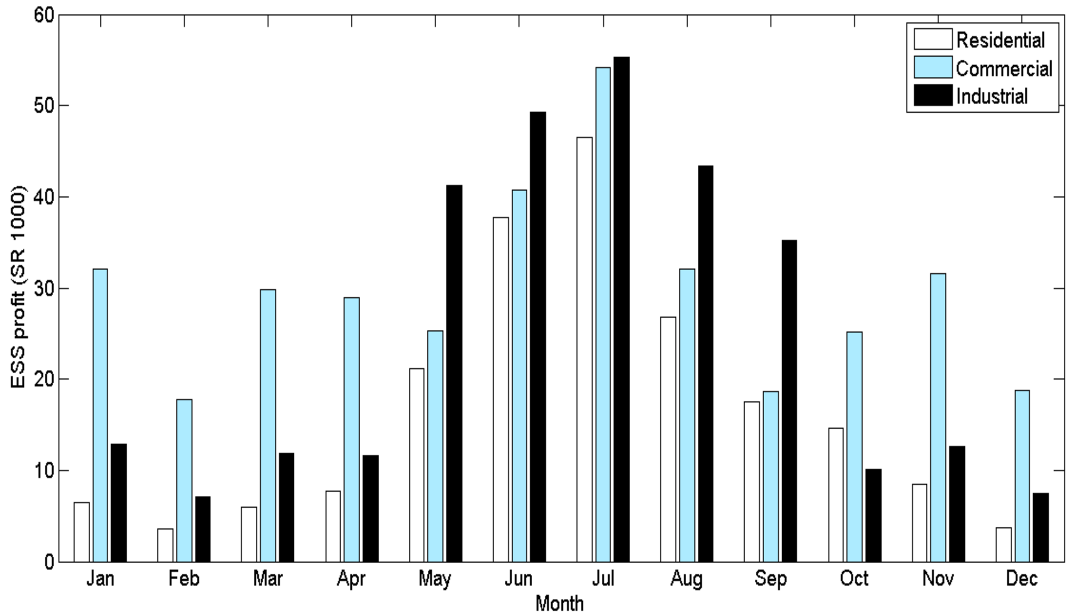

Figure 6.10 Monthly profit from ESS and power plant combination for different customer types

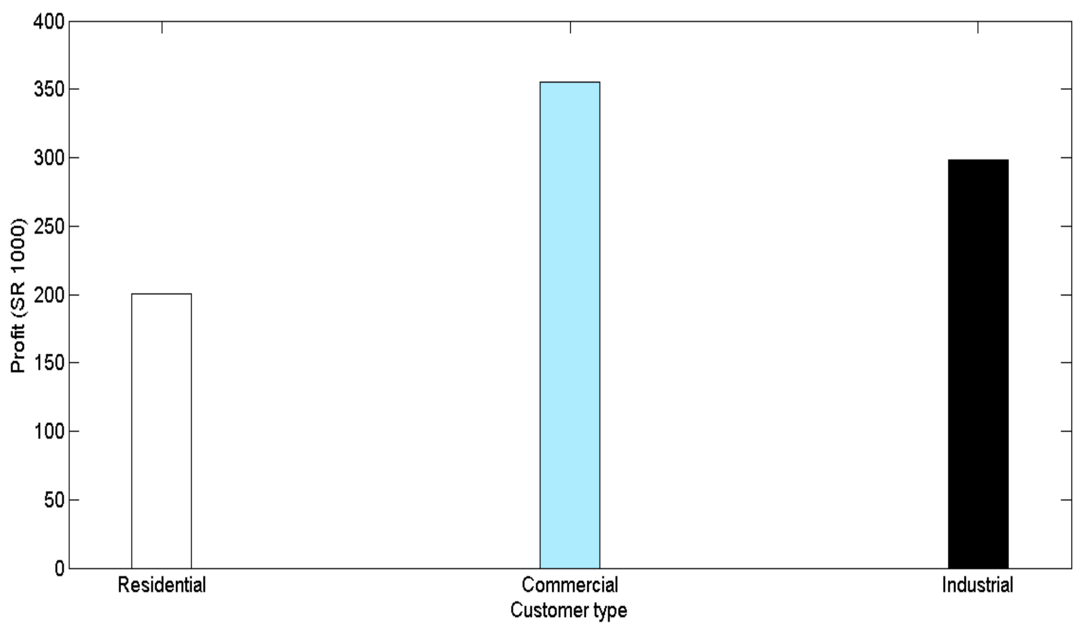

Figure 6.11 Annual profit from ESS and wind power plant combination for different customer types

The annual profits at residential, commercial and industrial customer's electricity tariff rates are shown in Figure 6.11. The annual profit is maximum at commercial customer's electricity tariff rates while the annual profit at industrial customer's electricity tariff rates is more than that at residential customer's electricity tariff rates.

6.6.2.2 Residential and Industrial Substations

The effects of all residential sector and all industrial sector load demands and prices on developed optimal ESS scheduling algorithm are analyzed. The annual all residential and all industrial sector modified load demands are taken from residential and industrial substations of eastern province region of Saudi Arabia respectively and are shown in presented in Section 5.3.

The annual prices of all residential and all industrial sector are obtained using Tables 5.2 and 5.4. Now these prices and demands are used in simulating and examining the performance of developed optimal ESS scheduling algorithm. The simulation results are shown in Figure 6.12 and 6.13.

The monthly and annual profits in case of all residential and all industrial sector are shown in Figure 6.12 and 6.13 respectively. From Figure 6.12, it is clear that it is more economical to operate both ESS and wind power plant in industrial sector to get maximum profit. The monthly profit at industrial electric tariff rates is maximum during month of July due to large wind power availability and high deviation between maximum and minimum industrial electricity tariff rates. The annual profit from combined ESS and wind power plant optimal operation in industrial sector is SR 297,940 while in residential sector, it is SR 85,112.

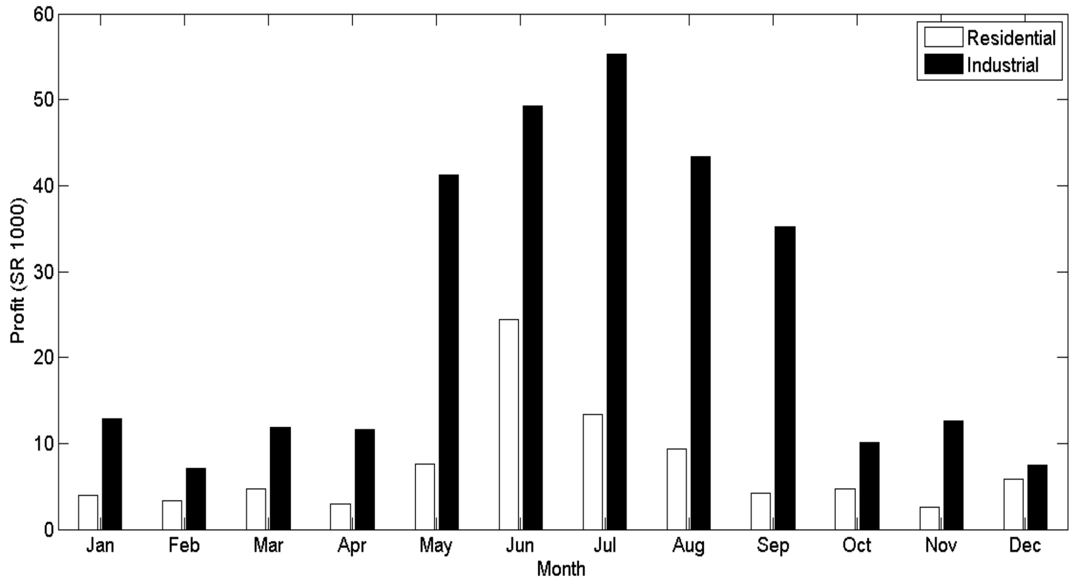

Figure 6.12 Monthly profit from ESS and wind power plant combination for all residential and all industrial sectors

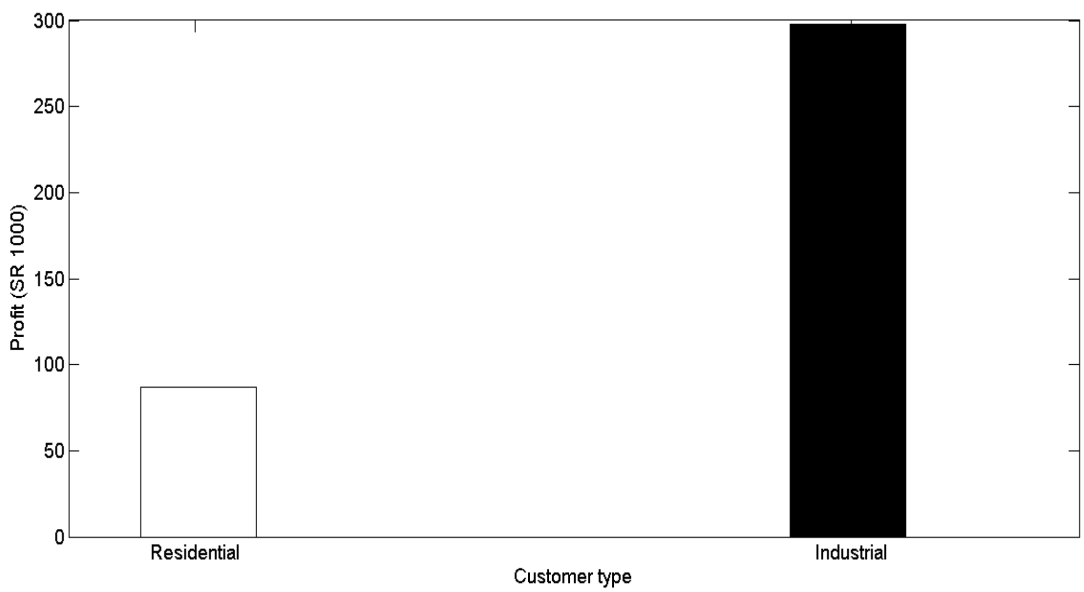

Figure 6.13 Annual profit from ESS and wind power plant combination for all residential and all industrial sectors

Table 6.3 Annual Profit from optimal ESS scheduling with and without wind power plant

Substation type	Customer type	ESS profit (SR)	ESS and wind power plant combined profit (SR)
Mixed residential, commercial and industrial	Residential	2,230	200,190
	Commercial	63	355,080
	Industrial	85,112	297,940
Residential	Residential	32,917	87,080
Industrial	Industrial	85,112	297,940

6.7 Conclusion

In this chapter, an optimal combined ESS and wind power scheduling algorithm is developed and analyzed considering distribution feeder thermal limit, electricity price, load demand, maximum energy and power capacity of ESS and its charging and discharging efficiency and wind power plant parameters. The developed algorithm has been implemented on different customer type’s tariff rates such as residential, commercial and industrial customers. Simulation results show that the developed optimal algorithm has proven to be economical for combined ESS and wind power scheduling.

CHAPTER 7

Conclusions and Future Work

7.1 Conclusions

In this thesis, three research problems of ESS applications have been studied which are distribution feeder deferral using ESS, optimal scheduling of ESS on constrained distribution feeder and optimal combined ESS and wind power plant scheduling on constrained distribution feeder. After introduction of ESS, these problems are modeled and evaluated. The simulation results yield the significant amount of benefit. The proposed algorithms and models can be very helpful to various organizations, including utilities companies, distribution system operators and end-user customers.

In distribution feeder deferral, the potential benefit of ESS distribution deferral benefit can be quantified as Net Present Value (NPV). The NPV is the present value difference between two investments: the distribution feeder upgrade without/with ESS deferral. The NPV is a function of feeder load growth rate, feeder length, ESS round-trip efficiency, maximum power capacity as well as energy capacity. The sensitivity study results, in Chap.4, indicate a long feeder with proportional large capital cost will obtain a significant benefit.

In optimal scheduling of ESS on constrained distribution feeder, an optimization algorithm is developed which considers the effects of distribution feeder thermal limit, electricity price, load demand, maximum energy and power capacity of ESS and its charging and discharging efficiency. The proposed algorithm has been simulated for different customer types like residential, commercial and industrial customers. The results show that the developed optimal algorithm has proven to be economical for ESS scheduling. The effects of ESS parameters and feeder thermal limit on proposed algorithm are also analyzed.

In optimal combined scheduling of ESS and wind power plant on constrained distribution feeder, an algorithm is developed and analyzed considering distribution feeder thermal limit, electricity price, load demand, maximum energy and power capacity of ESS and its charging and discharging efficiency and wind power plant parameters. The developed algorithm has been implemented on different customer type's electricity tariff rates and demand such as residential, commercial and industrial customers. Simulation results show that the developed optimal algorithm has proven to be economical for combined ESS and wind power scheduling.

The main conclusion of this work is that the introduction of the ESS provides an opportunity to defer upgrading feeders. It may also provide substantial financial benefits to the grid and system operators.

7.2 Future Work

The following are the recommendations for further research in this work:

- In this thesis, optimal ESS and wind power scheduling algorithms are implemented on electricity tariff rates which are not competitive electricity market prices. These algorithms can be implemented on competitive electricity market energy prices.
- In this research, optimal ESS and wind power scheduling algorithms consider energy prices only. Ancillary services market and prices can also be considered in these algorithms.
- Various optimization techniques such as particle swarm optimization, genetic algorithm, etc. can be used to implement these optimal ESS and wind power scheduling algorithms.
- Wind power plant is used with ESS for combine optimal scheduling in this research. PVs can also be considered with or without wind power plants for combined optimal scheduling with ESS.
- More ESS characteristic parameters can be considered. The relations and effects between different parameters should also be addressed.

Appendix A

Forecasting using ARIMA Model

Autoregressive Integrated Moving Average (ARIMA) model is linear model that is able to represent time series. The general form of ARIMA model, which has the general expression (p, d, q) is given as [97]:

$$\left(1-\sum_{i=1}^{p}\varphi_i\, B^i\right)(1-B)^d y_t = c + \left(1-\sum_{j=1}^{q}\theta_j\, B^j\right)a_t \qquad (A.1)$$

where φ_i are the coefficients of autoregressive (AR) polynomial and p is the order of this polynomial; θ_j are the coefficients of moving average (MA) polynomial and q is the order of this polynomial; a_t is the white noise with zero mean and standard deviation σ. c is a constant which represents the deterministic trend of the series and $(1-B)^d$ is the differencing term where d gives the order of differencing.

ARIMA models should be improved to represent a time series which shows seasonal characteristic appropriately, desired in forecasting data having periodicity. The general form of the seasonal ARIMA models, which has the general expression $(p,\ d,\ q)\times(P, D, Q)_S$, are given as [97]:

$$\left(1-\sum_{i=1}^{p}\varphi_i\, B^i\right)\left(1-\sum_{i=1}^{P}\Phi_i\, B^{iS}\right)(1-B)^d(1-B^S)^D\, y_t$$
$$= c+\left(1-\sum_{j=1}^{q}\theta_j\, B^j\right)\left(1-\sum_{i=1}^{Q}\Theta_j\, B^{jS}\right)a_t \qquad (A.2)$$

where Φ_i are the coefficients of seasonal autoregressive (SAR) polynomial and P is the order of this polynomial; Θ_j are the coefficients of seasonal moving average (SMA) polynomial and Q is the order of this polynomial; $(1-B^S)^D$ is the seasonal differencing term where D and S give the order of seasonal differencing and the order of seasonality, respectively.

After appropriate ARIMA model has obtained using historical wind speed data in Matlab and ARIMA coefficients are obtained, ARIMA process in time t, y_t , can be expressed in as [97]:

$$y_t = c+\varphi\left(y_{t-1}, y_{t-2}, \ldots., y_{t-p}\right)+\Phi(y_{t-S}, y_{t-S-1}, \ldots., y_{t-S-P})$$
$$+\theta\left(a_{t-1}, a_{t-2}, \ldots., a_{t-q}\right)+\ \Theta\left(a_{t-S}, a_{t-S-1}, \ldots., a_{t-S-Q}\right) \qquad (A.3)$$

Appendix B

Sequential Quadratic Programming

Sequential quadratic programming (SQP) is the most successful method for solving nonlinear optimization problems numerically. The nonlinear optimization problem is defined as:

$$minimize \quad f(x_1, \ldots., x_n) \qquad (B.1)$$

$$subject\ to: \quad h_k(x_1, \ldots., x_n) = 0, \;\; k = 1,2, \ldots, l \qquad (B.2)$$

$$g_j(x_1, \ldots., x_n) \leq 0, \;\; j = 1,2, \ldots, m \qquad (B.3)$$

$$x_i^l \leq x_i \leq x_i^u, \;\; i = 1,2, \ldots, n \qquad (B.4)$$

Where f is the objective function; h and g are equality and inequality constraints respectively.

The objective is expanded in quadratic manner, while constraints are expanded linearly. This is called sequential quadratic programming.

$$minimize \quad \tilde{f}(\Delta x) = f(x_i) + \nabla f(x_i)^T \Delta x + \frac{1}{2} \Delta x^T \, \nabla^2 f(x_i) \, \Delta x \qquad (B.5)$$

$$Subject\ to: \quad \widetilde{h_k}(\Delta x): h_k(x_i) + \nabla h_k(x_i)^T \Delta x = 0; \quad k = 1,2, \ldots., l \qquad (B.6)$$

$$Subject\ to{:}\ \tilde{g}_j(\Delta x){:}\ g_j(x_i)j + \nabla g_j(x_i)^T \Delta x = 0; \quad j = 1,2,\dots.,m \qquad (B.7)$$

$$\Delta x_i^l \leq \Delta x_i \leq \Delta x_i^u,\ \ i = 1,2,\dots,n \qquad (B.4)$$

The developed SQP problem is solved using SQP algorithm defined in [89].

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