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Optimal fuzzy logic based coordination control for improved power flow of a smart grid using smart metering

Graduation Thesis

by

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Abstract

An abstract of optimal fuzzy logic based coordination control for improved power flow of a smart grid using smart metering

by

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Over the years, the demand and usage of electricity have skyrocketed, but the electric transmission and distribution processes have remained the same since the early 20th century. The current work develops an optimal power flow control algorithm for smart grids using fuzzy logic between the end consumers and the distribution grid. The fuzzy controller determines when to draw power from the grid or from an energy storage unit that is charging during low electricity price hours. The input parameters for the model are hourly power price and grid load. This smart grid system utilizes fuzzy logic and smart meters to achieve two goals. The first goal is to reduce cost for end consumers by charging an energy storage unit during low cost periods and then releasing energy during high cost periods. The second objective of this system is to prevent overload of the electricity grid by shifting the power drawn from high demand period to low demand period. Tests run using actual data from ISO during one year, demonstrate significant cost savings and grid load reduction.

Acknowledgements

Table of Contents

List of Figures

List of Tables

1

Introduction

1.1 General Introduction

Over the past years worldwide energy demand has grown rapidly. According to predictions from the International Energy Agency between 2007 and 2050, global energy consumption is expected to increase over 117%. Emerging countries such as China, India, South Africa show growth, ranging from 104% to 509% while already developed countries will also face the problems of replacing ageing electricity network infrastructure [1]. The electric power industry needs to be transformed in order to cope with the needs of modern society. Smart Grid offers an upgrade from the 20th century power grids.

Smart grids are a key suite of technologies to deal with current and future needs in the electricity sector while also enabling us to effectively adopt low-carbon energy technologies such as different forms of renewable energies and electric vehicles. An objective of the Smart Grid is to provide technology and systems that will allow consumers to automatically manage their energy use and costs. These technologies can assist the grid in increasing the usage of alternative energy sources, such as renewable energy. A key feature of the Smart Grid is Demand Response, where the consumer can reduce his energy consumption during critical usage periods, either automatically through energy management systems or manually when alerted of these critical periods through the smart meter. Introduction of consumer decisions for reducing energy usage will provide significant load reduction which may offset investing in new power plants for a few years.

In the next coming years global dependence on conventional energy sources will drive the need for implementing Smart Grids. Conventional energy resources include petroleum, coal, natural gas and nuclear energy. Fossil fuels make up the bulk of the world's current primary energy sources. The technology and infrastructure already exist for the use of fossil fuels. Petroleum energy density in terms of volume and mass ranks currently above that of alternative energy sources. Fossil fuels are currently economical, and suitable for decentralized energy use. Disadvantages on conventional energy sources are listed. Firstly the combustion of fossil fuels leads to the release of pollution into the atmosphere. The fossil fuels are mainly based on organic carbon compounds. They are according to the Intergovernmental Panel on Climate Change the causes of the global warming. Secondly the process of extraction of material and generation of energy from these sources comes at the risk of damage to surrounding environments. One example of such pollution is the Deepwater Horizon Oil Spill near the Gulf of Mexico that brought 39 species close to extinction [2]. Lastly conventional energy sources come at limited supply and these resources could become unavailable in the near future, much sooner than we originally thought.

In order to help keep up with increasing demand and also to reach the goals of European Union of reducing greenhouse gas emission by 20%, renewable energy sources need to be embedded in energy production. Main sources of renewable energy is wind, sunlight, tidal waves, rain and geothermal heat. One major advantage renewable energy has over conventional is the lower environmental effects and the near limitless supply. Renewable energy is based on sources that fluctuate during the course of any given day or season. Large shares of various renewable energy can increase balancing issues between conventional energy and renewable. More flexible generating capacities such as hydro power plants, storage using pumped-hydro plants and load-management through the use of smart grids can help balance incorporating renewable energy to current conventional energy generation.

Smart grid technologies emerged from earlier attempts at using electronic control, metering, and monitoring. In the 1980s, automatic meter reading was used for monitoring loads from large customers, and evolved into the Advanced Metering Infrastructure of the 1990s, whose meters could store how electricity was used at different times of the day [3]. Smart meters add continuous communications so that monitoring can be done in real time, and can be used as a gateway to demand response-aware devices and "smart sockets" in the home. Early forms of such demand side management technologies were dynamic demand aware devices that passively sensed the load on the grid by monitoring changes in the power supply frequency. Devices such as industrial and domestic air conditioners, refrigerators and heaters adjusted their duty cycle to avoid activation during times the grid was suffering a peak condition. Beginning in 2000, Italy's Telegestore Project was the first to network large numbers (27 million) of homes

using smart meters connected via low bandwidth power line communication [4]. Some experiments used the term broadband over power lines (BPL), while others used wireless technologies such as mesh networking promoted for more reliable connections to disparate devices in the home as well as supporting metering of other utilities such as gas and water [5].

Nowadays, many people ask how real the impact from the introduction of smart grid is. The answer is simple: smart grids will bring the utility a lot of benefits. Although not all these benefits will be in monetary form (i.e. reliability and customer satisfaction), some of them will be in a form of monetary reductions from the current costs, other will reduce future costs. Especially in the form of deferred or even cancelled capital investments. Benefits of switching from a typical electrical grid to the Smart Grid greatly outweigh the costs. The previous standard of electrical grid consisted of: generation, transmission, distribution and customers. Smart Grid improves on all four parts of an electrical grid by using technologies such as Home Area Networks, Advanced Metering Infrastructure, Distributed Generation, Demand Response, Energy Storage Units and Smart Charging. In general, advantages of switching over to Smart Grid include: increased network reliability through self-healing and fault detection, flexibility in network topology using bidirectional power flow to further increase the involvement of renewable energy sources in generation, load balancing by automatically reducing peak load, peak leveling and time of use pricing allowing customers to pay cheaper electricity bills by shifting their loads on off-peak times and increased sustainability by permitting a greater penetration of renewable energy sources.

In conclusion Smart Grid offers a lot advantages over a typical electrical grid at the cost of having to replace ageing infrastructure. It is however a necessary tool that needs to be implemented in order to efficiently meet our growing energy needs as a society minimizing our impact on the environment.

1.2 Design Introduction

The primary goal of this research is providing a Smart Grid to i) reduce peak load and ii) reduce cost for end consumers. To achieve this goal the Smart Grid utilizes:

- Millions of real-time communicating smart meters.
- Individual energy storage units per household.
- Fuzzy controllers incorporated within smart meters that control the charge levels of the energy storage unit.

The secondary goal of the proposed design is to maximize the efficiency of renewable energy resources as well as realize a reliable and sustainable future electricity grid even if the future load is uncertain and renewable generation is highly variable and unpredictable.

The approach which was decided to be implemented was based on Mamdani's Fuzzy Inference System. This approach reached more than satisfactory levels of cost reduction and grid load shifting from peak times. The proposed design was tested using real-time datasets. Results extracted from simulation indicated that the design exceeds expectations and performs admirably.

1.3 Overview of Chapters

The chapters are organized as follows

Chapter One:

This chapter introduces the current state of a typical electrical grid and what advantages a smart grid has to offer.

Chapter Two:

This chapter gives a detailed overview of currents practices in smart grid technology. Information about all technologies featured in Smart Grid technologies are presented and explained in this chapter.

Chapter Three:

This chapter gives some background information of the design of fuzzy controllers and on Fuzzy Logic Systems. Moreover, the Datasets which were used are presented along with an overview of the General Schema of the design of the present grid model.

Chapter Four:

This chapter gives an overview of the proposed Mamdani's Fuzzy Inference System for the present work.

Chapter Five:

This chapter presents the steps used in implementing the proposed Fuzzy Inference System using Matlab software for the present work.

<u>Chapter Six:</u>

This chapter presents the results that were achieved during the simulation of the design using Matlab software.

<u>Chapter Seven:</u>

This chapter gives a summary of the conclusions that were extracted during this research and the future work that is planned.

2

Smart Grid Overview

2.1 Introduction

Today's electricity networks need to overcome many obstacles such as, load increase and deregulation as well as power plant problems. These problems are caused by the fact that the system is made up from aging infrastructure and as such was not designed to operate at current levels. As a result sub-optimal power quality and often blackouts are caused [6]. The constant increase in demand yearly and the aging components of the electricity network make it difficult to keep the system running and up to date. The grid has to become more modern and smarter, generating, transmitting and distributing electricity efficiently and in a more optimal way.

Smart Grid offers a solution to the increasing complexity of current electricity networks which is caused by different causes like the non-linearity of the system, dynamic behavior and uncertainties. The rapid advancement in technology makes the current system even more complex by having to implement technologies such as electric cars and the utilization of renewable energy in an efficient manner. Smart grid offers a possible solution to this added complexity through optimal power flow, management of data and communications and efficient control of all power sources.

2.2 Current state of Energy Systems

2.2.1 Management of Conventional Energy Sources

An electrical grid is a one-way network responsible for delivering electricity from generating power plants to end consumers. Generating power plants are usually located far away from highly populated areas, often close to fuel sources, dams or near water sources when it comes to nuclear energy. Power plants are large in size to take advantage of economies of scale and generate electricity which is later converted to high voltages where it is transferred to the transmission network. The transmission network transfers electricity long distance, even across international borders at times, till it reaches a substation where it is converted in lower voltage in order to fir the distribution grid. Exiting the substation, electricity enters the distribution wiring until it arrives the service location where it will be turned down in voltage to the required service voltage, 230V for Greece [7].

2.2.2 Management of Renewable Energy

Managing renewable energy is a lot different and a lot more difficult than conventional energy sources. Renewable energy integration brings problems in regards to all three operations of an electrical grid. Generation of renewable energy faces the problem of decentralized power generation. For example wind turbines are spread across vast geographical regions where strong wind speeds are often, with both offshore and onshore wind turbines [8]. Another drawback is that renewable energy such as wind or solar depends on weather conditions and becomes available to the grid operator at random times during the day. The grid operator has limited control over when renewable energy becomes available and cannot program for it.

Efficient integration of renewable energy is a serious problem for modern day electricity systems and without the introduction of Smart Grids it will be near impossible. Customers and utility will both benefit from a true integration of renewable energy generation into the current system. With the majority of European countries racing towards meeting the "20/20/20" goal by 2020, 20% reduction in greenhouse gas emissions, 20% increase in the share of renewable energy sources in energy production and a 20% reduction in energy consumption, introducing Smart Grids is necessary [9].

2.3 Smart Grid

A Smart Grid is the technology that brings the electric network to the digital age. Upgrading to a Smart Grid enables the electric grid to be informed of cases that can affect supply and demand for power, allowing the grid to respond to these changes and at the same

time use these changes as input in determining prices real time. Cases such as transformer failures, or weather conditions affecting demand, such as extreme cold or heat waves, can be addressed.

The need for an efficient electric grid system emerged for three main reasons. The accelerated growth of decentralized energy, more precisely in the form of renewable energy sources, secondly the liberalization of power markets and the competition that came with it and thirdly the need of reducing greenhouse-gas emissions through the efficient use of energy [10]. A Smart Grid adds intelligence and automation to all parts of an electricity system, from generation to distribution. As far as generation is concerned, decentralized, renewable, small scale power plants are connected through broadband connections to centralized generation and then embedded to the electricity system. Optimal power flow is achieved through communication systems and intelligent software that balances the generation of centralized and decentralized sources, while also ensuring a reduction in energy waste.

2.3.1 Self-healing

One of the main features of Smart Grids that will enable the electricity network to join the 21st century is the ability of self-healing. Equipping a grid with self-healing ability enables it to respond to threats, material failure and other unexpected problems. System monitoring and real-time reaction is achieved by using phasor measurement units (PMU) and other sensors to monitor voltage and current parameters of a specific area. This allows for observing the performance of generation and discovers any problems that could cause a disturbance.

Self-healing requires an intelligent communication and monitoring system, such system enables fault-tolerance allowing the system to operate properly in case of errors, threats, failures and unexpected problems. The electricity infrastructure is highly interconnected which makes them suitable for intelligent self-healing technology. Through the use of intelligent agents that simulate the operation of a human being, they can sense and measure parameters for every component involving generation and communication within the network. Intelligent agents are used at all levels of an electricity network, and utilized to monitor the operation and management of the system while also allowing the remote and real-time control of it and self-healing ability [11].

2.3.2 Advanced Metering Infrastructure

Advanced Metering Infrastructure (AMI) is a system that measures, collects, and analyses energy usage data from advanced devices, such as electricity/gas/water meters. The

data can be sent back and forth using a two-way communication network. The energy usage statistics can be collected upon request or on a pre-defined schedule.

The AMI includes hardware, software, communications, and customer systems and meter data management software. Therefore, AMI can be explained as a two-layer structure: application layer and transport layer [12]. The application layer is responsible for data collection and analysis, operational control, and real-time monitoring. The transport layer is responsible for a two-way information transfer between utility and customer. The usage of various network protocols such as LAN, WAN and HAN enables all the stages of the communication network to function.
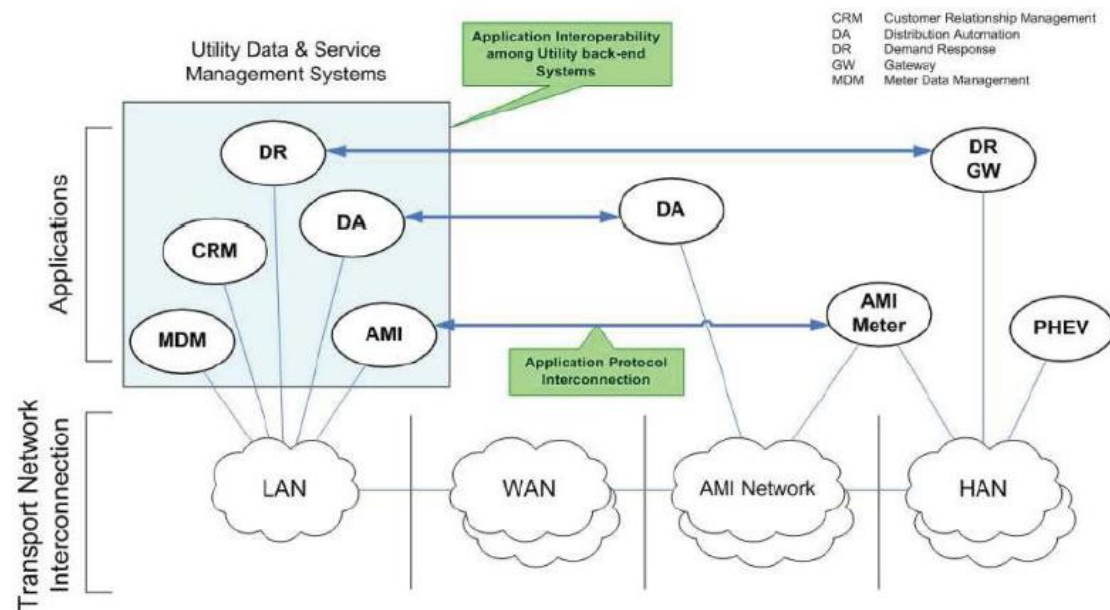
Figure 2-1: Structure of AMI Communications Network   (Source EKA-Systems.com)

2.3.3   *Demand Response*

Practically speaking, electricity cannot be easily stored on a large scale. As a result, supply and demand must remain in balance in real time. Traditionally utilities have leveraged peaking power plants to increase power generation to meet demand. Demand response works from the other side of the equation – instead of adding more generation to the system, it pays energy users to reduce consumption. Utilities pay for demand response capacity because it is typically cheaper and easier to procure than traditional generation. Demand response solutions range from simple advanced metering systems to fully automatic home systems.

Historically, the customer loads of electricity distribution systems have mostly been uncontrollable. The load of a customer seen by different market players (distribution, transmission, supplier, and aggregator) has only depended on the behavior of the customer and the related appliances. The average load profiles of equal types of days and hours (working days, Saturday, Sunday) are quite stable. The load profiles depend mainly on weather conditions and duration of day light. The distributed generation and energy storage resources at the customer load have been negligible.

Recent advancements in technology (like Smart Metering, Home Area Networks, Power Electronics, batteries) allow changing from a static consumer grid connection to a multifunctional interactive network for electricity market players. A demand response system is comprised from two components: a smart load controlling device and a smart meter. Additional features of demand response include a display that allows continuous interaction between consumer and utility grid and a website where a customer logs in that contains information about electricity usage and tariff-schemes available for selection.

Demand response offers a cheaper, cleaner and more reliable solution on handling peak load hours than adding a new power plant. Both utilities and consumers benefit from introducing this solution. Consumers will shift their load to off-peak hours where electricity is cheaper and utilities will save money by not having to retain spinning reserve generators for handling peak load. The fact that both parties will save money will be a huge driver for adoption of demand response technique.
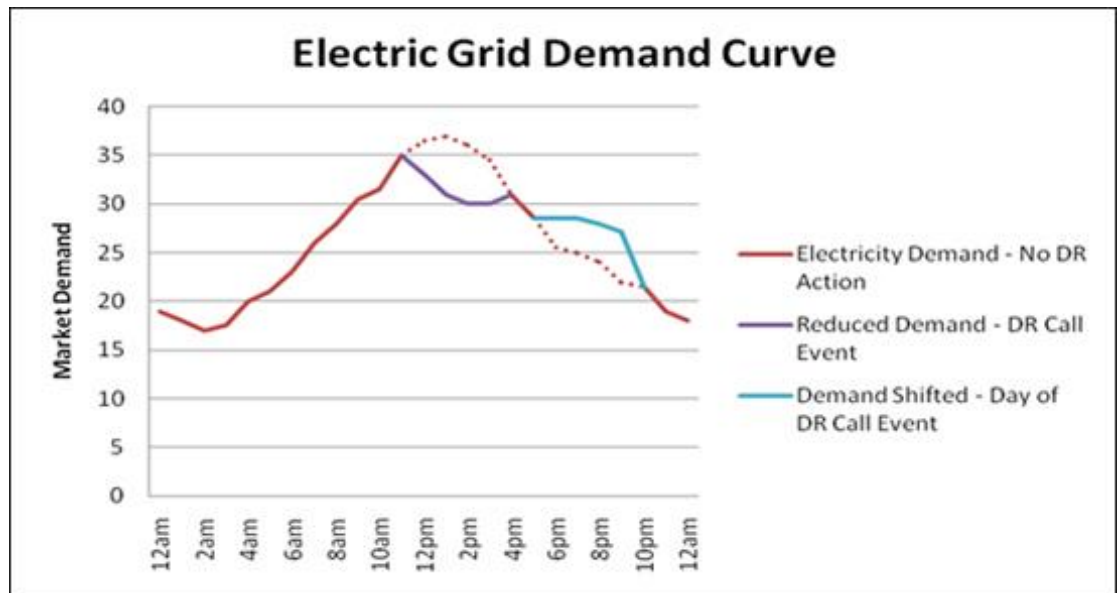
Figure 2-2: Demand Response example of reducing peak Load (Source: greenbiz.com)

2.3.4 Home Area Network

A home network or home area network (HAN) is a type of local area network with the purpose to facilitate communication among digital devices and appliances present inside or within the close vicinity of a home. HAN is an important tool as a component of a Smart Grid. It enables Smart Grid applications to communicate with various home appliances.

HAN is considered an extension of Advanced Metering Infrastructure, making possible two-way communication between electric appliances or devices, users and utility. Utilizing a real-time monitoring system, a HAN allows a customer to manage smart home appliances in order to take advantage of the time-of-use tariff system. The Smart Meter control system automatically gets notified of price rates at time of use according to generation/consumption data.
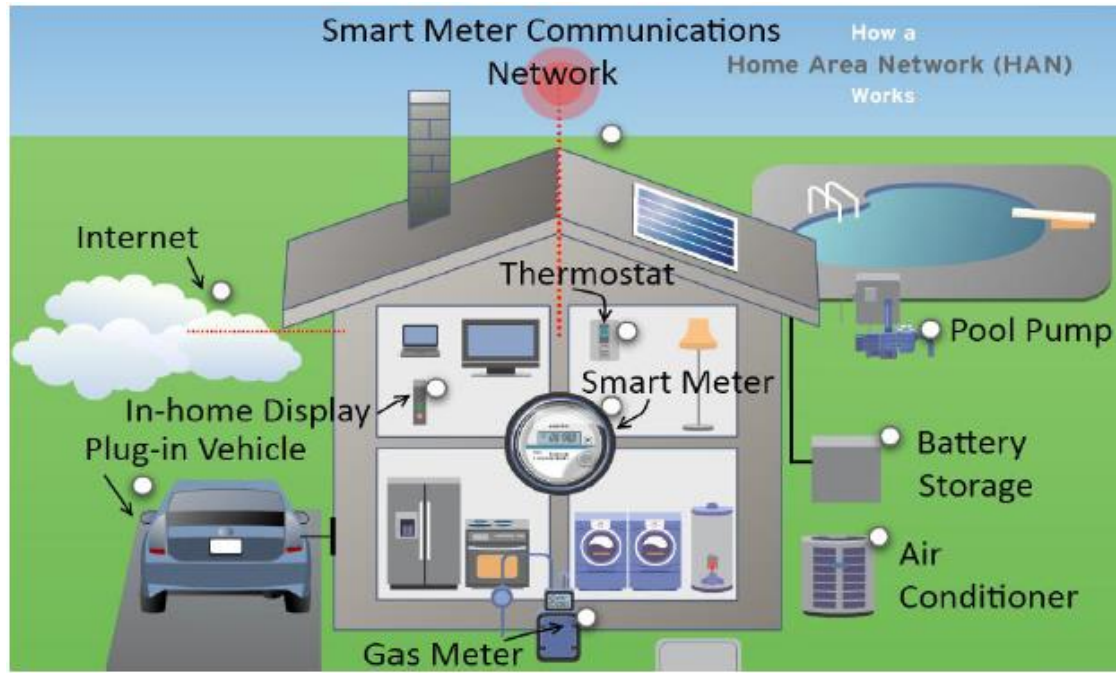
Figure 2-3: Home Area Network (Source electronicdesign.com)

2.3.5 Energy Storage Units

Energy storage is defined as a method of storing certain forms of energy in order to perform certain operations at a later time [13]. Different forms of energy storage include: chemical, biological, electrochemical, electrical, mechanical, thermal and fuel conservation storage etc. A next generation grid without the capabilities energy storage has to offer is extremely limited. Energy storage, distributed across the electricity grid, are able to provide dispatchable power to be used during peak hours, thus allowing power suppliers and end consumers to balance supply and demand. By properly utilizing energy storage we can eliminate the use of expensive power plants that are used as means to overcome the difficulties of peak load at certain times. This technology also makes distribution networks less likely to rapidly and unpredictably change as it will help smooth out the load. As a result customers will avoid consumption at high-price tariffs.

Another major reason as to why energy storage is a must-have for a next generation grid, is that energy storage solutions are crucial for storing energy from renewable generators like wind and solar. These forms of energy are produced in certain times, times where extra energy is not necessarily needed. As a result, energy storage solutions are an extremely important part of an electricity grid, increasing the efficiency in which renewable energy is utilized therefore decreasing greenhouse gas emissions.

2.3.6   Smart Charging

Electric Vehicles (EV) become more and more popular nowadays. Therefore, a question of charging of the EVs emerges. Electric vehicles can disturb the power system in a major way, adding additional peaks to the already observed variable renewables peaks. But, if used smartly, they hold a great promise to making the system more fit for the future – as storage, flexible demand conducive to renewables integration and grid support. The answer to the negative and the positive scenario is the same: smart charging. In addition to delivering benefits for the power system, smart charging also helps to achieve a more sustainable, low-carbon transport. Electric vehicles are cleaner, quieter and two to three times more energy efficient compared to conventional cars. Equally important, it adds value to the customer by maximizing convenience of recharge and reducing costs.

It is a task of software applications to design EV charging station in such a way that cars would charge during off-peak times (e.g. after 9 p.m.). Both customer and the grid utility will benefit from it. The off-peak charging will smooth the load while reducing the price of electricity (e.g. night tariff will be used).
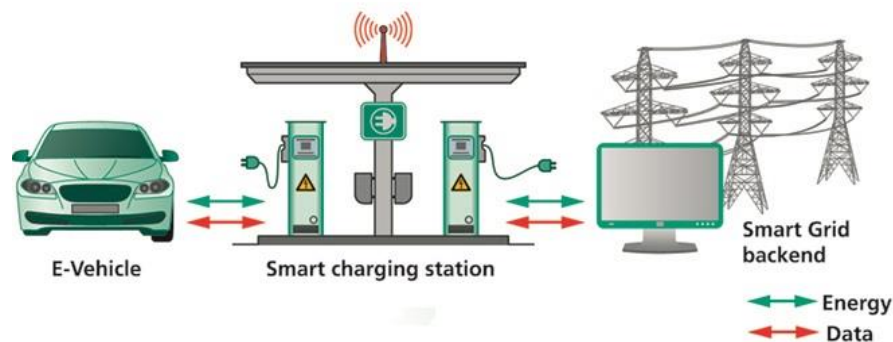
Figure 2-4: Smart Charging concept (Source: chargedevs.com)

2.3.7   Distributed Generation

Integrating renewable energy sources to an electrical grids power generation capacity can be a tricky task, despite the fact that they have been utilized for many years. Distributed generation (DG) is an approach that employs small-scale technologies to produce electricity close to the end users of power. DG technologies often consist of modular (and sometimes renewable-energy) generators, and they offer a number of potential benefits. In many cases,

distributed generators can provide lower-cost electricity and higher power reliability and security with fewer environmental consequences than can traditional power generators.

In contrast to the use of a few large-scale generating stations located far from load centers--the approach used in the traditional electric power paradigm--DG systems employ numerous, but small plants and can provide power onsite with little reliance on the distribution and transmission grid. DG technologies yield power in capacities that range from a fraction of a kilowatt [kW] to about 100 megawatts [MW]. Utility-scale generation units generate power in capacities that often reach beyond 1,000 MW.

In order to reach mass penetration of renewable energy sources, electrical grids must be able to deliver energy directly to end-users. Microgrid is an independent, small and self-reliant grid that generates and stores the power for the consumers within it. The microgrid can be connected to the conventional distribution grid during normal operations, but in case of any faults on the distribution grid side the microgrid can be isolated. While being isolated or 'islanded' it will be able to continue to meet the electric requirements independent of the distribution grid. The same can work in the opposite directions: the owners of renewable energy sources inside the microgrids can sell the energy back into the distribution grid or even directly to a neighbor across the street.
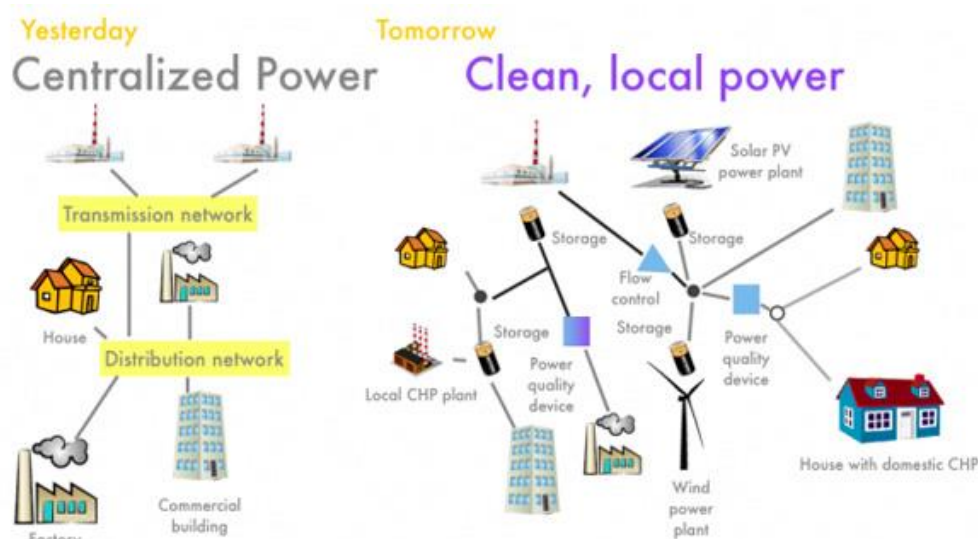
Figure 2-5: Distributed Generation(Source microgridknowledge.com)

3

Proposed Fuzzy logic optimal power flow control system using Energy Storage Unit solutions

In this chapter, I propose a fuzzy logic based solution for Energy Management Systems consisting of Energy Storage Units. In this research, a hypothetical Energy Storage Unit with no loss and zero maintenance cost is used, in order to simplify calculations. The proposed Fuzzy Logic System makes use of real time hourly price and grid load as inputs to the fuzzy inference system and using it to calculate whether or not the Energy Storage Unit will charge or discharge and at what level. Real time data are critically important for effective and efficient strategies regarding the electricity market and more importantly when referring to a Smart Grid.

Section 3.1 gives background information on fuzzy logic. Section 3.2 presents the framework of the proposed design. Section 3.3 discusses the details of the proposed fuzzy logic control system.

3.1 Background Information of Fuzzy Logic and Fuzzy Controllers

Fuzzy logic is an approach to computing based on "degrees of truth" rather than the usual "true or false" (1 or 0) Boolean logic on which the modern computer is based.

The idea of fuzzy logic was first advanced by Dr. Lotfi Zadeh of the University of California at Berkeley in the 1960s. Dr. Zadeh was working on the problem of computer understanding of natural language. Natural language (like most other activities in life and indeed the universe) is not easily translated into the absolute terms of 0 and 1. (Whether everything is ultimately describable in binary terms is a philosophical question worth pursuing,

but in practice much data we might want to feed a computer is in some state in between and so, frequently, are the results of computing.)

Fuzzy logic includes 0 and 1 as extreme cases of truth (or "the state of matters" or "fact") but also includes the various states of truth in between so that, for example, the result of a comparison between two things could be not "tall" or "short" but ".38 of tallness."

Fuzzy logic seems closer to the way our brains work. We aggregate data and form a number of partial truths which we aggregate further into higher truths which in turn, when certain thresholds are exceeded, cause certain further results such as motor reaction. A similar kind of process is used in artificial computer neural network and expert systems.

Fuzzy controllers are used to control consumer products, such as washing machines, video cameras, and rice cookers, as well as industrial processes, such as cement kilns, underground trains, and robots. Fuzzy control is a control method based on fuzzy logic. Just as fuzzy logic can be described simply as "computing with words rather than numbers'', fuzzy control can be described simply as ''control with sentences rather than equations''. A fuzzy controller can include empirical rules, and that is especially useful in operator controlled plants.

There is no design procedure in fuzzy control such as root-locus design, frequency response design, pole placement design, or stability margins, because the rules are often nonlinear. Therefore we will settle for describing the basic components and functions of fuzzy controllers, in order to recognize and understand the various options in commercial software packages for fuzzy controller design.

The purpose of Fuzzy Logic is to map an input space to an output space with a human-thinking like mechanism. This mechanism is consisted of a series of if-then statements called rules. All rules are evaluated in parallel and the order of the rules does not affect the result. See Appendix B.

3.2 Datasets Used

Datasets were collected from ISO New England Inc, freely available online. See Appendix E. The necessary data for a proper simulation are hourly grid load and electricity price. [17].

The proposed Fuzzy Logic System makes use of real time hourly price and grid load as inputs to the fuzzy inference system and using it to calculate whether or not the Energy Storage Unit will charge or discharge and at what level. Real time data are critically important for effective and efficient strategies regarding the electricity market and more importantly when referring to a Smart Grid.

3.3 Proposed Design Structure

3.3.1 Power Smart Pricing

The proposed design takes advantage of the Smart Meter being integrated between the distribution network and end consumer to achieve two goals.

Firstly: reduce the end users monthly bill.

Secondly: to shift peak load thus avoiding overload and blackout cases. By enabling intercommunication between power suppliers and the end consumer, the Smart Meter informs the end consumer with real time price and grid load. The proposed design structure is shown below in Figure 3-1.
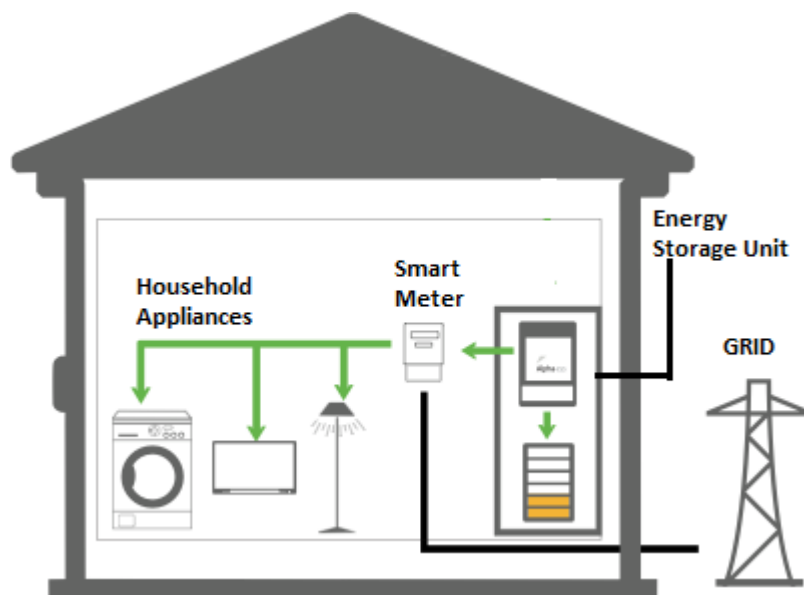
Figure 3-1 Proposed Smart House with ESU. Bidirectional power flow from both the electrical grid and the energy storage unit.

Figure 3-1 shows a modernized household equipped with Smart Meter and Energy Storage Unit, along with all other household appliances such as air-conditioning, washing machine, lighting, television, etc. The house in Figure 3-1 is physically connected to the distribution grid. The owner of the house pays for the power consumption on a monthly basis in the conventional way. However, there is something different called *Power Smart Pricing* applied in the proposed design. Power Smart Pricing indicates that the price customers pay for electricity varies from hour to hour, depending on the actual market price. The prices are set a day ahead by the hourly wholesale electricity market run by the power supplier. Power Smart Pricing has been applied by a few power suppliers such as ISO New England and Ameren Illinois.

3.3.2 Smart Meter in the Proposed Design

The Smart Meter is the brain of the proposed design:

Firstly it is responsible with maintaining a constant connection between the end consumer residence house and the distribution grid. Real time data regarding grid load and hourly power price are sent from the power suppliers through the smart meters two-way communication. On the other end, power suppliers are sent data informing them of the hourly power consumption of each individual house called the household load. So that power supplier gets informed about household Load of every single family on a real time basis. After all these information being collected and organized, power supplier will get an accurate grid load for some certain area of its coverage. This information will be helpful in every aspect of grid management and price determination.

Secondly, it is responsible for directing power flow between the distribution grid and redirecting it to household appliances and the Energy Storage Unit.

The Smart Meter is also in charge of controlling the two switches directing power flow between the distribution grid and the household appliances.

The first switch controls when to draw power from the grid called "Grid Switch".

The second one controls when the ESU will charge or release power called the "ESU switch".

Basically, the Smart Meter is needed for controlling the "ESU Switch" which determines the state in which the ESU will work on.The Smart Meter is also responsible for maintaining a steady power flow to household appliances and also making sure the ESU does not charge beyond 100% capacity.
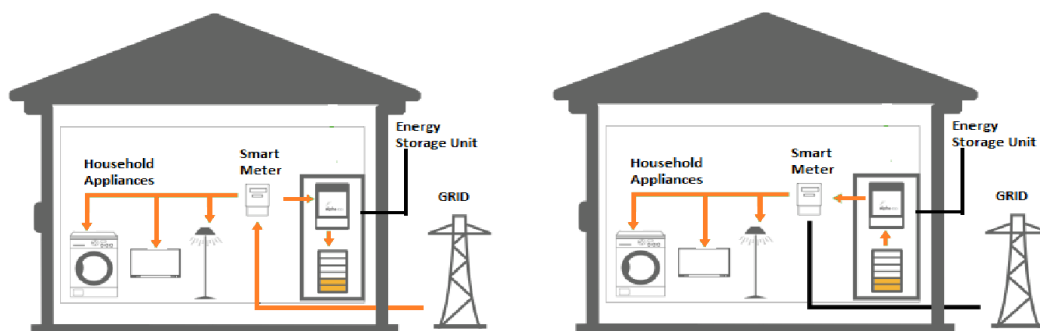
Figure 3-2 The flow of electricity when the Grid Switch is closed and the ESU Switch is open.

In Figure 3-2 the connection between household appliances and the ESU via the control of the Smart Meter is illustrated. The ESU has two basic states: "ESU Charge" and "ESU Release". The first state, "ESU Charge", means that the ESU is drawing power from the distribution grid when such available power comes at a low enough price. The second state,

"ESU Release", means that the household appliances are drawing power from the ESU, implying that power from the distribution grid is expensive.

3.3.3 *Energy Storage Unit in the Proposed Design*

The Energy Storage Unit makes up the second most important component of the Proposed Design. The ESU, as already mentioned, has states of "Charge" and "Release" which are controlled by the Smart Meter via the "ESU Switch", which in turn controls power flow to the ESU unit. These two states however are not sufficient and some intermediate states need to be introduces to make our system more accurate and precise. Because of this we allowed our system to work on a wide range of states such as "Charge 75%", telling the ESU to charge with drawn power equal to 75% of the household power drawn or "Release 25%" thus releasing stored power equal to 25% of the household power drawn.

The ESU is a means to store cheap energy during off-peak hours and later using it at peak hours where energy price is more expensive in order to save energy, reduce costs and also reduce the overall grid load. Different forms of energy storage include: chemical, biological, electrochemical, electrical, mechanical, thermal and fuel conservation storage etc.

Nowadays, most companies offer solutions consisting of Lithium-Ion batteries. These batteries can typically store energy with capacities ranging from 4.4kWh to 13.2kWh. Some solutions offered are the Tesla Powerwall offering 7kWh capacity, the Bosch BPT-S 5 Hybrid with 4.4 to 13.2 kWh capacity and a service life of 7000 charge and discharge cycles and the Samsung ESS with capacities of 5.5kWh and 8kWh [17][18][19]. However these solutions come with extra cost associated with the maintenance of the storage unit as well as the fact that these devices lose power storage capacity over time. In the proposed design we assume zero loss of power storage capacity over time and a zero maintenance cost, as to simplify the problem and focus on the benefits of ESU integration on a Smart Grid without the disadvantages of current battery technologies.

In summary, the proposed design is made from an ESU that has zero maintenance cost, zero performance downgrade over time and more accurate and precise "Charge" and "Release" states. By allowing Energy Storage Unit to works in a more accurate way, the proposed design can fit in some more complex situation. This fact offers great potential to develop an intelligent strategy based Energy Management System. In next chapter, an intelligent strategy will be presented using a Fuzzy Inference System to control the different states of the ESU as to save energy and lower the total Grid Load.

3.4 Working States of the ESU

A hypothetical house with 1000W installed appliances is used for simulation purposes, connected to a Smart Grid and with an ESU installed. Using some simple formulas a total household consumption can be calculated per hour with the addition of the ESU. During each of the working states of the ESU, its power drawn or released can vary between "Release100%" and "Charge100%". The power consumption of the household can be calculated as follows:

Table 3-1 Explanation of the variables used to calculate ESU working states

Variable	Description
TPD[h]	Total power demand of entire household (including ESU and Household Appliances) during hour h
C[h]	Power drawn from the grid by the ESU during hour h
HA[h]	Power drawn from the grid by household appliances during hour h
R[h]	Power released to appliances by the ESU during hour h
x[h]	ESU working state during hour h

Therefore the total power demand for the entire household during a specific hour h is calculated according to equation 3-1

$$TPD[h] = C[h] + HA[h] + R[h] \qquad (3\text{-}1)$$

Working states of the ESU determine whether the ESU is charging or releasing power and at what percentage of the current household appliances power drawn. The working state of the ESU is calculated by the Fuzzy Logic system and is given as x[h].

Below are some example explaining the working states of ESU.

While x[h] > 0, ESU is charging and R[h] = 0.

Example1

$x[h] = 1$

$C[h] = 1 * HA[h] = HA[h]$.

$$TPD[h] = C[h] + HA[h] + R[h] = HA[h] + HA[h] + 0 = 2 * HA[h].$$

This means that the ESU is charging at 100% of household hppliances and household appliance demand is drawn from the grid. Assuming that household appliances installed power is 1000W and 600W are currently in use, the total power being drawn at hour h would be: 600Wh for appliances and 600Wh for the ESU making the total demand 1200Wh for hour h.

Example2

$x[h] = 0.5$

$C[h] = 0.75 * HA[h] =$

$TPD[h] = C[h] + HA[h] + R[h] = 0.75HA[h] + HA[h] + 0 = 1.5 * HA[h].$

This means that the ESU is charging at 50% of household appliances and household appliance demand is drawn from the grid. Assuming that household appliances installed power is 1000W and 600W are currently in use, the total power being drawn at hour h would be: 600Wh for appliances and 300Wh for the ESU (50% of 600Wh) making the total demand 900Wh for hour h.

While x[h] < 0, ESU is releasing and C[h] = 0.

Example 3

$x[h] = -1$

$R[h] = 1 * HA[h] = HA[h]$

$TPD[h] = C[h] + HA[h] + R[h] = 0 + HA[h] - HA[h] = 0$

This means that the ESU is releasing at 100% of household appliances and household appliance demand is being met by the ESU alone making drawing from the grid not necessary.

Example 4

$x[h] = -0.5$

$R[h] = 0.75 * HA[h]$

$TPD[h] = C[h] + HA[h] + R[h] = 0 + HA[h] - 0.5HA[h] = 0.5 HA[h]$

This means that the ESU is releasing at 50% of household appliances and household appliance demand is being met by the ESU by 50% while the rest 50% is being drawn from the Grid. Assuming that household appliances installed power is 1000W and 600W are currently in use, the total power being drawn at hour h would be: 600Wh for appliances of which 300Wh are supplied by the ESU releasing energy at 50% of household making the total demand drawn from the grid 300Wh for hour h.

While x[h] = 0, ESU is not releasing or charging and C[h] = 0 and R[h] =0.

Example 5

$x[h] = 0$

$TPD[h] = C[h] + HA[h] + R[h] = 0 + HA[h] - 0 = HA[h]$

Cases like this example means that the ESU has been fully charged and power price is cheap enough and grid load low enough that the ESU does not need to release energy. During this state the ESU is neither releasing energy neither charging.

In Chapter 4 the proposed Fuzzy Inference System is discussed and shown in full detail.

4

Design of the Fuzzy Logic Smart Grid Model

Controller

In this chapter, the construction of a Fuzzy Logic controller (FLC) is discussed. First the essential components needed to construct a Fuzzy Logic Controller are introduced, followed by the model creation in Matlab.

4.1 Structure of a fuzzy controller

A Mamdani type Fuzzy Logic Controller is made of four components as show in the block diagram in Figure 4-1:

1. Fuzzification

2. Rule Base

3. Inference Engine

4. Defuzzification
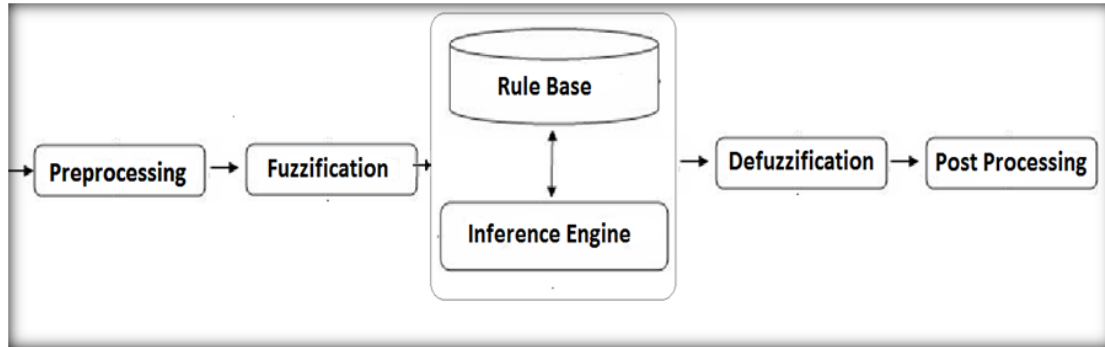
Figure 4-1 Block components of a typical Fuzzy Logic Controller

4.1.1   Fuzzification

As discussed previously in section 3.1, a fuzzy system works in a way similar to the human brain and thus includes degrees of truth to a statement instead of "true" or "false" like Boolean logic. In the proposed system, electricity price of 25 €/MWh can be considered both .50 "cheap" and .43 "medium" as shown in figure 4-2 on the membership function of input price. In this step, input of power price and grid load are being fuzzified through the membership functions. Before the Fuzzification step power price values ranged from 19.94 to 558 /MWh and grid load ranged 8294 to 27707 MWh. After the fuzzification takes place price is defined as "cheap", "medium" and "expensive", while grid load is defined as "low" and "high" .
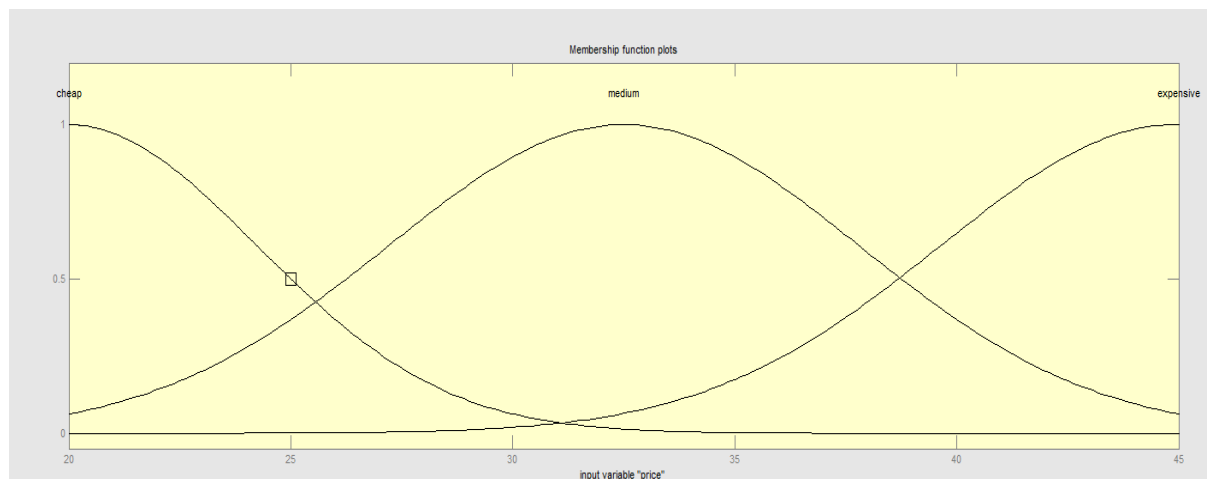
Figure 4-2 Price Membership Function. This specific membership function is of Gaussian type. Cheap is defined between 20-34 €/MWh, Medium 20-45 €/MWh and Expensive 27-45 €/MWh.

4.1.2 Fuzzy Rule Base

4.1.2.1 Rule formats:

The fuzzy reasoning process involves data and linguistic control rules or in plain words "if then" rules. This is what is called a Fuzzy Rule Base. After the Fuzzification of inputs, the Fuzzy Logic Controller performs what is called Application of Implication Method for the input set, in our case the Fuzzified Power Price and Grid Load, to each rule separately. The Fuzzification process basically maps inputs to different fuzzy sets. As mentioned before a power price of 25€/MWh can be considered both .50 "cheap" and .43 "medium". The same applies to grid load, a grid load of 13500 MWh can be considered both low (0.2) and high (0.5). The Implication method examines how much this set of inputs applies to each rules as shown in Figure 4-3.
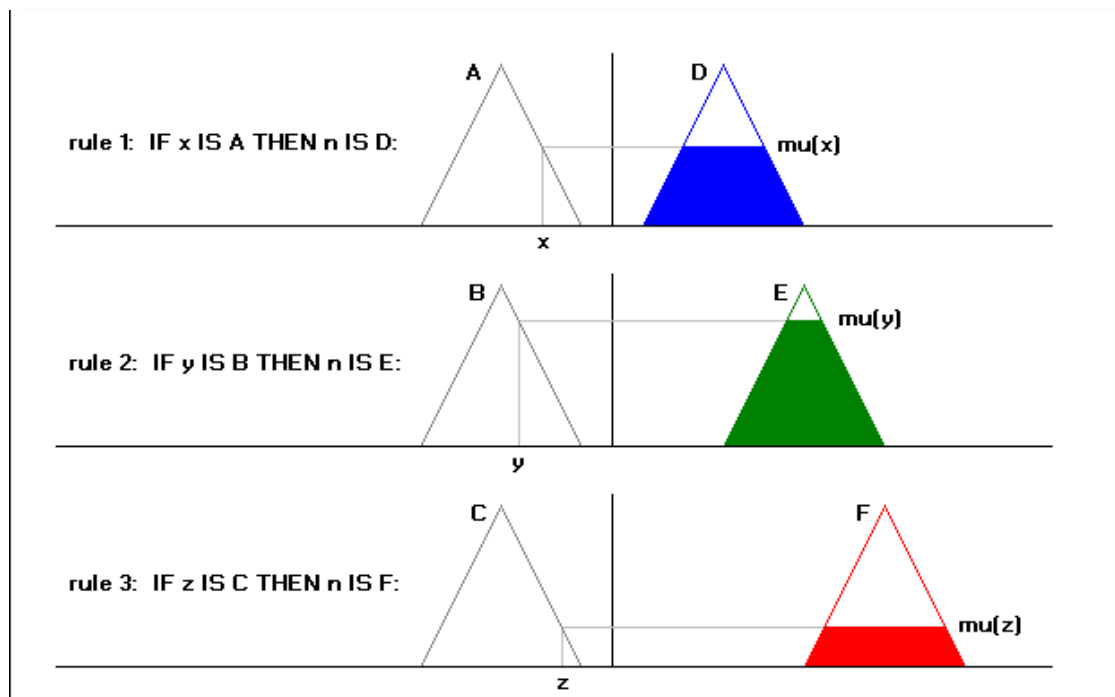
Figure 4-3 Implication Method on Fuzzy Rule set. Variables x, y, z are used as examples for Membership Functions A, B and C.

4.1.2.2 Connectives:

In mathematics, sentences are connected with the words *and, or, if-then* and *if and only if*, or modifications with the word *not*. These five are called *connectives*. It also makes a difference how the connectives are implemented. The most prominent is probably multiplication for fuzzy *and* instead of minimum.

4.1.2.3 Modifiers:

A linguistic *modifier,* is an operator that modifies the meaning of a term. For example, in the sentence *"very close to 0"*, the word **very** modifies *Close to 0* which is a fuzzy set. A modifier is thus an operation on a fuzzy set. *The modifier **very*** can be defined as squaring the subsequent membership function *e.g.* **very a = a².**

4.1.2.4 Universes:

Elements of a fuzzy set are taken from a *Universe of discourse* or just *universe*. The universe contains all elements that can come into consideration. Before designing the membership functions it is necessary to consider the universes for the inputs and outputs. Take for example the rule

The Fuzzy Ruleset can be formed in a combination of user experience, expert's domain knowledge, modeling the action of the operator, process observation and gradual learning. In the proposed design a set of tests with different rules and fuzzy sets were carried out to see which ones gave the better results. A full list of the rules and fuzzy sets will be shown later in section 4.2 showing the process of a fuzzy inference system implementation using Matlab software.

4.1.3 Fuzzy Inference Engine

The Inference Engine (reasoning mechanism) is the kernel of the Fuzzy Controller. It works with the linguistic variable to obtain the result. The linguistic variables come in the form of words used in day-to-day language expression. This step applies the method known as Aggregation of Output of Rules. Because decisions are based on the testing of all of the rules in a Mamdani's Fuzzy Inference System, the rules must be combined in some manner in order to make the decision. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. The input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. Therefore there are six inputs for this step in the proposed design (see page 30). The output of the aggregation process is one fuzzy set for each output variable as shown in Figure 4-4. Thus there is one output after this step for the proposed design, which later is translated into the ESU charging or releasing levels.
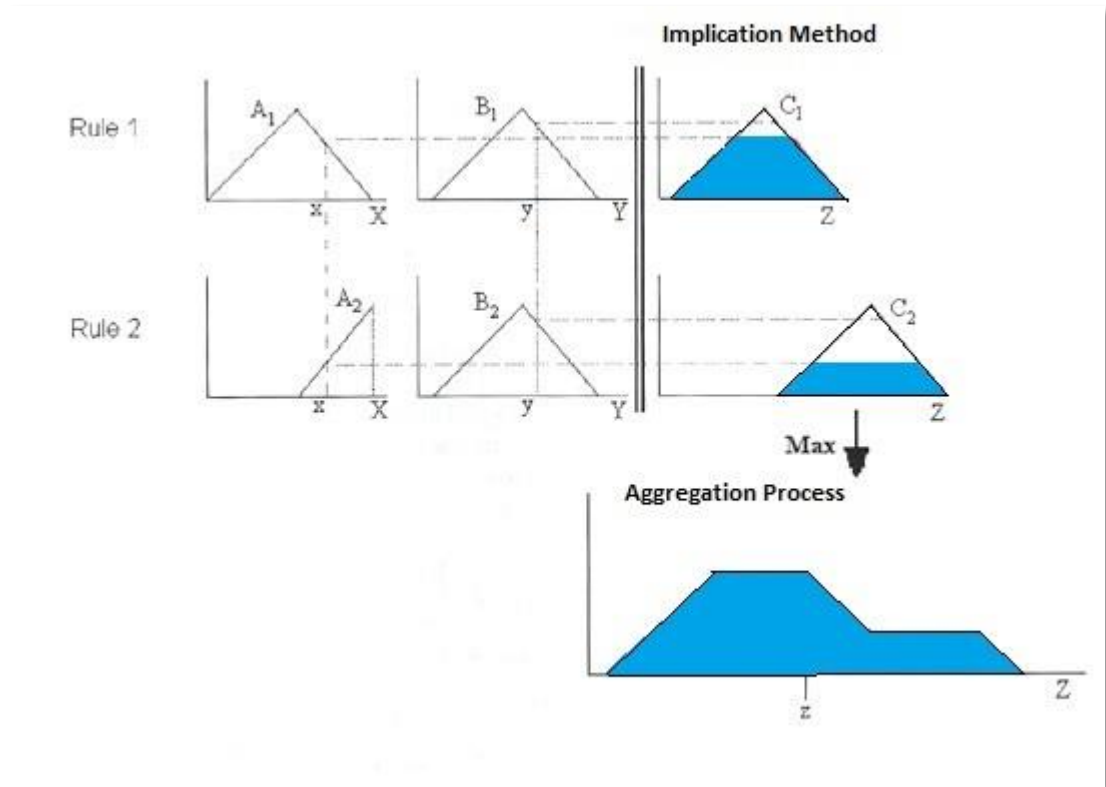
Figure 4-4 Fuzzy Inference System Aggregation Process. Graphical construction of the control signal generated in the Matlab Fuzzy Logic Toolbox.

4.1.4   Defuzzifier – Centroid calculation

The input for the defuzzification process is the fuzzy set from aggregate and the output is the single number x[n] which represents the state that Energy Storage Unit (ESU) should be working on during hour h. The aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set. The most popular defuzzification method is the centroid calculation, which returns the center of area under the curve. Centroid calculation has been applied in the proposed design.

4.2 Fuzzy Controller for the Smart Grid

The Smart Grid Fuzzy Controller is capable of making automated decisions for resource allocation. It takes some predefined inputs, and then based on the given parameters, it decides whether the ESU will charge from the grid if the power price and grid load at the given time are low enough or if the ESU will release power to household appliances as to reduce the overall electricity bill and lower the grid load. The inputs as previously mentioned are Power Price and Grid Load, while the output of the Fuzzy Controller is the ESU working state and the control of the ESU switch and the Grid switch. As shown in Figure 4-5 below.
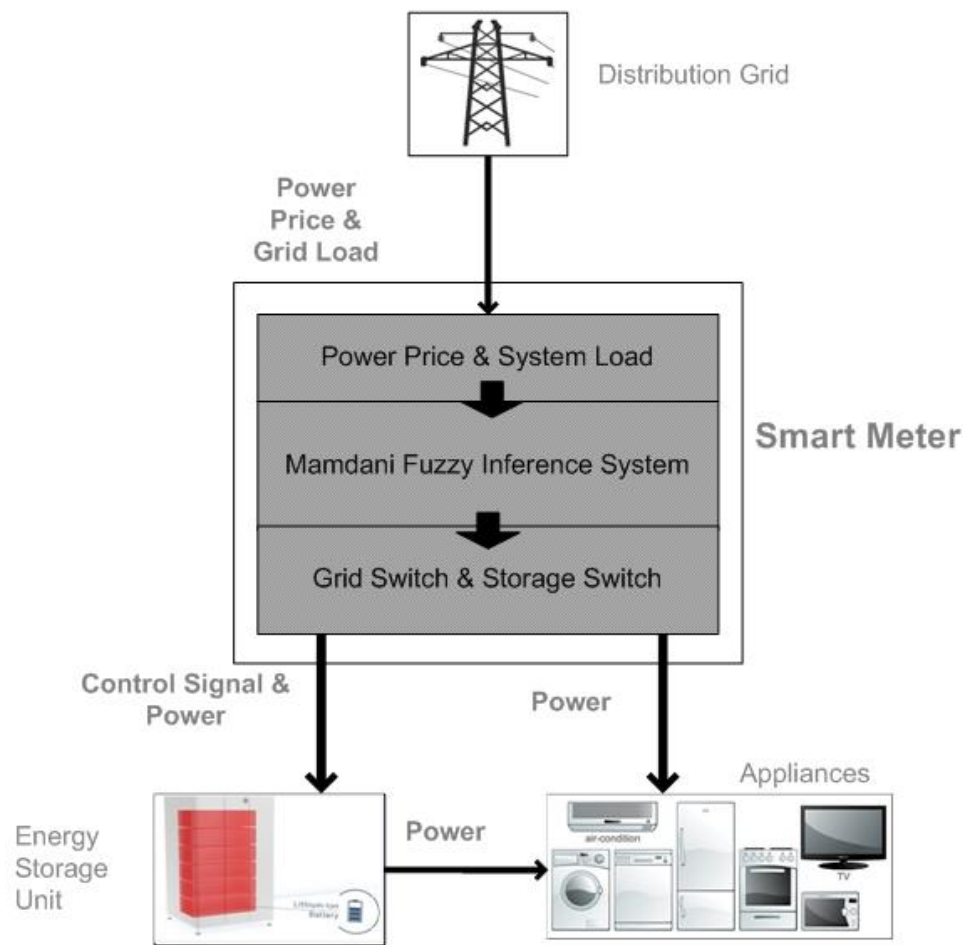
Figure 4-5 Framework of the proposed Fuzzy Logic Controller System.

The Smart Meter is connected to the Distribution Grid, the Energy Storage Unit and household Appliances. It receives information from the Distribution Grid regarding to the hourly Power Price and the current Grid Load. The Fuzzy Logic Controller integrated in the Smart Meter, processes these values as inputs to the Fuzzy Inference System and produce the output signal which controls the ESU release or charge levels and also outputs a control signal for the ESU switch and Grid Switch. This control signal determines how power will flow throughout the house from the following three cases.

Table 4-1 Different states of power flow

Case Study	Power Flow
1	If price and grid load is low enough, the Grid Switch directs power to household appliances from the Grid and also the ESU switch will direct power flow to the Energy Storage Unit so that is charges
2	If power price and grid load are low enough but the ESU is fully charged, the Grid Switch will direct power only to the household appliances and the ESU switch will make sure the ESU does not overcharge.
3	. Lastly if the power price and grid load are high enough, the Grid switch will open thus making the household appliances draw power from ESU.

4.2.1 Proposed Fuzzy Inference System Design

In this section, the details of the proposed design based on Mamdani's Fuzzy Inference System will be presented. Details include fuzzification of input and defuzzification for output, fuzzy operators, and if-then rules. The whole process simulates the process of decision making of human mind. Figure 4-6 illustrates the rules of proposed Mamdani's Fuzzy Inference System. It was proposed as a two-input, one-output and six-rule system. As shown in Figure 4-6, input 1 is power price and input 2 is grid load. Output is the signal that controls ESU. Six rules represent the knowledge base which determines how FIS works. These rules are based on consideration of cost reduction for end consumers and grid stabilization for power supplier. Out of the two considerations, cost reduction weighted much higher than grid stabilization. There are four trends which can be seen from six rules.

- **Trend 1:** When power price is cheaper, ESU is charging more.

- **Trend 2**: When power price is more expensive, ESU is releasing more.

- **Trend 3**: When grid load is lower, ESU is charging more.

- **Trend 4**: When grid load is higher, ESU is releasing more.

These trends are the guidelines towards creating our rules. Trends 1 and 2 are more inclined on i) reducing the overall cost for the customer while on the other hand Trend 3 and Trend 4 are focused ii) on reducing Grid Load at peak times and therefore helping in avoiding blackouts.

Table 4-2 The target that each trend aims to achieve.

Aim	Trend
Reduce the overall cost for the customer	**Trend 1:** When power price is cheaper, ESU is charging more.
	Trend 2: When power price is more expensive, ESU is releasing more.
Reducing Grid Load at peak times	**Trend 3**: When grid load is lower, ESU is charging more.
	Trend 4: When grid load is higher, ESU is releasing more.
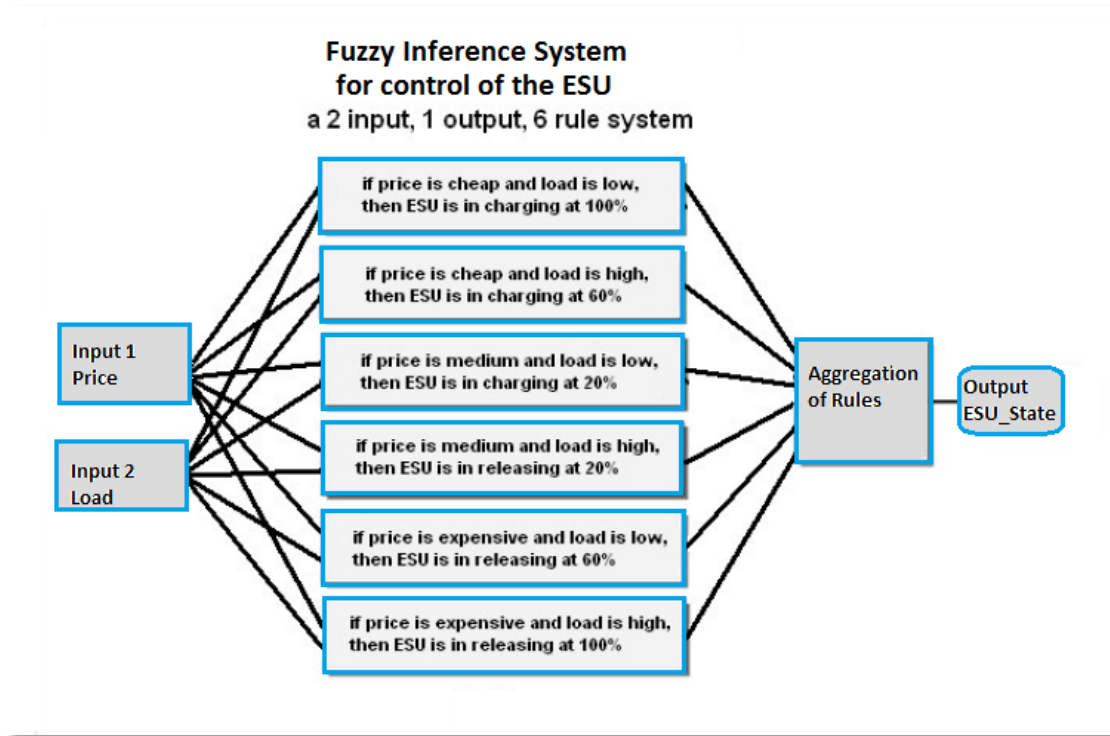
Figure 4-6 Ruleset of Proposed FIS. Six rules in order to achieve the trends of Table 3.

Table 4-3 Ruleset of proposed design

Rule No.	Rule
1	If price is cheap and load is low, then ESU is charging at 100%.
2	If price is cheap and load is high then ESU is charging at 60%.
3	If price is medium and load is low, then ESU is charging at 20%.
4	If price is medium and load is high, then ESU is releasing at 20%.
5	If price is expensive and load is low, then ESU is releasing at 60%.
6	If price is expensive and load is high, then ESU is releasing at 100%.

In Figure 4-7 the block diagram of the Fuzzy Controller containing the Fuzzy Inference System proposed is shown.

As shown on the figure, crisp values for Power Price and Grid Load are sent from the Smart Meter as inputs to the Fuzzy Inference System and the output which describes the working state of the Energy Storage Unit is sent out as output. The Fuzzy Inference system follows the four steps described in section 4.1: the Fuzzifier, the Rule Base, the Inference Engine and the Defuzzifier. Power Price and Grid Load are fuzzified through the Membership Functions. Afterwards the fuzzified values are used in the Application of Implication Method

for each separate rule, in our case the 6 rules shown in Figure 4-6. Next the Inference Engine applies Aggregation of Output of Rules and Lastly the Defuzzifier performs centroid calculation to produce a crisp output to be sent over to the Energy Storage Unit.
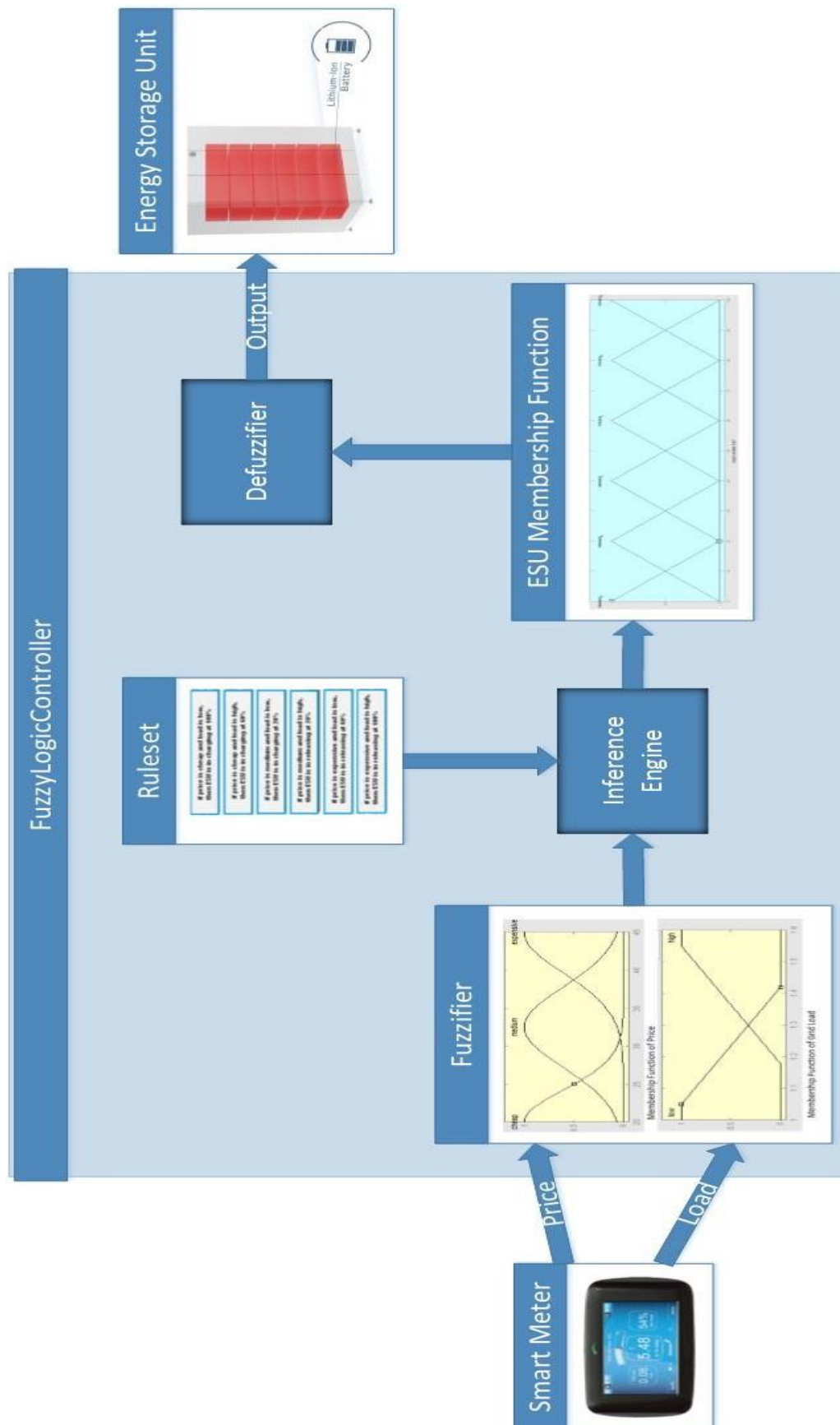
Figure 4-7 Block Diagram of proposed Fuzzy Logic Controller.

5

Fuzzy Logic Controller Implementation in Matlab®

In Chapter 5, details about the methodology and implementation of the design are shown. In section 5.1, background information about the Matlab® platform are presented. In section 5.2, details of the development of the Mamdani's Fuzzy Inference system are shown.

5.1 Overview of Matlab® platform and Fuzzy Logic Toolbox

5.1.1   Matlab® Overview

MATLAB® (Matrix laboratory) is a multi-paradigm numerical computing environment and fourth-generation programming language. A proprietary programming language developed by MathWorks, MATLAB® allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, Fortran and Python. Although MATLAB® is intended primarily for numerical computing, an optional toolbox uses the MuPAD symbolic engine, allowing access to symbolic computing capabilities. An additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamic and embedded systems. In 2016, MATLAB® was registered to around 5000 colleges and universities around the world. MATLAB® users come from various backgrounds of engineering, science, and economics.

Therefore, Matlab® is an extremely useful tool for programming and algorithm development. It supports all phases of data analysis from data acquisition, in our case extracting data from an excel document containing ISO grid's data. (see Appendix C)

5.1.2 Fuzzy Logic Toolbox

Fuzzy logic toolbox is an integrated tool to the vast array of Matlab® tools offered. It provides Matlab functions, graphical tools and a Simulink block for analyzing, designing and simulating systems based on fuzzy logic. The fuzzy logic toolbox can be opened by typing **fuzzy** in the Matlab® command window.

The fuzzy logic toolbox consists of five graphical user interface windows that help build and view a fuzzy inference system. (see Appendix D)

5.2 Development of the proposed Fuzzy Logic Model using Matlab®

In this section the development of the proposed fuzzy inference system is shown using Matlab® software step by step.
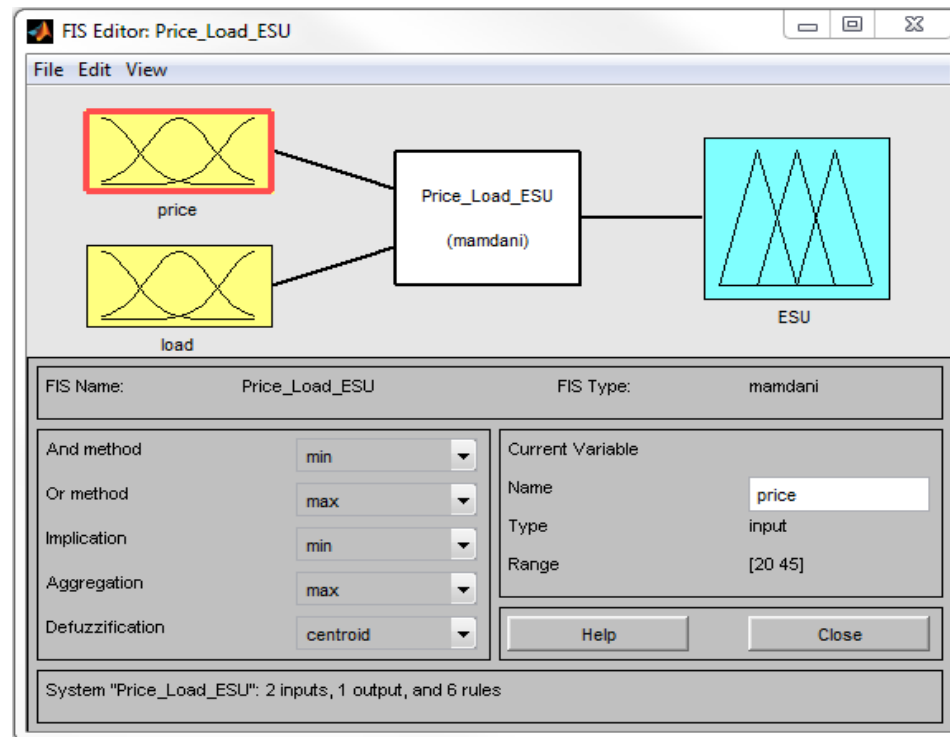
Figure 5-1 Current FIS system shown in FIS editor. Inputs are power price and grid load while the single output is the ESU working state. And method is set to "min" and Or method is set to "max". Implication method used is set to "min" while Aggregation method is set to "max". Lastly defuzzification method is set to "centroid". The right hand sub window shows the details of the selected variable. In this case price, which has an input range of €20-45.

Figure 5-2 shows the membership functions for input power price. Power price is fuzzified through 3 membership functions: cheap, medium and expensive. The three membership functions were selected to be of Gaussian type due to achieving the best results in various tests performed.
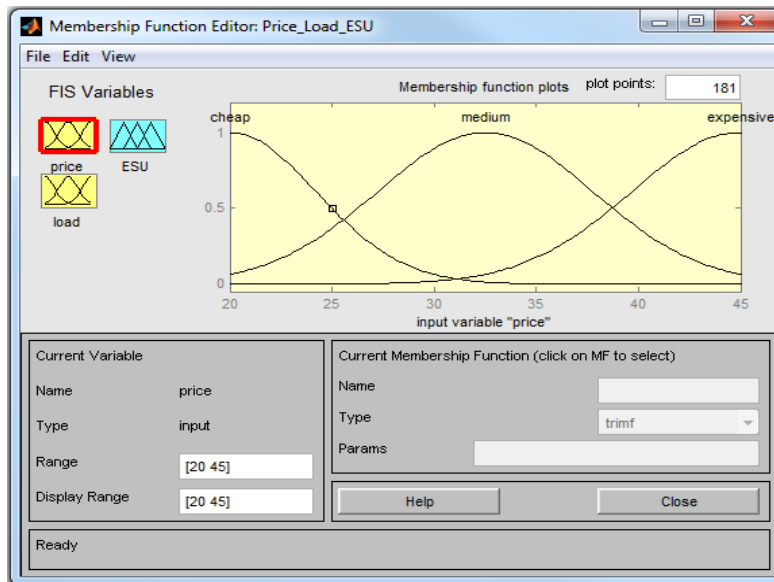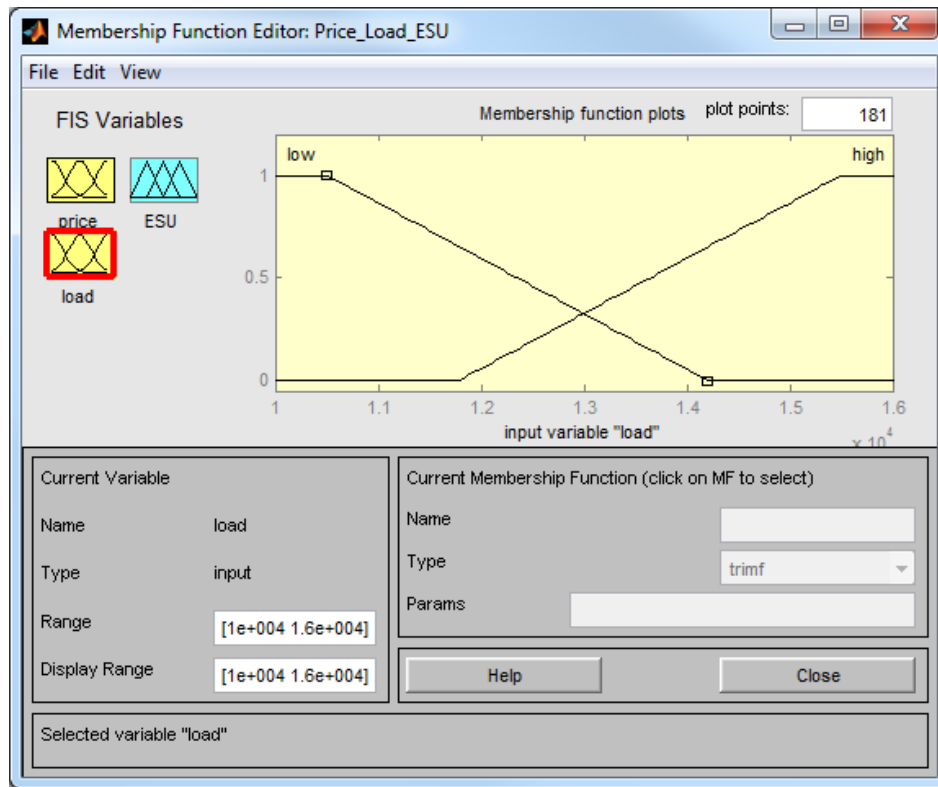

Figure 5-2 Gaussian type membership Functions for input "Power Price". Membership function editor displays information about the current variable, and the current membership function such as name, type and params. A dropdown appears for type when selecting one allowing you to choose between values such as "gaussmf" for Gaussian membership function and "trimf" for triangular membership function. Params is for setting the parameters of each function such as mean μ and variance σ^2.

Table 5-1 Power Price membership functions and ranges.

Variable	Membership Function	Range
Power Price	Cheap	20 – 32.5 €/MWh
	Medium	20 – 45 €/MWh
	Expensive	32.5 – 45 €/MWh

Figure 5-3 shows the membership functions for input grid load. Grid load is fuzzified through 2 membership functions: low and high. The two membership functions were selected to be of Ramp type due to the certainty of Grid load when given specific values. For example when given a Grid Load of 11000MW there is 100% certainty that it will be considered low. This was observed by the datasets used in our simulation.

Figure 5-3 Ramp type membership Functions for input Grid Load.

Table 5-2 Grid Load membership functions and ranges.

Variable	Membership Function	Range
Grid Load	Low	10 000 – 14 000 MWh
	High	11 750 – 16 000 MWh

Figure 5-4 shows the selected membership functions for output ESU working state. There are six different membership functions.

Due to the nature of the output of the implication method, these membership functions overlap with two other neighboring ones and have set boundaries. Triagonal membership functions were selected because they are the fastest type, thus reducing execution time. Something which is very important when dealing with systems of this scale.
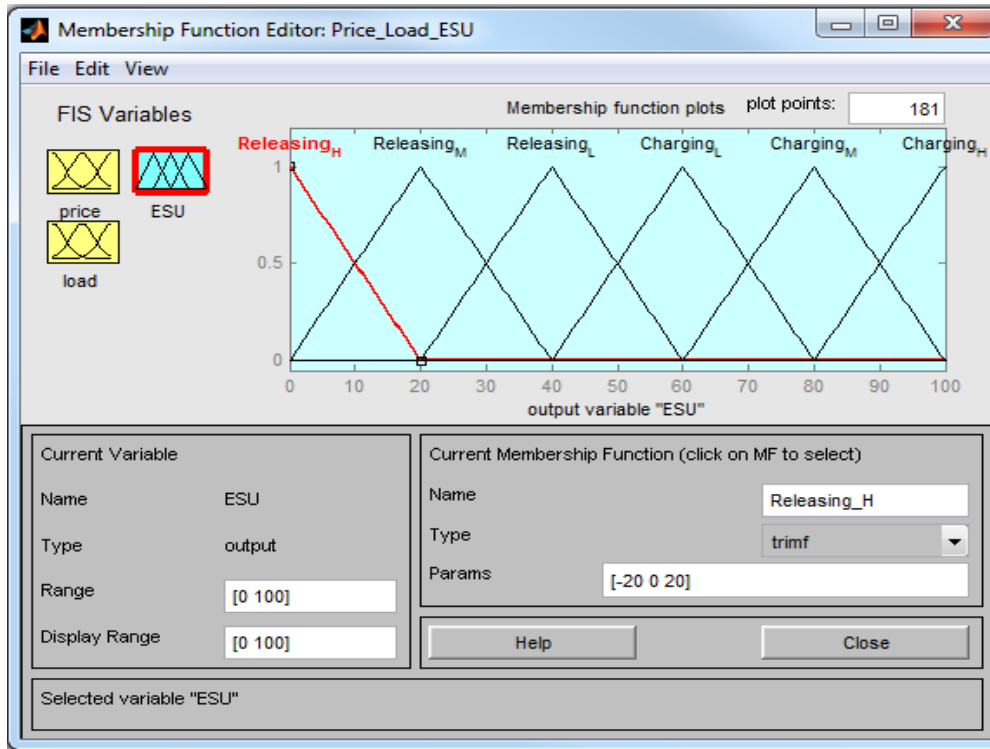
Figure 5-4 Triangle type membership Functions for output ESU working state.

Figure 5-5 shows the selected rules for the proposed FIS system. These rules were selected based on the trends presented in section 4.2.1.

Table 5-3 ESU state membership functions and ranges.

Variable	Membership Function	Range
	Charging High	80 - 100
	Charging Medium	60 – 100
ESU Release/Charging Level	Charging Low	40 – 80
	Releasing Low	20 – 60
	Releasing Medium	0 – 40
	Releasing High	0 – 20
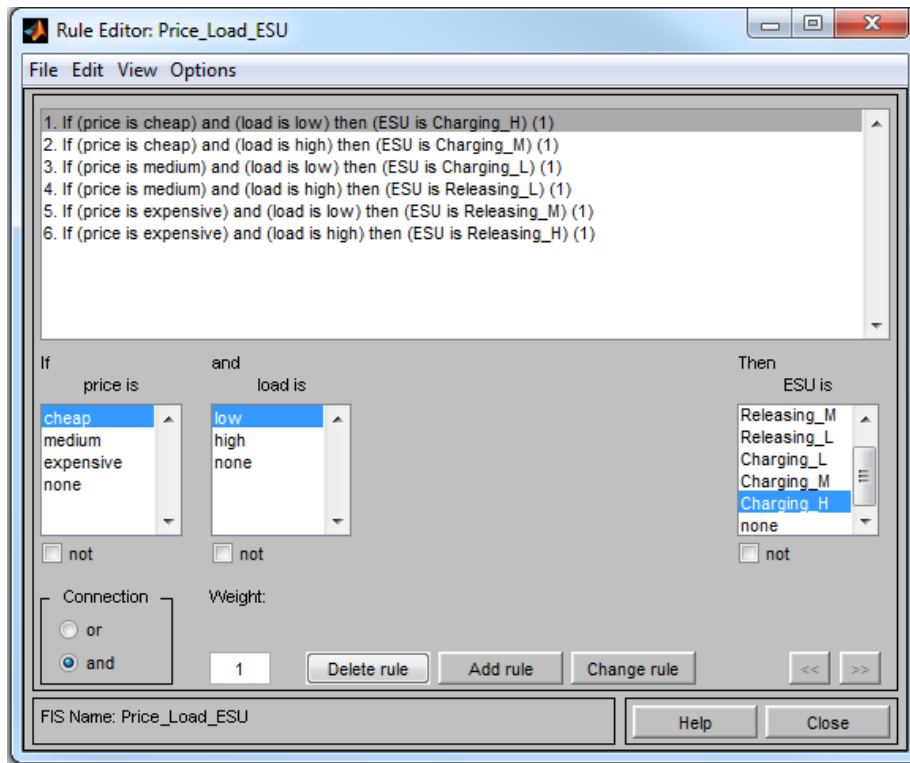
**Figure 5-5 Current Rules for proposed FIS system. Charging H means ESU is charging 100%, Charging M means charging at 60%, Charging_L means charging at 20%, Releasing_L means releasing at 20%, Releasing_M means releasing at 60% and Releasing_H means releasing at 100%.**

Table 5-4 Ruleset results for every combination of inputs.

Power Price	Grid Load	ESU State
Cheap	Low	Charging_High
Cheap	High	Charging_Medium
Medium	Low	Charging_Low
Medium	High	Releasing_Low
Expensive	Low	Releasing_Medium
Expensive	High	Releasing_High

Figure 5-6 shows a snapshot of the Rule Viewer for selected inputs of Power Price and Grid Load at 22.2 €/MWh and 13000MWh respectively. The output is given as 62.8
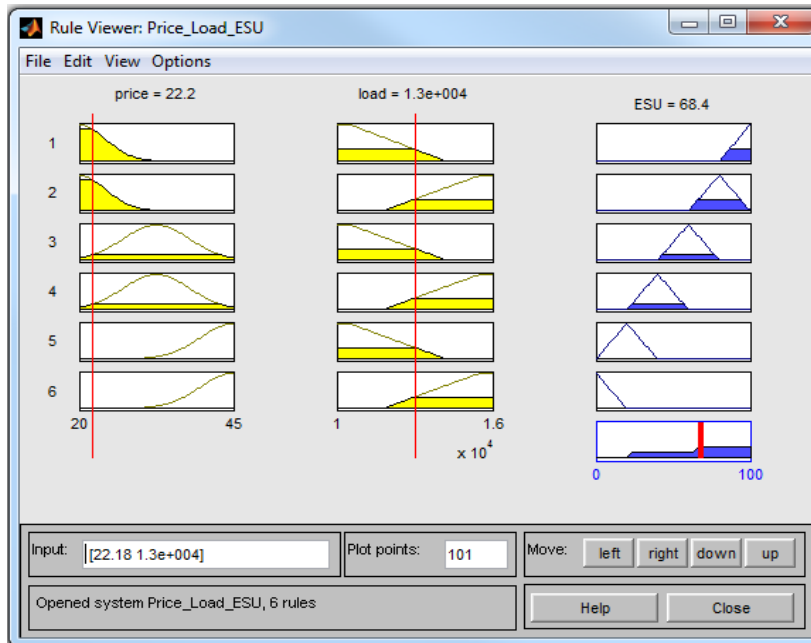
Figure 5-6 Ruleviewer of Proposed FIS system. We have 6 lines each with 3 figures. Each line represents a rule. Eg. First line represents rule "If price is cheap and load is low then ESU is Charging_H". The third figure is the result of the implication method on the first and second figure. Finally the figure on the 7th line is the result of the aggregation of the figures produces by all 6 rules. The vertical red line indicates the centre of mass of the aggregated figure which as you can see is on 68.4. A value over 50% means charging and a value below 50% means releasing.

Figure 5-7 shows proposed Design in Surface viewer mode.
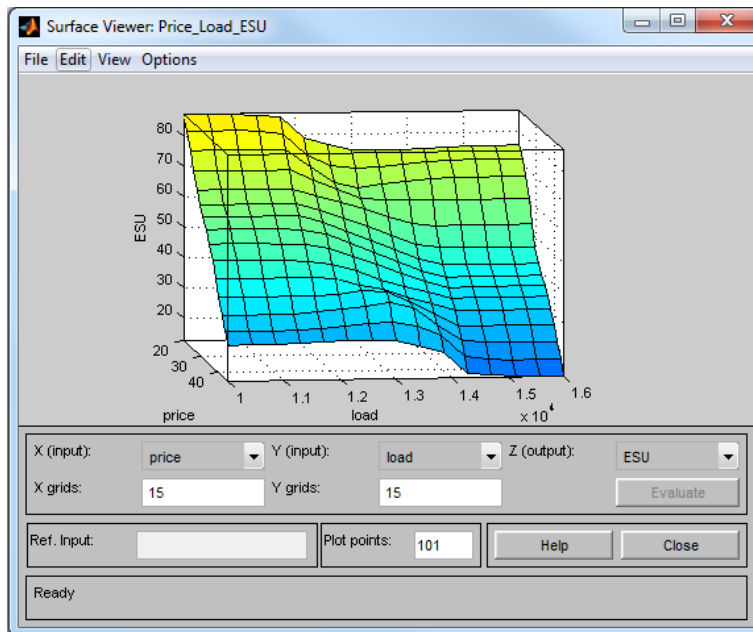
Figure 5-7 Surface Viewer. Surface viewer is a 3d representation of the current set of rules. X axis is the input price, ranging from € 20 to € 45. Z axis is the input load ranging from 10000MWh to 16000MWh. Output is the ESU charging or releasing level ranging from 0 to 100%.

6

Results and Evaluation

In Chapter 6, results regarding the performance of the Smart Fuzzy System will be discussed and will be evaluated regarding the cost saving due to reduction of grid load.

Section 6.1 presents the results of an Electricity Grid without the use of a Smart Fuzzy System.

In section 6.2, the results of an Electricity Grid using a Smart Fuzzy System to charge an Energy Storage Unit at off peak load times to store "cheap" energy in order to be used at a later time is discussed. In section 6.3 an evaluation is given of the performance of the Smart Fuzzy System in comparison to the performance of a typical grid. The results were based on measurements taken throughout the whole year and as a typical day January 1st was selected due to this date being in the winter, a season where high energy needs are observed due to the increased heating needs of a household.

6.1 Electrical Grid Power consumption without using a Smart Fuzzy System

Figure 6.1 illustrates the hourly power price curve of the entire grid during January 1st for the New England area. Again this date was selected due to it being in the winter season and also having a high peak for both price and load at standard peak hours, 15:00 to 20:00. Figure 6.2 shows the hourly grid load curve during a typical day. As shown in the two figures, power price is significantly affected by the peak load, during the hours of 15:00 to 20:00. The highest load was observed during 17:00 to 18:00, the hour which most people come home from work. Figure 6.3 shows the hourly power cost curve. Power cost was calculated by multiplying load and price as shown in equation (6.1) below.

Cost = Price * Load (6.1)

In Figure 6.3, the lowest hourly cost was observed at 14:00 when people are still at work and kids are not home from school yet and the highest was at 18:00 when people come home from work and start household activities.
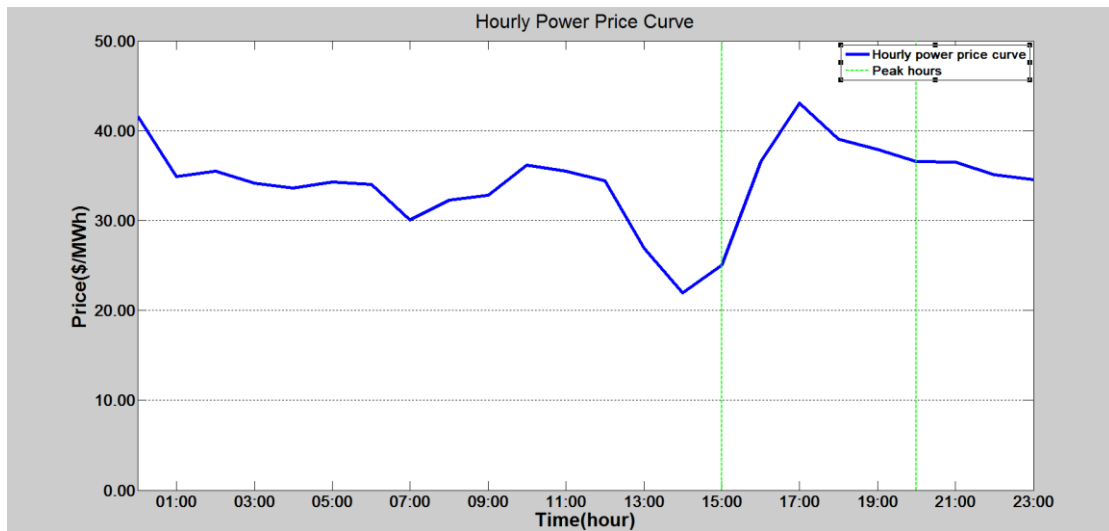
Figure 6-1 Power Price Curve on January 1 for New England. Peak hours 15:00 to 20:00.
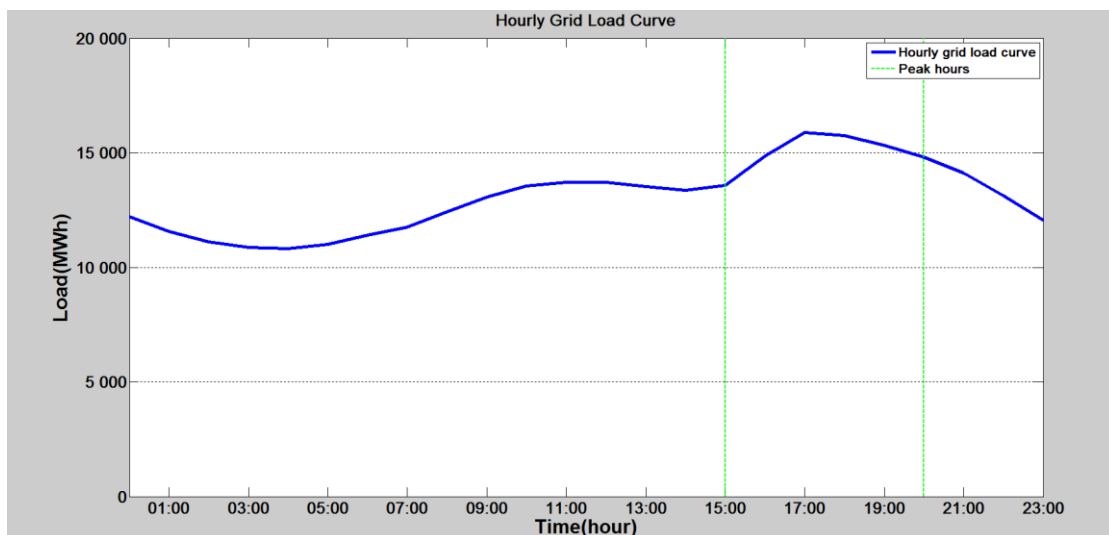
Figure 6-2 Grid Load Curve on January 1 for New England. Peak load from 15:00 to 20:00.
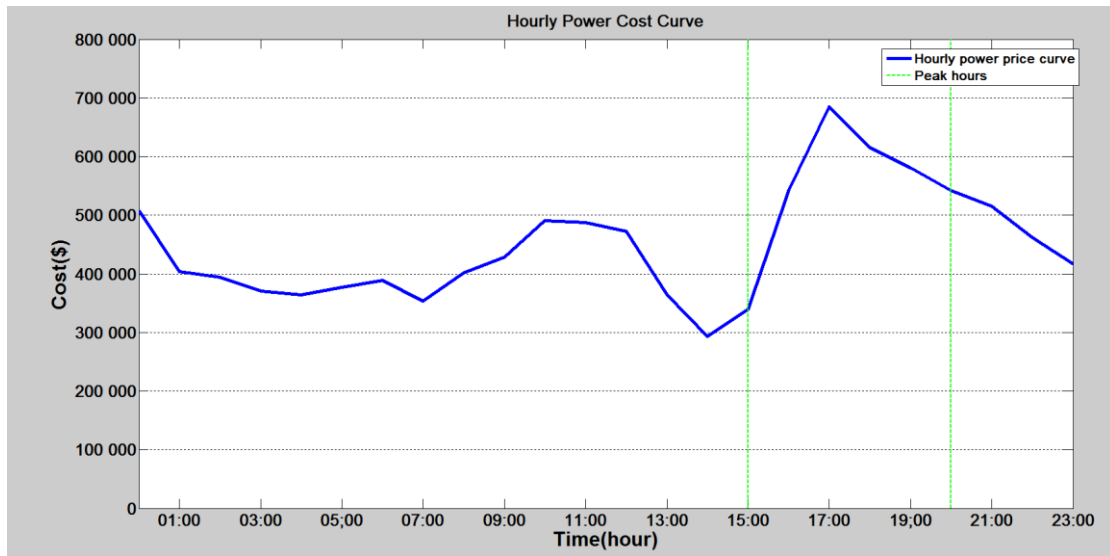
Figure 6-3 Cost of Power Consumption on January1 for New England. Highest cost at 15:00 to 20:00.

Figure 6.4 shows the average daily grid load per month. As shown the highest logged grid load was during July when people have strong cooling needs due to the warm weather and also during January when people have strong heating needs during the winter. The lowest grid load appeared in May when the climate is moderate and people have minimal needs in heating and cooling. Figure 6.5 shows the average daily power cost per month. It is clear form these two figures that power load and power production cost are correlated as months that had the highest average grid load are the ones with the highest average power cost.
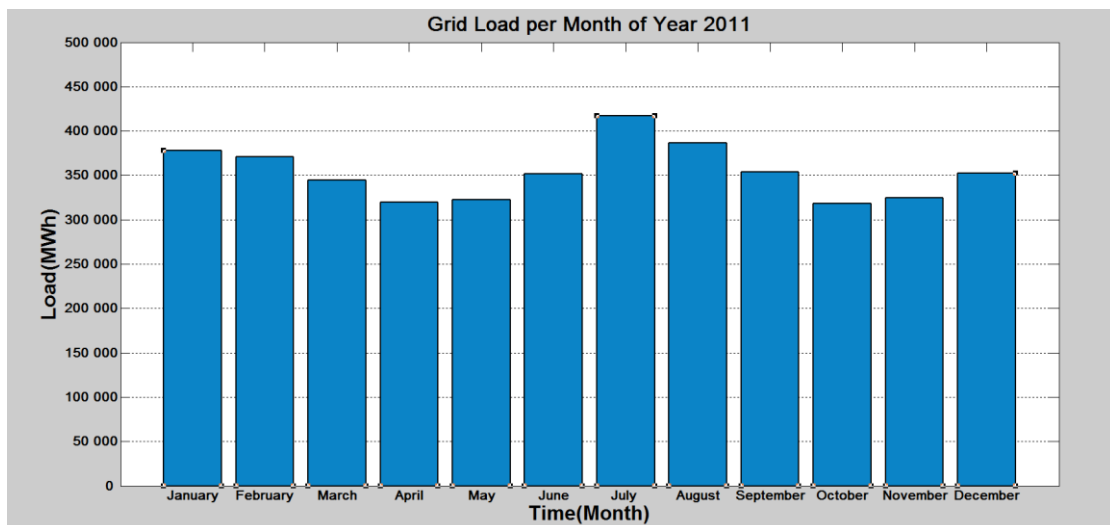
Figure 6-4 Average Daily Grid Load per Month. Highest monthly load on July and January with July having 12% higher peak load.
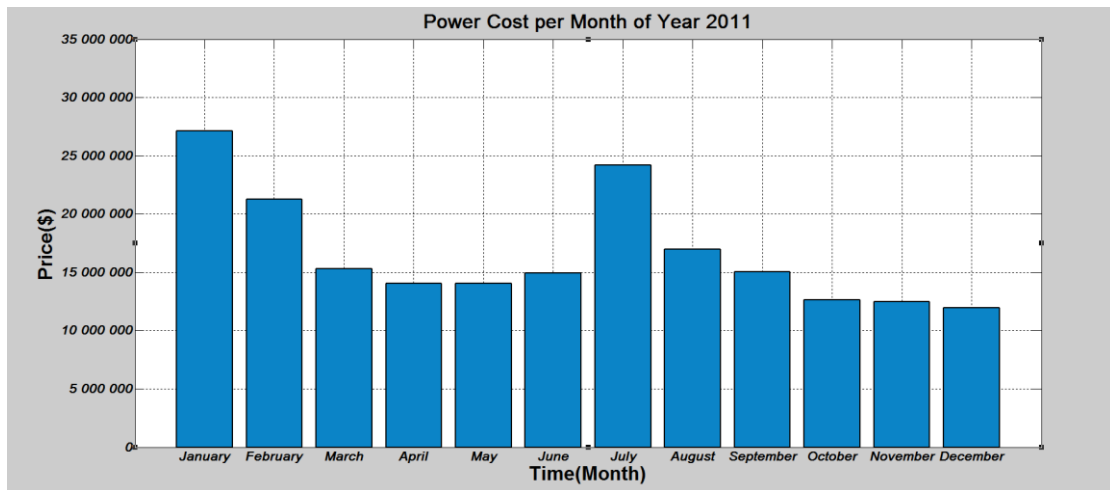
Figure 6-5 Average Daily Cost of Power Consumption per month. This figure shows total power cost per month, to better represent how seasons affect the peak power cost.

6.2 Electrical Grid Power consumption using the proposed Smart Fuzzy Logic Controller vs the conventional grid

Figure 6-6 shows the hourly grid load curve for a grid using a fuzzy logic controller compared to one using the standard system. Figure 6-7 displays the hourly power cost curve for a grid using a fuzzy system during a typical day.
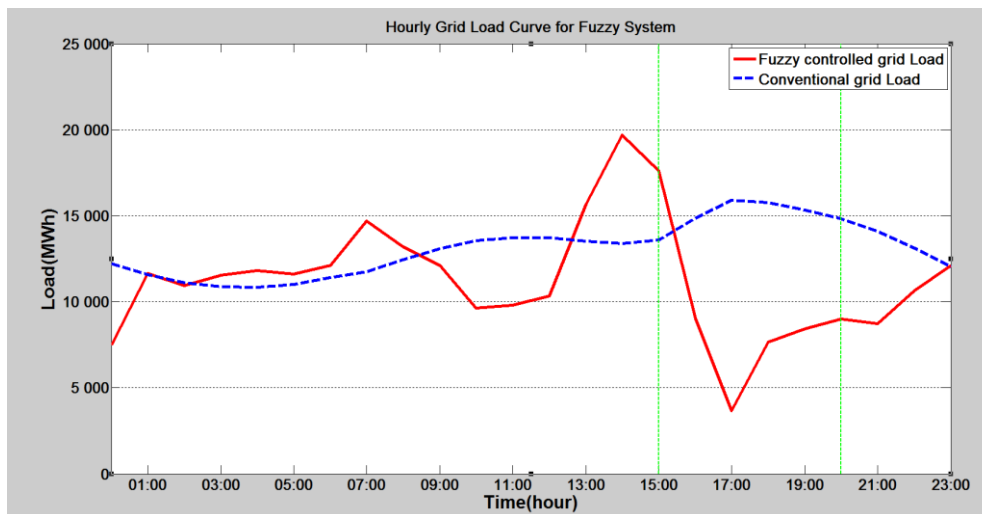
Figure 6-6 Grid Load Curve using Fuzzy System on January 1st vs conventional system.
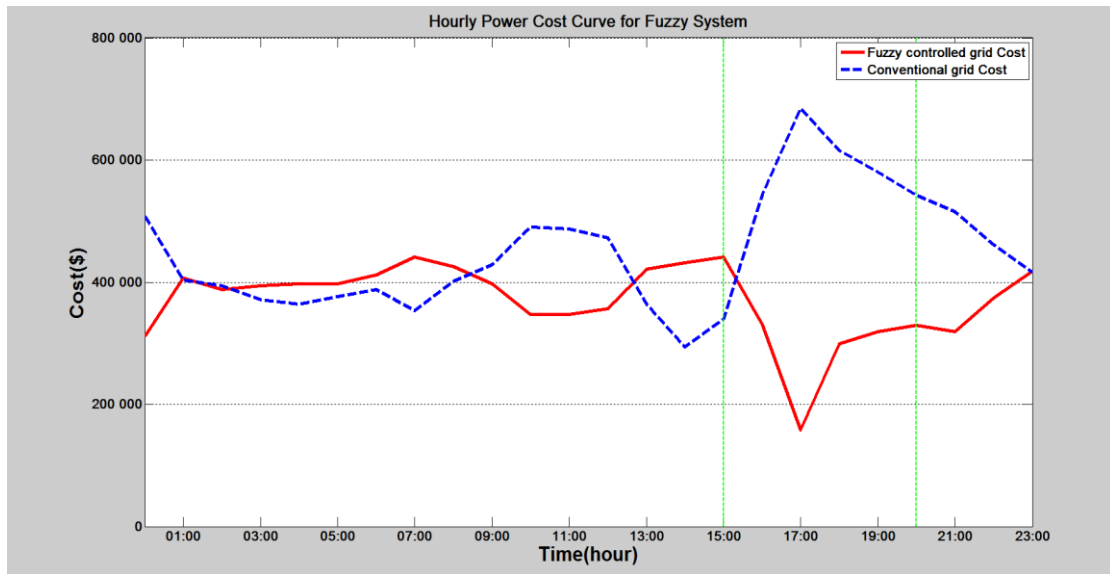
Figure 6-7 Hourly Power Cost Curve using Fuzzy System on January 1st.

6.3 Power savings during quarterly period for a typical household

Figure 6-8 shows the cost savings achieved when using the Smart Fuzzy System instead of a typical electricity grid. The cost is assuming a typical household power consumption per three month period. As seen in the graph and in more details from table 6.1, a grid utilizing smart logic can achieve savings rates up to 31.3% during the July to September period.
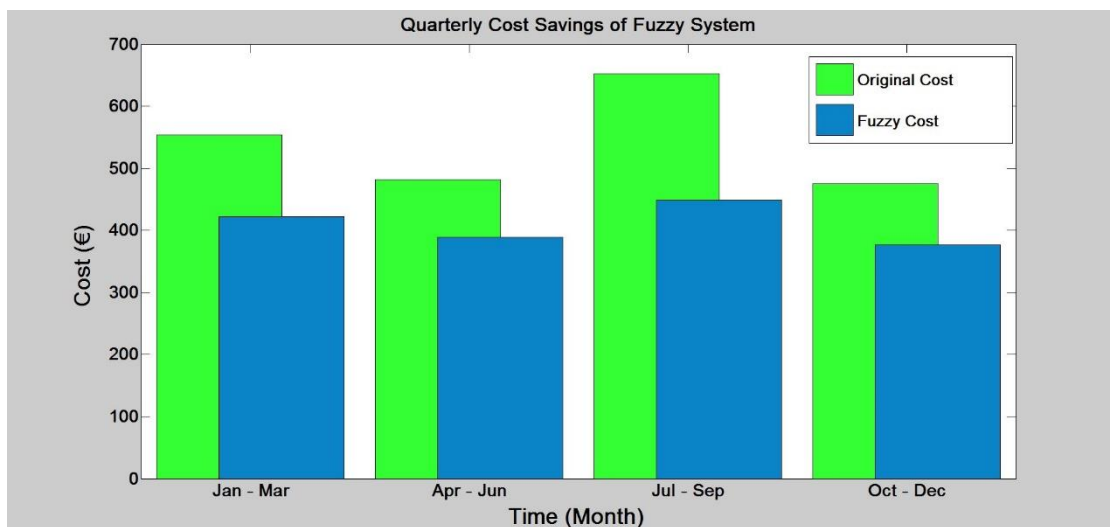
Figure 6-8 Quarterly Cost of Fuzzy Logic Controlled System vs conventional grid.

Table 6-1 Quarterly savings rates of Grid utilizing Fuzzy Logic Controller.

Months	Original Cost (€)	Fuzzy Cost (€)	Fuzzy Savings
Jan - Mar	553.2	422.1	23.6%
Apr – Jun	482.1	389.3	19.2%
Jul – Sep	652.3	448.1	31.3%
Oct - Dec	474.7	376.2	20.7%

From what is shown in the previous figures and Figure 6-8 and Table 6.1 it can be concluded that the original goal of this research, which was to develop a fuzzy controller that works along with a smart meter to convert a conventional electricity grid to a Smart Grid so that end consumers benefit from reduced price and grid overload is no longer a factor.

Figures 6-2, 6-4 and 6-6 better illustrate the shifting in peak load from peak hours to non – peak hours. Specifically for consumers with the energy storage unit solution peak load has shifted from the hours between 15:00 to 20:00 to 12:00 16:00.

Lastly Figures 6-3, 6-5 and 6-7 present the cost reduction that can be achieved when switching to Smart Grid and more specifically to a Fuzzy Inference System. Cost savings as were observed in Table 6-1, can reach as high as 31% during the summer period and average around 21% during normal periods.

7

Conclusions and future work

7.1 Summary and Conclusion of work

In this thesis the Smart Grid concept was discussed and a Mamdani's Fuzzy Inference System was proposed to be used as the main algorithm for optimal power flow. The design of a Smart Meter with a fuzzy controller was illustrated that is responsible for charging an energy storage unit. This approach was compared to the current working system, using datasets obtained from ISO New England and was found to perform extremely well both in regards to cost saving for the end consumer as well as a means to prevent grid overload during peak hours.

7.2   Future Work

There are many ways in which this research can be improved. One issue with Fuzzy Logic is that it cannot incorporate statistical data in a direct fashion. Historical data are incorporated in the form of rules. The power industry is highly statistics driven. There should have been some way to incorporate the decisions that are based on statistical findings. Currently the only way to incorporate changes is to alter the rule base, and that change has to be done manually.

Another improvement to the current system is to enable a feature that utilizes the Energy Storage Unit even when the end consumer is away from home and doesn't have energy consumption. The system would continue to charge during low price periods and during time periods when the system is nearing full capacity, the ESU could be transferring energy back to the electrical grid to assist with power generation. A system will be in place to ensure the end consumer gets compensated for it automatically through bill reduction at the end of the month.

8

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Appendix A. Matlab Code

```matlab
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
close all
clear all

%Read data sets from excel file and input them in num array
filename2011='WorkingData2011.xlsx';
num2011=xlsread(filename2011);

%Read the excel file as A numerical,B text, C raw in order to keep
the dates in table C
[A B C] = xlsread('WorkingData2011.xlsx');
Dates=C([2:8761],1);

%
Using evalfis we are able to evaluate our Fuzzy Inference System
fismat=readfis('Price_Load_ESU2');



%Input for evalfis is our 2 tables from the excel file corresponding
to power price and grid load
input2011 = num2011(:,[2:3]);




times=[47.75;60.65];
load=[17639;19039];
input=[times,load];
output2011= evalfis(input2011,fismat);
output= evalfis(input,fismat);



%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



%Figure1 hourly Price Curve on January1/1/2011

y=input2011(2:25,1)';
Xtick_hours =
['00:00';'01:00';'02:00';'03:00';'04:00';'05:00';'06:00';

'07:00';'08:00';'09:00';'10:00';'11:00';'12:00';'13:00';'14:00';'15:0
0';'16:00';'17:00';'18:00';
    '19:00';'20:00';'21:00';'22:00';'23:00'];
t = 0:23;
figure();
plot(t, y, 'b','linewidth',4)

xlabel('Time(hour)','fontsize',24,'fontweight','bold')
```

```matlab
ylabel('Price(€/MWh)','fontsize',24,'fontweight','bold')
title('Hourly Power Price Curve')
set(gca,'ygrid','on')
set(gca,'XLim',[0 23])
set(gca,'XTick',[0:1:23])
set(gca, 'XTickLabel',Xtick_hours);



%Figure2 Hourly Grid Load Curve 1/1/2011


y=input2011(2:25,2)';
% Uncomment the following line to preserve the X-limits of the axes

% Uncomment the following line to preserve the Y-limits of the axes
Xtick_hours =
['00:00';'01:00';'02:00';'03:00';'04:00';'05:00';'06:00';

'07:00';'08:00';'09:00';'10:00';'11:00';'12:00';'13:00';'14:00';'15:0
0';'16:00';'17:00';'18:00';
    '19:00';'20:00';'21:00';'22:00';'23:00'];
t = 0:23;
figure();
plot(t, y, 'b','linewidth',4)

xlabel('Time(hour)','fontsize',24,'fontweight','bold')
ylabel('Load(MWh)','fontsize',24,'fontweight','bold')
title('Hourly Grid Load Curve','FontWeight','demi','FontSize',20);
set(gca,'ygrid','on')
set(gca,'XLim',[0 23])
set(gca,'XTick',[0:1:23])
set(gca, 'XTickLabel',Xtick_hours);
%set(gca,'YTickLabel',Ytick_load);
set(gca,'YLim',[0 20000]);




%Figure3 Hourly Power COST Curve 1/1/2011
%For Cost the following formula is used: COST= LOAD*PRICE;

load2011_1_1=input2011(2:25,2);
price2011_1_1=input2011(2:25,1);

cost2011_1_1=load2011_1_1.*price2011_1_1;

y=cost2011_1_1(1:24)';
create_hourlyfigure_cost(t,y);

Xtick_hours =
['00:00';'01:00';'02:00';'03:00';'04:00';'05:00';'06:00';

'07:00';'08:00';'09:00';'10:00';'11:00';'12:00';'13:00';'14:00';'15:0
0';'16:00';'17:00';'18:00';
    '19:00';'20:00';'21:00';'22:00';'23:00'];
t = 0:23;
```

```matlab
figure();
plot(t, y, 'b','linewidth',4)

xlabel('Time(hour)','fontsize',24,'fontweight','bold')
ylabel('Cost(€)','fontsize',24,'fontweight','bold')
title('Hourly Power Cost Curve')
set(gca,'ygrid','on')
set(gca,'XLim',[0 23])
set(gca,'XTick',[0:1:23])
set(gca, 'XTickLabel',Xtick_hours);




%Figure4 Monthly Grid Load of 2011 Bar Graph
y=input2011(1:24,2);
[monthly_energeia,monthly_timi]=calculate_monthly_data(input2011);




month_days=[31,28,31,30,31,30,31,31,30,31,30,31]';
daily_average_load_per_month=monthly_energeia./month_days;
daily_average_price_per_month=(monthly_timi./month_days)/24;
daily_average_cost_per_month=daily_average_load_per_month.*daily_aver
age_price_per_month;




%bar(monthly_energeia);
create_monthlyfigure_load(daily_average_load_per_month);

%Figure 6 Monthly Price of 2011 Bar Graph
figure();
bar(daily_average_cost_per_month);
title('Monthly Cost?')

create_monthlyfigure_cost(daily_average_cost_per_month);
figure();
bar(monthly_timi);
title('Monthly Price')



%%
%---------------------     FUZZY VALUES ----------------------


%%%%TESTING
%find number of elements in output of FIS greater than 50
b=output2011>50;
zero_values=output2011==50;
c=sum(b);
d_d=sum(zero_values);



%%%Converting the output of FIS system to range [-1,1] to easily
convert
%%%energy consumption or energy release of ESU.
```

```matlab
range = max(output2011) - min(output2011);
output2011 = (output2011 - min(output2011)) / range;
range2 = 1 - (-1);
output2011 = (output2011*range2) + (-1);



%%%%Testing
b_1=output2011>0;
b_2=output2011==50;
Output_values_positive_count=sum(b_1);
Output_values_zero_count=sum(b_2);



%%%CONVERT FUZZY OUTPUT TO LOAD.
%Multiply fuzzy output (-0.5 for releasing 50%) with Grid Load at
given time(eg.16000)
%If it was releasing 50% of grid load then 16000 -(16000*0.5) = 16000
%-8000=8000 therefore we need to multiply element wise the fuzzy
output
%which is -0.5 with the grid load and add.



ESU_Release_or_Charging_Energy=output2011(2:25).*input2011(2:25,2);
Fuzzy_load_1_1=load2011_1_1+(output2011(2:25).*input2011(2:25,2));




%%%%%FUZZY GRAPH FOR JANUARY 1 GRID LOAD
t = 0:23;
y=input2011(2:25,2)';
figure();
plot(t,Fuzzy_load_1_1,'color','r','linewidth',4); hold on;
plot(t,y,'color','b','linewidth',4);
xlabel('Time(hour)','fontsize',24,'fontweight','bold')
ylabel('Load(MWh)','fontsize',24,'fontweight','bold')
title('Hourly Grid Load Curve for Fuzzy
System','FontWeight','demi','FontSize',20);
legend('Fuzzy Load','Original Load' );
Xtick_hours =
['00:00';'01:00';'02:00';'03:00';'04:00';'05:00';'06:00';

'07:00';'08:00';'09:00';'10:00';'11:00';'12:00';'13:00';'14:00';'15:0
0';'16:00';'17:00';'18:00';
    '19:00';'20:00';'21:00';'22:00';'23:00'];
set(gca,'ygrid','on')
set(gca,'XLim',[0 23])
set(gca,'XTick',[0:1:23])
set(gca, 'XTickLabel',Xtick_hours);




%%%%%%%%%%FUZZY GRAPH FOR JANUARY 1 POWER COST
%power cost classic
cost2011_1_1;
y=cost2011_1_1(1:24)';

y2=Fuzzy_load_1_1.*price2011_1_1;
```

```matlab
figure();
plot(t,y2,'color','r','linewidth',4); hold on;
plot(t,y,'color','b','linewidth',4);
xlabel('Time(hour)','fontsize',24,'fontweight','bold')
ylabel('Cost(€)','fontsize',24,'fontweight','bold')
title('Hourly Power Cost Curve for Fuzzy
System','FontWeight','demi','FontSize',20);
legend('Fuzzy Cost','Original Cost' );
Xtick_hours =
['00:00';'01:00';'02:00';'03:00';'04:00';'05:00';'06:00';

'07:00';'08:00';'09:00';'10:00';'11:00';'12:00';'13:00';'14:00';'15:0
0';'16:00';'17:00';'18:00';
    '19:00';'20:00';'21:00';'22:00';'23:00'];
set(gca,'ygrid','on')
set(gca,'XLim',[0 23])
set(gca,'XTick',[0:1:23])
set(gca, 'XTickLabel',Xtick_hours);

total_fuzzy_11=sum(y2);
total_orig_11=sum(y);

savings_11=((total_fuzzy_11-total_orig_11)/total_orig_11)*100;

%%%%%%%%%FUZZY POWER COST CALCULATION FOR ALL THE YEAR

%Excel cells per month
%January->2-745, February->746-1417, March->1418-2161,April 2162-
2881,
%May->2882-3625, June 3626-4345, July->4346-5089,August-> 5090-5833
%September->5834-6553,October->6554-7297,November->7298-8017
%%December->8018-8761

Fuzzy_load_1_1 = load2011_1_1 + (output2011(2:25) .*
input2011(2:25,2) );
Fuzzy_cost_1_1 = Fuzzy_load_1_1 .* price2011_1_1;

Load_2011 = input2011(:,2);
Price_2011 = input2011(:,1);

Fuzzy_load_2011 = Load_2011(2:8761) +( output2011(2:8761) .*
Load_2011(2:8761) );
Fuzzy_cost2011= Fuzzy_load_2011.*Price_2011(2:8761);

Original_cost2011=Load_2011(2:8761).*Price_2011(2:8761);
%%%Cost for Jan-March

    %January->2-745, February->746-1417, March->1418-2161
Fuzzy_load_2011_Jan_Mar = Load_2011(2:2161) + (output2011(2:2161) .*
Load_2011(2:2161));
Fuzzy_cost2011_Jan_Mar = Fuzzy_load_2011_Jan_Mar .*
Price_2011(2:2161);

total_fuzzy_13=sum(Fuzzy_cost2011_Jan_Mar);

Original_cost2011_Jan_March = Load_2011(2:2161) .*
Price_2011(2:2161);
total_orig_13=sum(Original_cost2011_Jan_March);
```

```matlab
Savings13= ((total_fuzzy_13-total_orig_13)/total_orig_13)*100;


%%%% Cost for Apr-June
%    April 2162-2881, May->2882-3625, June 3626-4345
Fuzzy_load_2011_Apr_June = Load_2011(2162:4345) +
(output2011(2162:4345) .* Load_2011(2162:4345));
Fuzzy_cost2011_Apr_June = Fuzzy_load_2011_Apr_June .*
Price_2011(2162:4345);


total_fuzzy_46=sum(Fuzzy_cost2011_Apr_June);


Original_cost2011_Apr_June = Load_2011(2162:4345) .*
Price_2011(2162:4345);
total_orig_46=sum(Original_cost2011_Apr_June);


Savings46= ((total_fuzzy_46 - total_orig_46)/total_orig_46)*100;

%%%% Cost for Jul-Sep
%   July->4346-5089,August-> 5090-5833%September->5834-6553
Fuzzy_load_2011_Jul_Sep = Load_2011(4346:6553) +
(output2011(4346:6553) .* Load_2011(4346:6553));
Fuzzy_cost2011_Jul_Sep = Fuzzy_load_2011_Jul_Sep .*
Price_2011(4346:6553);


total_fuzzy_79=sum(Fuzzy_cost2011_Jul_Sep);


Original_cost2011_Jul_Sep = Load_2011(4346:6553) .*
Price_2011(4346:6553);
total_orig_79=sum(Original_cost2011_Jul_Sep);


Savings79 = ((total_fuzzy_79 - total_orig_79)/total_orig_79)*100;

%%%% Cost for Oct-Dec
%  October->6554-7297,November->7298-8017 December->8018-8761
Fuzzy_load_2011_Oct_Dec = Load_2011(6554:8761) +
(output2011(6554:8761) .* Load_2011(6554:8761));
Fuzzy_cost2011_Oct_Dec = Fuzzy_load_2011_Oct_Dec .*
Price_2011(6554:8761);


total_fuzzy_10_12=sum(Fuzzy_cost2011_Oct_Dec);


Original_cost2011_Oct_Dec = Load_2011(6554:8761) .*
Price_2011(6554:8761);
total_orig_10_12=sum(Original_cost2011_Oct_Dec);


Savings10_12 = ((total_fuzzy_10_12 -
total_orig_10_12)/total_orig_10_12)*100;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% BAR GRAPH
 figure();
 graph = [553.2 422.1 ; 482.1 389.3 ; 652.3 448.1 ; 474.7 376.4];
 bar(graph,'BarWidth',2);
 legend('Fuzzy Cost','Original Cost');
```

Appendix B. Background information on Fuzzy logic.

Figure B-1 illustrates an example of the fuzzy inference process taken from the Matlab manual on fuzzy systems. Generally, the fuzzy inference process is a method of interpreting the values in the input space and, using a set of rules, assigns values to the output space.

The main building block of Fuzzy Logic is the fuzzy set. In comparison to a classical Boolean set, a fuzzy set is a set without clearly defined boundary. In Figure 3-1 service is a typical fuzzy set. There are no clear boundaries between poor and good, or between good and excellent. Another example is determined to what extend March is winter or spring. March can either feel like winter or feel like spring depending on the weather and temperature associated. A warm March feels more like spring and less winter, whereas a cold March feels like more winter and less spring.
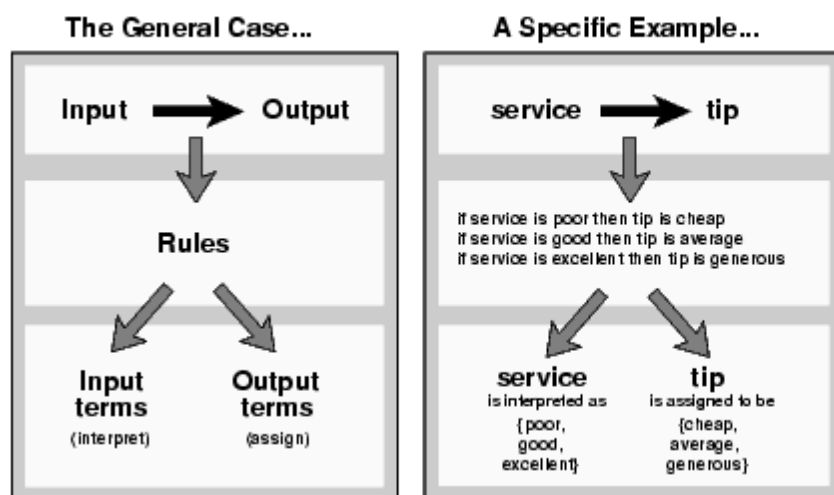
Figure B-1 Fuzzy inference process (Source Matlab Tutorial)

When talking about Fuzzy Logic, the truth of any statement is based on "degrees of truth" rather than true or false. What matters is not whether these statements are true or not, but how true these statements are. Membership function is a curve to describe the degree of truth for a statement. It defines how each point in the input space is mapped to a membership value. Figure 4-2 illustrates membership function of four seasons.
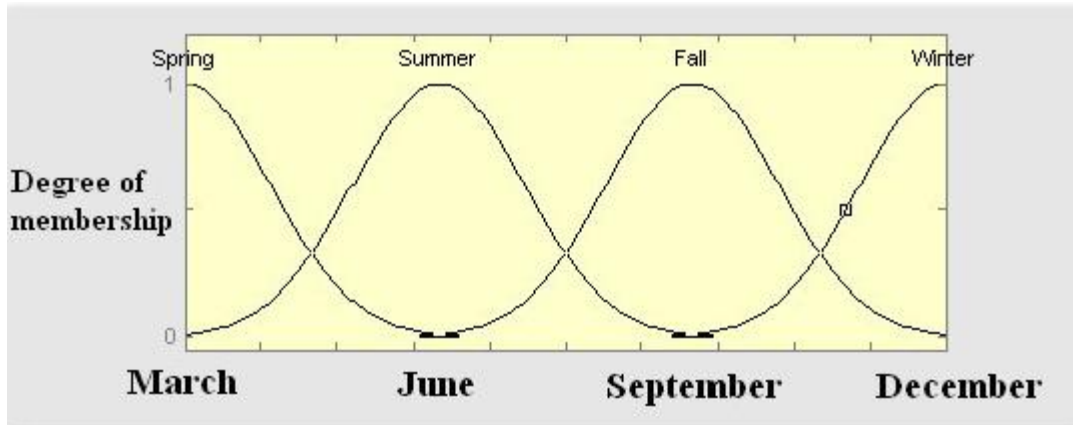
Figure B-2 Seasons Membership Functions (Source Matlab Tutorial)

If X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs. It is shown in Equation 4-1.

$$A = \{x, \mu A(x)\} | x \in X \tag{0-1}$$

$\mu A(x)$ is the membership function of x in A. The membership function maps each element of X to a membership value between 0 and 1. Through membership function, statements can be fuzzified. A single input fuzzy if-then rule is the following form.

If x is A then y is B

Both "x is A" and "y is B" are fuzzified statements. In this example, "x is A" is called the antecedent or premise, while the "y is B" is called the consequent or conclusion. An example of such a rule might be

If temperature is high then climate control is cooling

A single if-then rule can also has two input parameter such as

If x is A and y is B then z is C

In this situation, "and" is called fuzzy operator. Fuzzy operators can be "and", "or" and "not". Operation "A and B" will return the minimum value between A and B, operation "A or B" will return the maximum value between A and B, operation "not A" will return the value "1 - A". Through logical operation by fuzzy operator, two or more input spaces can be fuzzified and mapped to a single output space.

Fuzzy Inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The Fuzzy Inference process involves all the building blocks of a fuzzy logic system: Membership Functions, Logical Operators and If-Then Rules. There are two types of fuzzy inference systems: Mamdani's Fuzzy Inference System and the TSK (Takag-Sugeno-Kang) Fuzzy Inference System [14] [15] [16]. Systems using Fuzzy Inference are in use and have been successfully implemented in the fields of computer vision, expert systems, decision analysis, data declassification and automatic control.

The Mamdani FIS should be used whenever we have applications with a single output variable (MISO systems). For MIMO systems (usual in classification problems) the Mamdani FIS is maybe more appropriate, i.e. it can deal directly with MIMO, while Sugeno FIS would require dividing the MIMO into as many MISO systems as the number of output variables; often a cumbersome and time consuming task. In general, Mamdani's FIS is easier to implement and a process closer to the way of human thinking whereas TSK requires modelling of the input-output relationship in the form of linear equations. In this thesis the proposed solution is on the basis of Mamdanis's Fuzzy Inference System.

Appendix C. Matlab overview
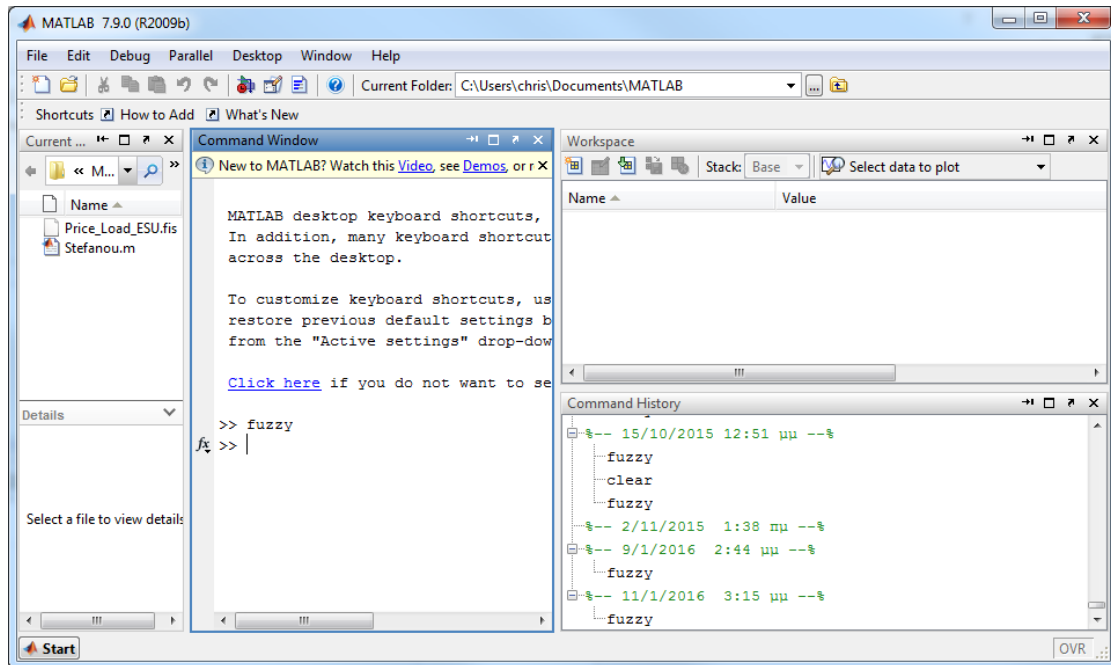
Figure C-1 Matlab 2009 Main window

On a Matlab window the following sub-windows are displayed:

- Workspace
- Current Directory browser
- Command History
- Command Window

The Workspace and array editor contain information regarding current variables and their respective values, also showing the variable type, variable array dimensions. In the array editor, variable values are inspected in detail and can also be edited.

The command history window retains a list of all commands entered previously and at what time, listed in descending order.

The current directory browser contains information regarding other Matlab related files contained in the directory working on.

The command window is the most important window in Matlab and it is where a user enters commands for Matlab to execute. In addition to that, M-files can also be executed in the command window as well as Simulink, Fuzzy tool, Genetic Algorithm tool and many others. M-files are files containing a series of Matlab commands to be executed

Appendix D. Fuzzy Toolbox

1. <u>Fuzzy Inference System Editor:</u> The FIS editor is the main window of the fuzzy logic toolbox. It defines the fuzzy inference system by specifying inputs, outputs, implication method used, aggregation method used and defuzzification method used as shown in figure 5-2
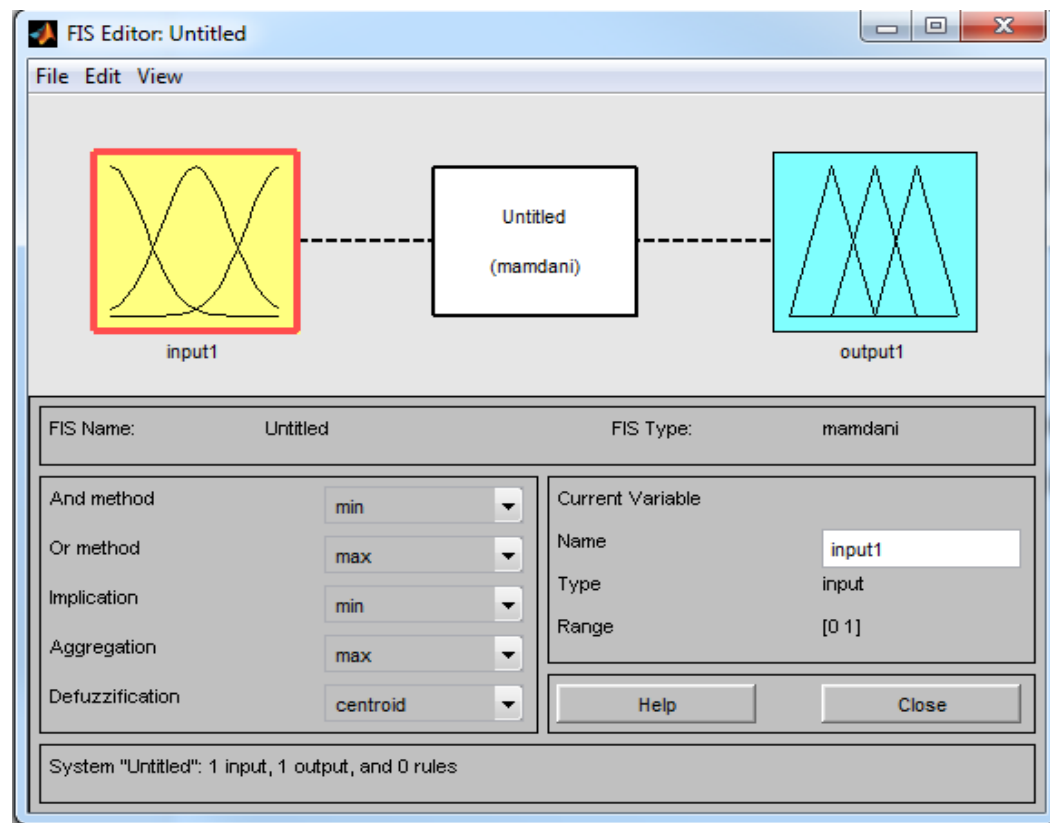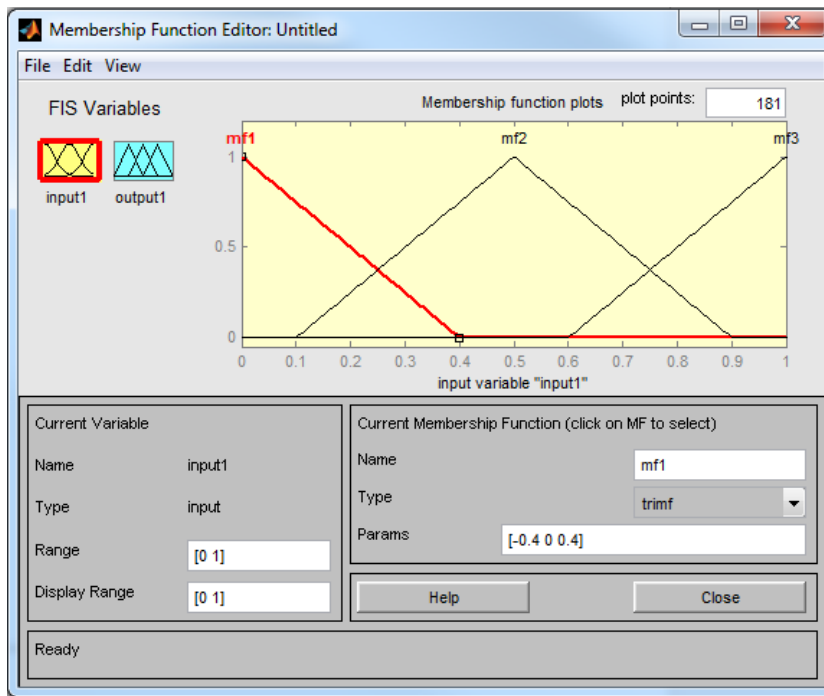

Figure D-1 Fuzzy Inference System Editor

2. <u>Membership Function Editor</u>: The membership function editor is used to define the form that each membership function will follow for each specific input. Figure 5-3 shows a Membership Function editor.

Figure D-2 Membership Function Editor

        <u>3. Rule Editor</u>: The rule editor is used to specify and edit the specific rules under which the fuzzy inference system operates. A list of possible inputs is shown, along with a set of and/or operators that are used to create a rule. Figure 5-4 illustrates the rule editor.
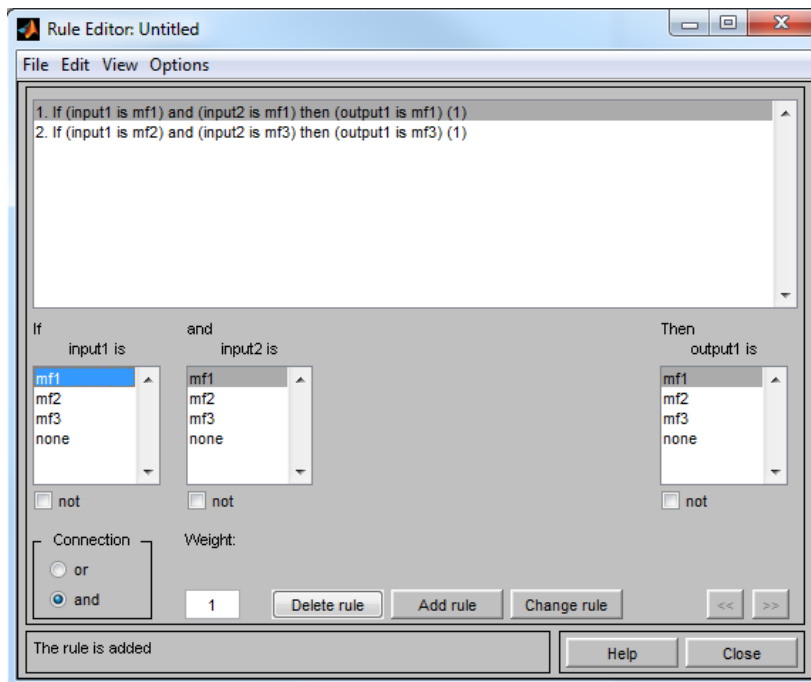
Figure D-3 Fuzzy rule editor

4. Rule viewer: This window is used to view the entire implication process from beginning to end. A set of inputs can be selected and the rule viewer shows the membership function result for each input as well as the result of the implication method applied to the fuzzified variables and the aggregation of them to produce the output. The defuzzified output is also given as a real number.
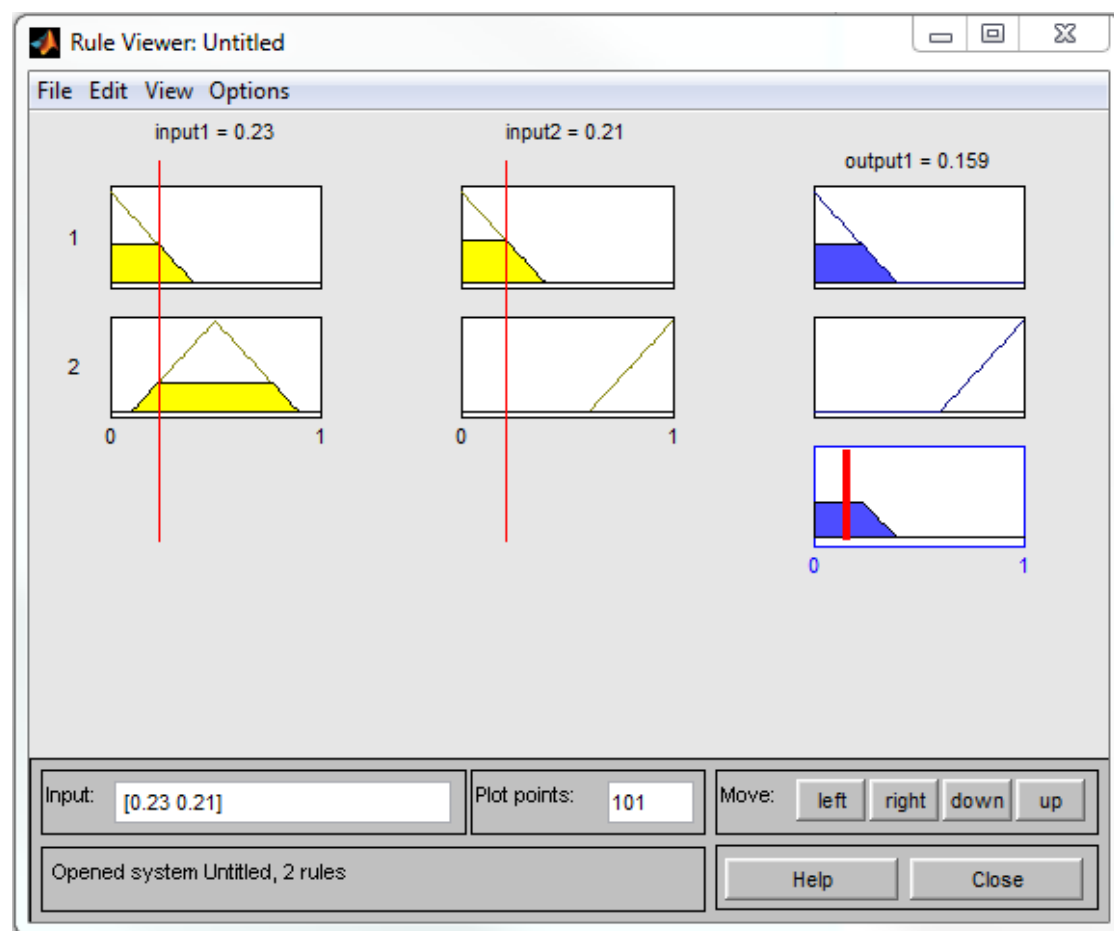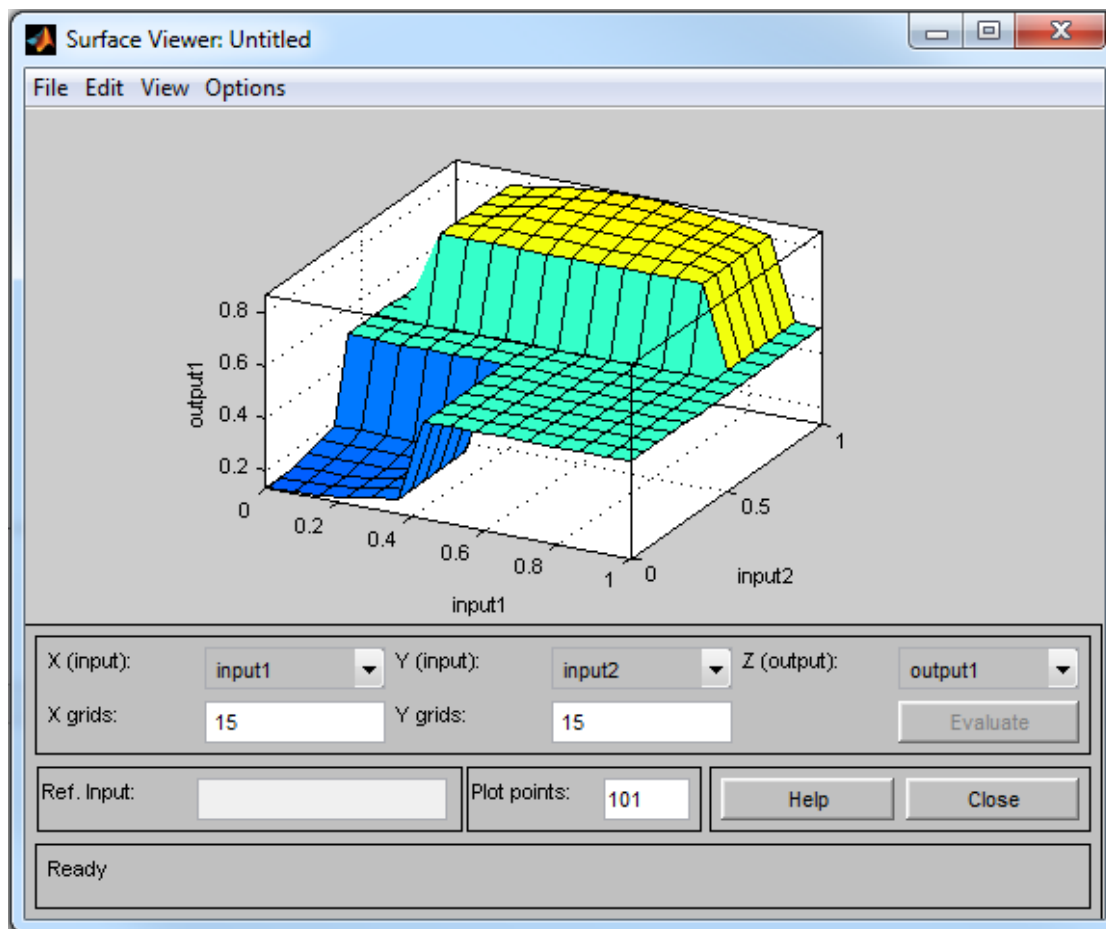

Figure D-4 Rule Viewer

Figure D-5 Surface Viewer

5. Surface Viewer: This tool generates a 3d graph showing the system. It illustrates the entire system performance over the entire range of inputs and outputs as shown in figure 5-6.

Appendix E. ISO New England information

It is an independent, non-profit Regional Transmission Organization (RTO), serving Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont . ISO-NE oversees the operation of New England's bulk electric power system and transmission lines, generated and transmitted by its member utilities, as well as Hydro-Québec, NB Power, the New York Power Authority and utilities in New York state, when the need arises. ISO-NE is responsible for reliably operating New England's 32,000 megawatts [MW] bulk electric power generation and transmission system. One of its major duties is to provide tariffs for the prices, terms, and conditions of the energy supply in New England [18].