Energy Trading Model for PV-Diesel Microgrids

A Project Report

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***T**o my Parents,*

***f**or all the love they gave me…*

Thesis Certificate

This is to certify that the thesis titled **Energy Trading Model for PV-Diesel Microgrids** submitted by Anuraag Reddy K, to the Indian Institute of Technology Madras, for the award of the Dual degree of **Bachelor of Technology** and **Master of Technology**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or parts have not been submitted to any other Institute or University for the award of degree or diploma.

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Anuraag Reddy Khairtabad

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*METM = Microgrid Energy Trading Model

Abstract

In India there is a shortage of installed electric power and the demand supply gap is expected to increase if we continue to generate power using conventional sources only. With about 300 clear and sunny days, India has a huge potential to generate clean solar energy and through this project we try to make the use of solar energy more cost effective [5].

Objective is to build a Microgrid Energy Trading Model [6] which makes profitable trading decisions by minimizing the overall costs of operation. The Microgrid under consideration operates in a fully deregulated market and has two sources (Solar and Diesel) of generation, battery storage [4] and is also connected to the utility grid. The load in the Microgrid is modeled as both schedulable and non-schedulable load and the schedulable load demand is met when the cost of power is at its lowest.

The trading model uses historic data and various forecasting techniques [1][2][6] like the Incremental Moving Average etc. to get Day-ahead forecasts of solar irradiation [13], load and the market prices. Based on the forecasts available the model issues directives to all the components of the Microgrid to maximize [3] the Trade balance and in turn increasing the return on investment (ROI). It also greatly reduces the energy produced from the Diesel Generator and hence helps in cutting the CO_2 emissions [20] making it more eco-friendly.

Key words: Schedulable Load, Day-ahead forecasting, Solar Irradiation, Trade balance, Return on Investment, CO_2 emissions

CHAPTER ONE

Introduction

1.1 Energy Trading

I would like to begin with the definition of trading [19]. So what is it? *A basic economic concept that involves multiple parties participating in the voluntary negotiation and then the exchange of one's goods and services for desired goods and services that someone else possesses.* Energy trading is much more than this and there are a few factors which make is special.

The development of electricity markets is based on the premise that electrical energy can be treated as a commodity. There are, however, important differences between electrical energy and other commodities such as barrels of oil or even cubic meters of gas. These differences have a profound effect on the organization and the rules of electricity markets. The most fundamental difference is that electrical energy is inextricably linked with a physical system that functions much faster than any market. In this physical power system, supply and demand – generation and load – must be balanced on a second-by-second basis. If this balance is not maintained, the system collapses with catastrophic consequences. Such a breakdown is intolerable because it is not only the trading system that stops working but also an entire region or country that may be without power for many hours. Restoring a power system to normal operation following a complete collapse is a very complex process that may take 24 hours or more in large, industrialized countries. The social and economic consequences of such a system wide blackout are so severe that no sensible government would agree to the implementation of a market mechanism that significantly increases the likelihood of such an event. Balancing the supply and the demand for electrical energy in the short run is thus a process that simply cannot be left to a relatively slow-moving and unaccountable entity such as a market. In the short run, this balance must be maintained, at practically any cost, through a mechanism that does not rely on a market to select and dispatch resources.

Another significant, but less fundamental difference between electrical energy and other commodities is that the energy produced by one generator cannot be directed to a specific consumer. Conversely, a consumer cannot take energy from only one generator. Instead, the power produced by all generators is pooled on its way to the loads. This pooling is possible because units of electrical energy produced by different generators are indistinguishable. Pooling is desirable because it results in valuable economies of scale: the maximum generation capacity must be commensurate with the maximum aggregated demand rather than with the sum of the maximum individual demands. On the other hand, a breakdown in a system in which the commodity is pooled affects everybody, not just the parties to a particular transaction. Finally, the demand for electrical energy exhibits predictable daily and weekly cyclical variations. However, it is by no means the only commodity for which the demand is cyclical.

The consumption of coffee, to take a simple example, exhibits two or three rather sharp peaks every day, separated by periods of lower demand. Trading in coffee does not require special mechanisms because consumers can easily store it in solid or liquid form. On the other hand, electrical energy must be produced at the same time as it is consumed. Since its short-run price elasticity of demand is extremely small, matching supply and demand requires production facilities capable of following the large and rapid changes in consumption that take place over the course of a day. Not all of these generating units will be producing throughout the day. When the demand is low, only the most efficient units are likely to be competitive and the others will be shut down temporarily. These less efficient units are needed only to supply the peak demand. Since the marginal producer changes as the load increases and decreases, we should expect the marginal cost of producing electrical energy (hence the spot price of this energy) to vary over the course of the day. Such rapid cyclical variations in the cost and price of a commodity are very unusual.

One could argue that trading in gas also takes place over a physical network in which the commodity is pooled and the demand is cyclical. However, the amount of energy stored in the gas pipelines is considerably larger than the amount of kinetic energy stored in electricity-generating units. An imbalance between production and consumption of gas would therefore have to last much longer before it would cause a collapse of the pipeline network. Unlike an imbalance in a power system, it can be corrected through a market mechanism.

1.2 Deregulation and Government policies [2][12]

1.2.1 Brief concepts on Regulation and Deregulation

During the nineties decade, many electric utilities and power network companies world-wide have been forced to change their way of operation and business, from vertically integrated mechanisms to open market systems. This can be specifically observed in countries like US, Sweden, Finland, Norway, us and some countries of South America. The reasons for change have been many and have differed over regions and countries

For developing countries like India, the main issues have been a high demand growth couples with inefficient system management and irrational tariff policies. This has affected the availability of financial resources to support investments in improving generation and transmission capacities. In such circumstances many utilities were forced to restructure their power sector under pressure from international funding agencies.

In developed countries, on the other hand, the driving force has been to provide electricity at lower prices and offer then a greater choice in purchasing economic energy.

The goal of changing the way of operation, i.e. re-regulation, or deregulation, as we say, is to enhance competition and bring consumers new choices and economic benefits.

Under deregulation, the former vertically integrated utility, which performed all the functions involved in power i.e. generation, transmission, distribution and retail sales, is dis-aggregated into separate companies devoted to each function. The electricity bill for the end consumer now involves at least two components: one from the distribution and transmission network operator responsible for the network and services, and the other from the company that generates the electrical energy.

All this seems to be very straightforward, but there are several complexities involved in restructuring and many issues have been raised.

Regulation: *Regulation means that the government has set down laws and rules that put limits on and define how a particular industry or company can operate.*

Nearly all industries in all countries are regulated to some extent. Very competitive businesses such as auto manufacturing, airlines and banking are all heavily regulated with myriad government requirements defining what they must, can and cannot do, and what and to whom and when they must report their activities.

Regulation of electric utilities is not the only way government can control the electric power industry within its jurisdiction. The other was is to own and operate the power company directly, as a government utility.

Deregulation: *Deregulation in power industry is as restructuring of the rules and economic incentives that government set up to control and drive the electric power industry.*

Characteristics of a regulated electric industry

- **i.** Monopoly franchise: only the local electric utility can produce, move, or sell commercial electric power within its service territory
- ii. Obligation to serve: the utility must provide service to all electric consumers in its service territory, not just those that would be profitable
- iii. Regulatory oversight: the utility's business and operating practices must confirm to the guidelines and rules set down by government regulators
- iv. Least-cost operation: the utility must operate in a manner that minimizes its overall revenue requirements
- v. Regulated rates: the utility's rates are set in accordance with government regulatory rules and guidelines
- vi. Assumed rate of return: the utility is assured a fair return on its investment, if it confirms to the regulatory guidelines and practices

1.2.2 Structure on regulated industry

The electric power industry has over the years been dominated by large utilities that had overall activities in generation, transmission and distribution of power within its domain of operation. Such utilities have often been referred to as vertically integrated utilities. Such utilities served as the only electricity provider in the region and we obliged to provide electricity to everyone in the region.

In the *Figure 1-1*, the money flow is unidirectional, i.e. from the customer to the electric company. Similarly, the information flow exists only between the generators and the transmission systems.

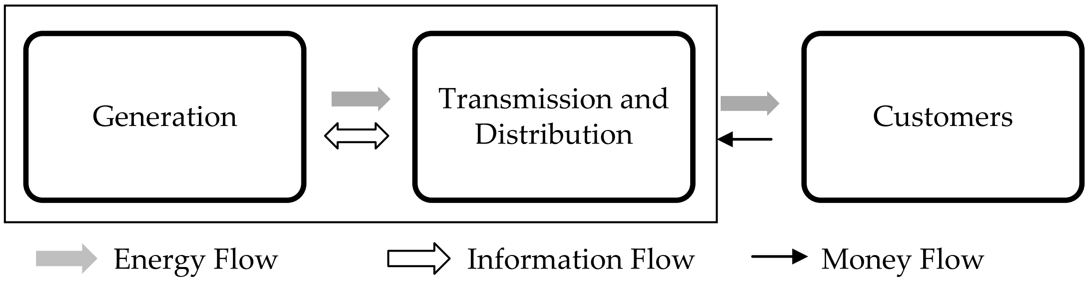

Figure 1-1: A typical structure of a vertically integrated electric utility

The utilities being vertically integrated, it was often difficult to segregate the costs involved in generation, transmission or distribution. So, the utilities often charged their customers an average tariff rate depending on their aggregated cost during a period.

1.2.3 Conditions that led to Deregulation

The Basic motivation was a change in the power industry scenario but there are many reasons that led to deregulation of power system. One force that led to the deregulation of electric power was the change in generation economies of scale that occurred throughout the 1980's.

Traditionally, the electric utility systems evolved with the central station concept because of significant economy of scale in power generation. Very large generators produced power at less than half the cost per kilowatt of small generator units, and the bigger the generator, the more economical the power produced.

For the reasons stated below, the shift in the economy of scale was observed:

i. Technological innovation improved the efficiency of small units for gas turbines, combined cycle, hydro and fuel cells over that of large ones
ii. Improvements in material, including new high temperature materials. Special lubricants, ceramics and carbon fiber, permit vastly stronger and less expensive small machinery to be built
iii. Computerized control systems have been developed that often reduce the number of on-sight personnel to zero

iv. Data communications and off-site monitoring systems can control the units from remote operations centers, where one central operator can monitor a dozen units at various sites, as if present as each.

Thus in many instances, it was possible to build new power plants that could provide energy at a lower price than what the customers were paying for that coming from the existing old and giant power plants. It became possible for the industrial and commercial users of electricity to build and operate their own plants to produce power cheaper than that of utility and also sell the excess power to small customers.

The reasons for initiating the idea of deregulation in power industry are many. Following are the main reasons:

1. The need for regulation changed

Main reason for change was the fact that the basic needs for regulation of electric industry had died away before the end of the 20th century. First, the original need for regulation, which was to provide risk free finance to build the infrastructure; did not exist anymore. Second, the omnipresent electric system created, was paid for decades ago. The revenues gained by the electric utilities was invested to renew their system and the level of risk in doing so was less as compared to that existed in the initial era.

Being a proved technology, the risk involved in investing money in such a technology was nullified. The electricity could be thought of an essential commodity; which can be bought and sold in the market price in a competitive manner, just like other commodities.

2. Privatization

Usually the motive was the government's firm conviction that the private industry could do a better job of running the power industry. His belief, of course came from the better privatization experiences of other industries. Deregulation does not need to be a part of the privatizations efforts. The deregulation to free up the rules always accompanies privatization.

3. Cost is expected to drop

Competition brings innovation, efficiency and lower costs. The rate of cost decline is different in different areas. The reasons for this are manifold. The overall experience all over the world is that the electricity prices have declined

4. Customer focus will improve

Although monopoly franchise utilities have an obligation to serve all customers, that does not promote the pro-active attention to customer needs. A monopoly franchise utility listens to its customers, when they explain their needs and then responds. A competitive electric service company anticipates customer's needs and responds in advance. The technological advances that will be applied under deregulation, address customer service. More important gain of competition in the electricity market is the customer value rather than lowering the cost.

5. Encourages innovation

The regulatory process and the lack of competition gave electric utilities no incentive to improve on yesterday's performance or to take risks on new ideas that might increase customer value. If a new idea succeeded in cutting costs, the utility still made only its regulated rate of return on investment. If it didn't work the utility usually have to bear a significant part of the failed attempt, as imprudent expenses

Under deregulated environment, the electric utility will always try to innovate something for the betterment of service and in turn save its cost and maximize the profit. By means of this, the utility will try to ensure that it will maintain its customer base in spite of competition.

Some other forces supporting the main reasons for motivating the deregulation can also be enlisted as follows:

i. Overstaffing in the regulated electric industry
ii. Global economic crises
iii. Political and ideological changes
iv. Managerial inefficiency in the regulated company
v. Lack of public resources for further development
vi. More demanding environment issues
vii. Pressure of financial institutions

It is unfair to blame the electric utilities for their unwillingness to take risks, and their lack of technological progress and lower customer focus under regulation. They were simply responding to the system of rules set down by the government. The problem was with the regulatory system itself. It had provided growth and stability when that was needed. But, too much stability means stagnation and that was the ultimate result in the electric utility industry.

Thus, what needed to be fixed was the regulatory framework, and, hence deregulation.

1.2.4 Overview of a deregulated industry

One of the principal characteristics of a competitive structure is the identification and separation of various tasks which are normally carried out within traditional organization so that these tasks can be open to competition whenever practical and profitable. This process is called unbundling. An unbundles structure contrasts with the so called vertically integrated utility of today where all tasks are coordinated jointly under one umbrella with one common goal, that is, to minimize the total costs of operating the utility.

One of the first steps in the restructuring process of the power industry has been separation of the transmission activities from the electricity generation activities.

The next step was to introduce competition in generation activities, either through the creation of power pools, provision for direct bilateral transactions or bidding in the spot markets.

On the other hand, the transmission system having significant economies of scale consequently had a tendency to become a monopoly. Thus it was felt necessary to introduce regulation in transmission so as to prevent it from overcharging for its services. The transmission system thus became a neutral natural monopoly subject to regulation by public authorities.

In brief, electric utilities are expected to split apart into unbundled companies, with each utility re-aligning itself into several other companies that respectively focus on each part of the new industry, i.e. power delivery and retailing. This is knows as disaggregation.

Under deregulation, the vertically integrated utility, one giant company that generates, transmits, distributes and sells electricity in a coordinated manner became a thing of the past. To function in and open access system, such utilities will have to rearrange their operational organization to match the unbundled functions they must perform. Each part of the organization will need to work in the new form. Generation will have to compete in the competitive power generation market. Transmission and Distribution will have to operate as an open provider of delivery services. Competition will be present for retailing.

The governments advocating deregulation want competition in energy production, and they want to see significant levels of customer choice in the retail market for electricity. At the same time, it recognizes that it is best to have only one transmission and one distribution system in any one area. Therefore, the purpose of deregulation is to restructure the electric industry so that power production and retail sales are competitive, while delivery is still a regulated, monopoly franchise business.

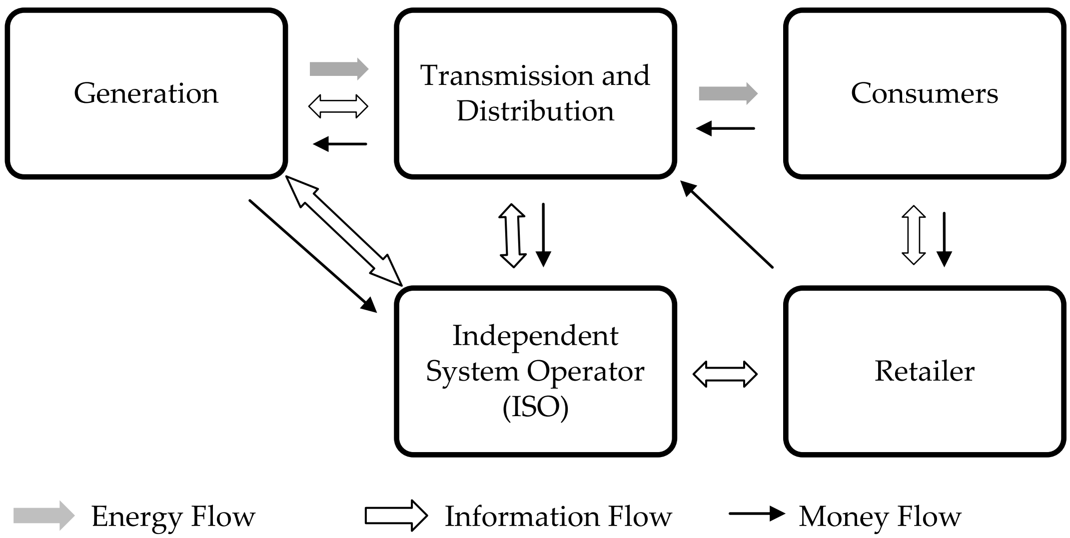

Figure 1-2: A typical structure of a deregulated system

A system operator is appointed for the whole system and it is entrusted with the responsibility of keeping the system in balance, i.e. to ensure that the production and imports continuously match consumption and exports. Naturally, it had to be an independent authority with no involvement in the market competition and could it own generation facilities for business. This system operator is known as Independent System Operator (ISO).

According to *Figure 1-2*, there is no change as compared to the *Figure 1-1* so long as the energy flow is concerned. Customer does its transactions through a retailer or transacts directly with generating company, depending on the type of a model.

Different power sellers will deliver their product to their customer, over a common set of transmission and distribution wires operated by the ISO. The generators, transmission and distribution utility and retailers communicate ISO. Mostly, customer communicates with the retailer, demanding energy. The retailer contacts the generating company and purchases power from it and makes it transferred to it customer's place via regulated T&D lines. The ISO is the one responsible for keeping track of various transactions taking place between various entities.

1.2.5 Government Policies [16]

Parliament of India, in 2003 passed the Electricity Act, an Act to consolidate the laws relating to generation, transmission, distribution, trading and use of electricity and generally for taking measures conducive to development of electricity industry, promoting competition therein, protecting interest of consumers and supply of electricity to all areas, rationalization of electricity tariff, ensuring transparent policies regarding subsidies, promotion of efficient and environmentally benign policies, constitution of Central Electricity Authority, Regulatory Commissions and establishment of Appellate Tribunal and for matters connected therewith or incidental thereto.

The Central Electricity Regulatory Commission (CERC) on February 6, 2007 issued guidelines for grant of permission to set up power exchanges in India. Financial Technologies (India) Ltd responded by proposing then tentatively named 'Indian Power Exchange Ltd' and applied for permission to set it up and operate it within the parameters defined by CERC and other relevant authorities. Based on the oral hearing on July 10, the CERC accorded its approval vide its order dated 31st August, 2007. IEX thus moved from the conceptual level to firmer grounds. On 9th June 2008 CERC accorded approval to IEX to commence its operations and 27th June 2008 marked its presence in the history of Indian Power Sector as Indian Energy Exchange Ltd (IEX), India's first-ever power exchange goes LIVE. Within 5 years it gets and Average Daily Volume for Q1 FY 2011 - 20,921 MWh with 86% market share in India. It also took the market price of a KWh to a record low of 13 paisa in November 2009, demonstrating the true potential of supply demand economics. Also, Benefits of having a deregulated market are worth talking about.

- <u>Access a diversified portfolio</u>: Exchange offers a broader choice to generators and distribution licensees so that they can trade in smaller quantities and smaller number of hours without additional overheads.
- <u>Payment security</u>: Exchanges stand in as the counter-party for all trades; so participants need not be concerned about the risk-profile of the other party

- Minimal transaction overheads/charges: All charges are public information and due to the economies of scale the charges are minimal
- Efficient portfolio management: Exchanges enables participants to precisely adjust their portfolio as a function of consumption or generation. Participants, especially distribution licensees, are enabled to precisely manage their consumption and generation pattern

1.3 Overview of the Project

1.3.1 Microgrid under consideration

The Microgrid under consideration, as shown in the *Figure 1-3* has multiple sources of generation i.e. Solar panels and Diesel generator set. The Microgrid is connected to the utility grid through an Energy trading model which takes profitable decisions satisfying all the constraints. What makes the trading decisions complicated is the presence of the Battery, which is the only element with memory. In simple words, using it in the i^{th} hour will have an effect on using it in the $(i+1)^{th}$ hour unlike any other element.

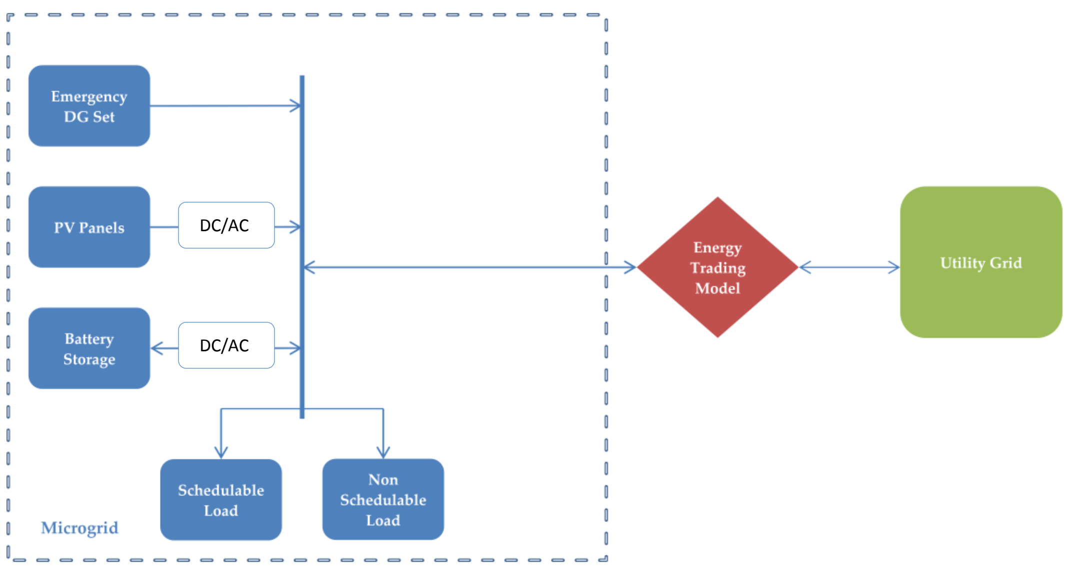

Figure 1-3: Single line diagram of the Microgrid with arrows indicating the direction of the flow of power

The electricity markets intrinsically have very cyclical patterns, each cycle being 24 hours. So to take care of the battery (memory element) we forecast the data 24 hours in advance and obtain the most profitable trades for the next 24 hours and implement only the next hour's trade. Thus every hour we project the next 24 trades and implement the next hour trade only. This way, we sell the energy stored in the battery at the maximum possible price, thus generating maximum returns. The working of the model is explained in detail in the further chapters.

The roadmap of the project is also briefly discussed to give the readers a better understanding of the approach to the problem. The project is split into two parts, the first being **forecasting** and the second being **trading**.

Part A: Forecasting

The most essential part of any forecast is acquiring good quality data. Once the data is acquired various techniques can be used for day ahead forecasting. For working of the model we need to forecast Solar energy output (SG), non schedulable demand (D) in the Microgrid and the market price of power (MP) a day in advance. Day ahead forecasting of solar irradiation is imperative in finding out the solar energy output and hence we need to find out on what measurable data it depends on. Forecasting is discussed in detail in the next chapter.

Part B: Trading

This is the core part of the project, where we build the model which makes key decisions on trading to maximize the trade balance. The detailed working of the model is discussed in the chapter on Energy trading architecture.

1.3.2 Scope of the project

The principle aim of the project is to increase the trade balance by making good trading decisions. The model forecasts solar irradiation using historic data a day in advance but it ignores the effect of clouds. It also forecasts the market price of electricity using the data from IEX using algorithms that are computationally less intensive as the model is designed to operate in remote areas. The model also assumes that the storage facility has a very high efficiency which is not true in the case of the present technology, there is heat loss. With the development of new storage technology we can hope for these kinds of high efficiency devices. The model also assumes that there are no constraints on selling of energy in blocks. The DC/AC conversion loss is not taken into consideration.

CHAPTER TWO

Microgrids

2.1 Microgrids and their importance [19]

Microgrids are modern, small-scale versions of the centralized electricity system. They achieve specific local goals, such as reliability, carbon emission reduction, diversification of energy sources, and cost reduction, established by the community being served. Like the bulk power grid, smart Microgrids generate, distribute, and regulate the flow of electricity to consumers, but do so locally. Smart Microgrids are an ideal way to integrate renewable resources on the community level and allow for customer participation in the electricity enterprise. They form the building blocks of the Perfect Power System. Microgrids allow power generation and consumption to be managed so that the load is balanced with the supply. Smart power meters allow power to be stored in batteries and reused at times of peak demand. This smart approach to managing energy use can result in lower energy costs to the consumer because it encourages making smarter choices about power use.

We can classify Microgrids broadly into four categories. They are:

i. Remote grids, which are necessary due to geographical features, such as islands. Consider a country like Indonesia that has more than twenty-three-thousand islands. It is simply not practical to connect all these to a single national grid. The power sources in these grids are on the same conventional lines are using fossil fuel.
ii. Military and security are grids necessary to maintain data and security during a national catastrophe. The power sources in these grids are also on the same conventional lines using fossil fuel.
iii. Commercial or industrial grids catering to a specific industrial community. The energy sources could be fossil fuel based or energy recovered for the process like waste heat, bio fuels, or waste products. These are mainly captive energy systems.

iv. Community grids that optimize and utilize the specific regional renewable resources to give cost effective power supply. Fossil fuel usage is only used as an emergency backup. This is the really effective Microgrid.

We also need to know why Microgrids play an important role in the future. The centralized transmission grid system is definitely the backbone of the electricity distribution system, but has its drawbacks.

i. The energy loss is almost 8 -10 %.
ii. There are high investment costs in transmission lines, step-up and step-down transformers, right of way and other legal issues.
iii. Grid management is a constantly juggling act where it balances the generation and the demand over a wide geographic area.
iv. The generating capacity has to match the peak load, which means a lot of excess capacity is built into the system, which increases the investment cost.
v. All the users feel the grid disturbances, outages, frequency changes and voltage fluctuations, blackouts and brownouts. This can affect the performance and life of electrical equipment.

The Microgrid, even though not a replacement of the national grid, improves certain aspects especially for communities and regions that have adequate renewable resources.

i. They have much smaller financial commitments.
ii. They use renewable resources hence are more environmentally friendly with lower carbon footprints.
iii. They require fewer technical skills to operate and rely more on automation.
iv. They are isolated from any grid disturbance or outage.
v. They place the consumer out of the grip of large corporations that run the generation networks.

Microgrids are cost effective only if you can tap into locally available renewable energy resources. Solar energy is available everywhere but with limitations. Wind, mini hydro, geothermal and bio mass are regionally available and can augment Solar energy. This combined with a storage device, battery or super capacitors and backup diesel generator makes Microgrids highly reliable and cheap. Storage devices in very large grid systems are not economically or technically proven. The advent of latest technologies in nano batteries and nano super capacitors makes electricity storage a reality in the smaller capacity range. This is an advantage for Microgrids. Advances in computerized control technology make it possible to have simple and efficient controls with less human interference and is the key ingredient that makes Microgrids feasible.

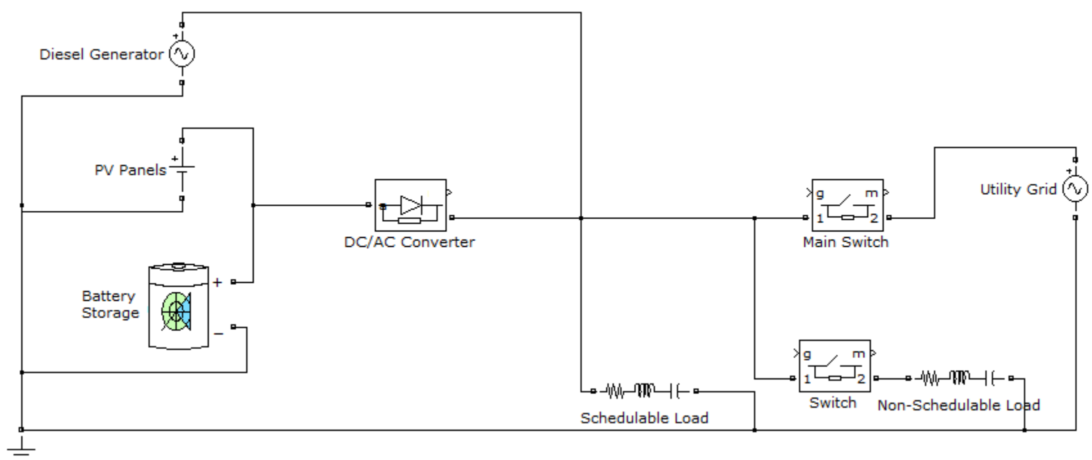

Figure 2-1: PV-Diesel Microgrid under consideration in Matlab® Simulink

High technology products like nano solar cells, nano super capacitors, nano batteries and fuel cells will make the Microgrid with storage capacities a reality. Advances in automation, power electronic control systems will also help in the popularity of Microgrids. Even hybrid cars plugged into the home wiring can act as a generating sources or a storage device. In larger communities mini nuclear plants could be the ideal source of energy for the Microgrids.

2.2 Structure and the components of a Microgrid [7]

Microgrid systems targeted in this study are autonomous areas having the power demand of several kilowatts including diesel engines (DG), photovoltaic panels (PV) and battery (B) and serves its own power demand (Load). *Figure 2-1* shows the structure of the proposed Microgrid. Microgrids can also be connected to the external power system by tie lines for reducing frequency/voltage fluctuation in the normal and emergency conditions. Such Microgrid systems are operated independently with zero tie-line flow under normal conditions. In this project a dynamic simulation is conducted assuming the Microgrid is operated independently from external electric power systems. To maintain the frequency near constant under autonomous operation, the demand-and-supply balance is controlled by the diesel governor and battery output control.

A. Diesel Generator

Diesel engine controls the output by the governor which is installed in the generator set. This achieves generally a good load following operation.

B. Battery Storage

The operating condition of the battery storage is decided depending on the frequency responses of the autonomous Microgrid system. The steady-state output of the battery storage is the amount of load with the total output of diesel engine and of photovoltaics subtracted.

C. Photovoltaic (PV) Panels

The output of photovoltaic cells change by the weather, so in this project, we have used the pattern of output that has been measured by the field tests of photovoltaic panels available on National Renewable Energy Laboratory website. For each daylight hour average output is assumed under the different weather conditions such as clear, cloudy, or rain. In addition, the capacity of the photovoltaic panels installed in the Microgrid is around 500 kW.

2.3 Microgrids and the Indian Scenario [21]

Uttar Pradesh is a state in India and About 42 per cent of Uttar Pradesh's villages are off-grid. Orissa, Bihar, and Jharkhand are in even worse condition with fewer than 35 per cent of rural households having electricity. As of 2010, it is estimated that 48 per cent of rural households are unelectrified nationally leaving approximately 400 million people without electricity.

While India makes global headlines for its impressive economic growth, the majority of Indians continue to live in poor conditions. Power is not by any means the only or biggest challenge of rural life in India. It is an enormous issues, but what makes the lack of power so unfortunate is that solutions exist and when implemented they enable economic opportunities that allow people to climb out of poverty.

When we think of economic opportunities that power provides, we think of irrigation and electrical machinery; but in fact for most rural Indians it is simply the luxury of light which allows them to work later into the evenings. With competing demands on public resources, it is understandable that the national grid model of power delivery, which requires enormous public subsidies to build and operate, has yet to meet the country's full demand. The government may have to prioritize on generation and transmission investments, providing power through the grid to only those it can do so economically, finding an alternative solution to powering the lives of those that live beyond the grid's edge.

Traditional thinking tells us that there should be efficiencies of scale in power: larger generation facilities feeding into larger transmission lines serving a larger customer base will be more efficient than smaller power generation that is distributed locally to serve only a small number of customers. But that argument rests on a model of demand that fairly accurately describes India's more power hungry and more densely located urban consumers than it does the majority of the country which is rural with more modest power demands. Because of the minimal power consumption requirements of poor, rural households, the costs of extending the distribution system multiple kilometers cannot often be justified by the minimal projected revenues.

Rather than producing power in Gujarat and delivering that power to a small village in Uttar Pradesh, transmitting power hundreds of kilometers to do so, power can be produced locally in smaller quantities and distributed very short distances. India has been a testing ground for innovations in off-grid, rural power. Solar lanterns and solar home systems have been designed for India and then taken to the rest of the world. Another innovation, the micro grid, has been demonstrated on a commercial basis only in India. Desi Power, Husk Power Systems, Saran Renewable Energies, Mera Gaon Micro Grid Power, and Naturetech Infra all operate micro grids on a commercial basis. While India offers an opportunity for commercial micro grid operations where other countries do not, there are still unnecessary risks to micro grid operation which inhibit adequate investment into the sector and limit the extent to which these companies can serve off-grid customers.

Grand programs to reach the rural poor have generally fallen far short of expectations. Approximately 30 per cent of India's generated power is lost in transmission. Most on-grid households still have to deal with power cuts, many get only a few hours of power at odd times of the day. The government has plenty of challenges to overcome before reaching the tens of millions of new customer households it has yet to reach. So at the current rate of electrification 200 million people will still be off-grid in 2020.

2.4 Summary

Microgrids are one of the most important things for energy security in the near future. They are the means for sustainable development, reduction of carbon emissions and electrification of remote corners of the world. But, there are a lot of challenges we need to face before we turn this technology into a reality. First and foremost we need to make it cost effective and that is how investments come pouring in into development of Microgrids. In this chapter we have seen the need for Microgrids and in further chapter we see how the return on investment is improved on a typical Microgrid using a case study.

CHAPTER THREE

Forecasting of Price and Irradiation

3.1 Acquiring relevant data

3.1.1 The need for data [12]

Most research projects need data in order to answer a proposed research problem. The data that need to be acquired, and the sources of such data, must be identified as a matter of utmost importance. No amount or depth of subsequent data analysis can make up for an original lack of data quantity or quality.

Research problems and objectives (or hypotheses) need to be very carefully constructed and clearly defined, as they dictate the data that need to be obtained and analyzed in order to successfully address the objectives themselves. In addition, the quantity of data, their qualities, and how they are sampled and measured, have implications for the choice and effectiveness of the data analysis techniques used in subsequent analysis. Thus, we need to keep the following points in mind before we proceed any further:

i. Most research requires data and data analysis.
ii. Data acquisition is of utmost importance and considerable effort should be made to obtain or generate good data.
iii. Good data are data whose characteristics enable the research objectives to be met.
iv. Data of poor quality or undesirably low quantity will lead to unsatisfactory data analysis and vague results.
v. The characteristics of the data, particularly their type, quantity, and how they were sampled, constrain the choice of data analysis techniques able to be used on the data.
vi. Data analysis can only be as good as the original data allow.

3.2 Techniques used for forecasting

3.2.1 Linear regression [13]

Linear regression calculates, or predicts, a future value by using existing values. The predicted value is a y-value for a given x-value. The known values are existing x-values and y-values, and the new value is predicted by using linear regression. We can use this method to predict future values provided we have large data sets and a highly dependent variable (y). Thus, the most challenging task of using this model will be to find the right dependent variable. We use this for forecasting of solar irradiation which is discussed in detail in further chapters.

Syntax

FORECAST(x, known_y's, known_x's)

The FORECAST function syntax has the following arguments:

- **X** Required. The data point for which you want to predict a value.
- **Known_y's** Required. The dependent array or range of data.
- **Known_x's** Required. The independent array or range of data.

Remarks

- If known_y's and known_x's are empty or contain a different number of data points, FORECAST returns the #N/A error value.
- If the variance of known_x's equals zero, then FORECAST returns the #DIV/0! error value.
- Formula used by the forecast function is shown below

$$Forecast = a + bx \tag{3.1}$$

$$a = \bar{y} - a\bar{x} \tag{3.2}$$

$$b = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sum(x-\bar{x})^2} \tag{3.3}$$

and where x and y are the sample means AVERAGE (known x's) and AVERAGE (known y's).

3.2.2 Moving Average model [15] with and illustration

The moving average forecast is based on the assumption of a constant model.

$$X_t = b + \epsilon_s \tag{3.4}$$

We estimate the single parameter of the model at time *T* as average of the last *m* observations, where *m* is the moving average interval.

$$\hat{b}_{\mathrm{T}} = \frac{\sum_{(t-T-m+1)}^{T} X_t}{m} \tag{3.5}$$

Since the model assumes a constant underlying mean, the forecast for any number of periods in the future is the same as the estimate of the parameter:

$$\hat{X}_{\mathrm{T+t}} = \hat{b}_{\mathrm{T}} \text{ for t = 1, 2….} \tag{3.6}$$

In practice the moving average will provide a good estimate of the mean of the time series if the mean is constant or slowly changing. In the case of a constant mean, the largest value of *m* will give the best estimates of the underlying mean. A longer observation period will average out the effects of variability. The purpose of providing a smaller *m* is to allow the forecast to respond to a change in the underlying process. To illustrate, we propose a data set (*Figure 3-1*) that incorporates changes in the underlying mean of the time series.

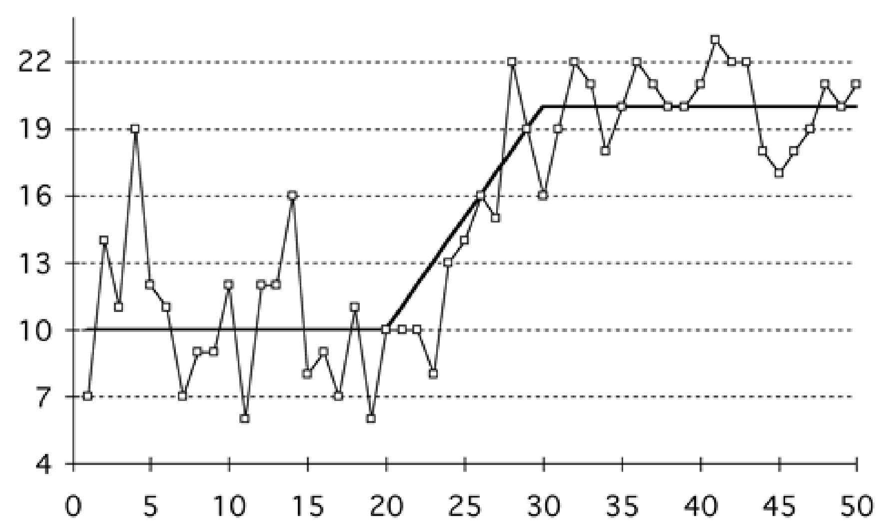

Figure 3-1: shows the time series used for illustration together with the mean demand from which the series was generated

The mean begins as a constant at 10. Starting at time 21, it increases by one unit in each period until it reaches the value of 20 at time 30. Then it becomes constant again. The data is simulated by adding to the mean, a random noise from a Normal distribution with zero mean and standard deviation 3. The results of the simulation are rounded to the nearest integer.

Table 3-1: *Simulated observations from the demonstration using MA model*

Time	Observations									
01 - 10	7	14	11	19	12	11	7	9	9	12
11 - 20	6	12	12	16	8	9	7	11	6	10
21 - 30	10	10	8	13	14	16	15	22	19	16
31 - 40	19	22	21	18	20	22	21	20	20	21
41 - 50	23	22	22	18	17	18	19	21	20	21

The estimates of the model parameter, $\widehat{b}$ for three different values of *m* are shown together with the mean of the time series in the figure below. The figure shows the moving average estimate of the mean at each time and not the forecast. The forecasts would shift the moving average curves to the right by *t* periods.

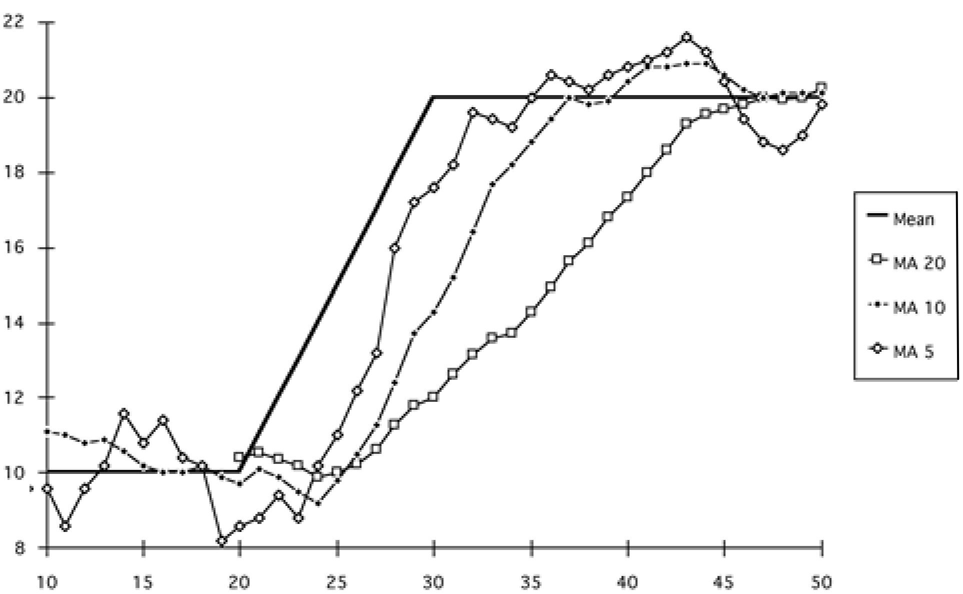

Figure 3-2: Shows the forecast using MA model for different intervals sizes (5, 10 and 20)

One conclusion is immediately apparent from the figure. For all three estimates the moving average lags behind the linear trend, with the lag increasing with *m*. The lag is the distance between the model and the estimate in the time dimension. Because of the lag, the moving average underestimates the observations as the mean is increasing. The bias of the estimator is the difference at a specific time in the mean value of the model and the mean value predicted by the moving average. The bias when the mean is increasing is negative. For a decreasing mean, the bias is positive. The lag in time and the bias introduced in the estimate are functions of *m*. Larger the value of *m*, the larger the magnitude of lag and bias.

3.3 Solar irradiation and its dependence on temperature

Solar irradiation is the primary source of energy for all life forms on earth and temperature has a very high dependence on solar irradiation. After collecting seven years of data from the National Renewable Energy laboratory and various websites, we decided on going ahead with the linear regression model.

$$\text{Solar Energy Forecast} = \text{Solar Irradiation} \times \text{Efficiency } (\eta)$$

Efficiency curve (η) can be obtained from the manufacturer of the PV cells.

Input parameters for forecasting Solar Irradiation using linear regression were:

- Historical Data (y)
- Temperature of the day (x)

We had the maximum temperature (T_{MAX}), minimum temperature (T_{MIN}) and the mean temperature (T_{AVG}) of every day. The challenging part is identifying the right input to the regression.

Table 3-2: *Tmax, Tmin and Tavg listed next to hourly Solar Irradiation (W-h/m²) of the same day*

Date	T	TM	Tm	Day\Hour	0	1	2	3	4	5
01-01-02	25	28	21.5	1	0	0	0	0	0	0
02-01-02	24.4	28.3	21.8	2	0	0	0	0	0	0
03-01-02	24.7	28.8	20.2	3	0	0	0	0	0	0
04-01-02	24.8	28.2	21.3	4	0	0	0	0	0	0
05-01-02	25.3	28.6	23	5	0	0	0	0	0	0
06-01-02	26.4	30	22.9	6	0	0	0	0	0	0
07-01-02	24.7	27.6	12	7	0	0	0	0	0	0
08-01-02	24.9	30	22.5	8	0	0	0	0	0	0
09-01-02	23.6	26.3	22.6	9	0	0	0	0	0	0
10-01-02	24.7	28.8	22.1	10	0	0	0	0	0	0
11-01-02	24.8	28.7	20.4	11	0	0	0	0	0	0
12-01-02	23.2	29	19.6	12	0	0	0	0	0	0
13-01-02	23.9	29.8	18	13	0	0	0	0	0	0
14-01-02	23.6	29.2	18.5	14	0	0	0	0	0	0
15-01-02	22.6	30	18.5	15	0	0	0	0	0	0
16-01-02	22.4	29.3	19.4	16	0	0	0	0	0	0
17-01-02	23.2	29.9	19	17	0	0	0	0	0	0
18-01-02	24.3	29.8	20.4	18	0	0	0	0	0	0
19-01-02	25.8	30.6	21.2	19	0	0	0	0	0	0
20-01-02	25.2	28.7	22	20	0	0	0	0	0	0

From *Table 3-2* we can see that in order to find out solar irradiation's dependence on temperature, we grouped the irradiation data hour wise and computed the correlation between temperature vectors and the hourly irradiation vectors. The plot of 24 correlations with each of the 3 temperature vectors is plotted below.

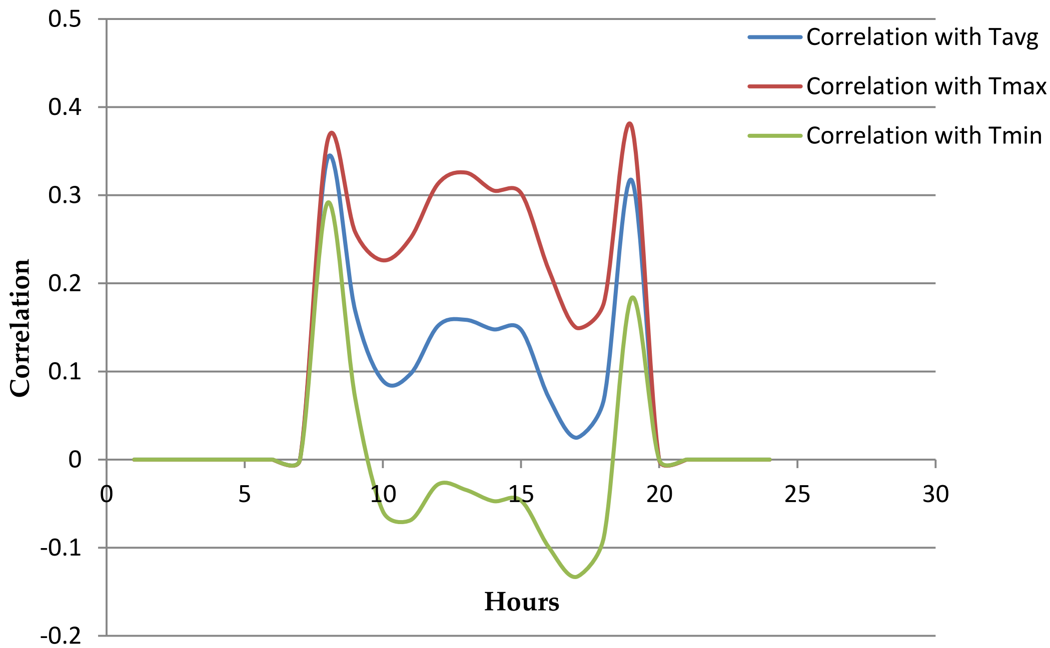

Figure 3-3: A plot of correlation between Solar Irradiation time series and temperature time series showing relatively high dependence of Solar irradiation on the maximum temperature of the day

The answer for the right input variable lies in the *Figure 3-3*. Correlation between the hourly irradiation time series and T_{MAX} is better than T_{MIN} or T_{AVG} for every hourly vector. Choosing T_{MAX} as our input variable we proceed with the forecast. Recalling equations 3.1, 3.2 and 3.3

$$Forecast = a + bx \tag{3.1}$$

$$a = \bar{y} - a\bar{x} \tag{3.2}$$

$$b = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2} \tag{3.3}$$

Where, $\boldsymbol{x}$ is T_{MAX} for that day and $\bar{\boldsymbol{x}}$ is the average of the T_{MAX} in the training set. $\bar{y}$ is the average of hourly irradiation in the i^{th} hour on all the days in the training set.

The forecast for three consecutive days (72 hours) is plotted in the *Figure 3-4* where we can see the forecast is very close to the actual irradiation except for a few steep valleys which is caused due to the cloud cover above the panels. Predicting the cloud movement requires a lot of information and computing hence it is out of the scope of this project. Hence we move on to the next forecast.

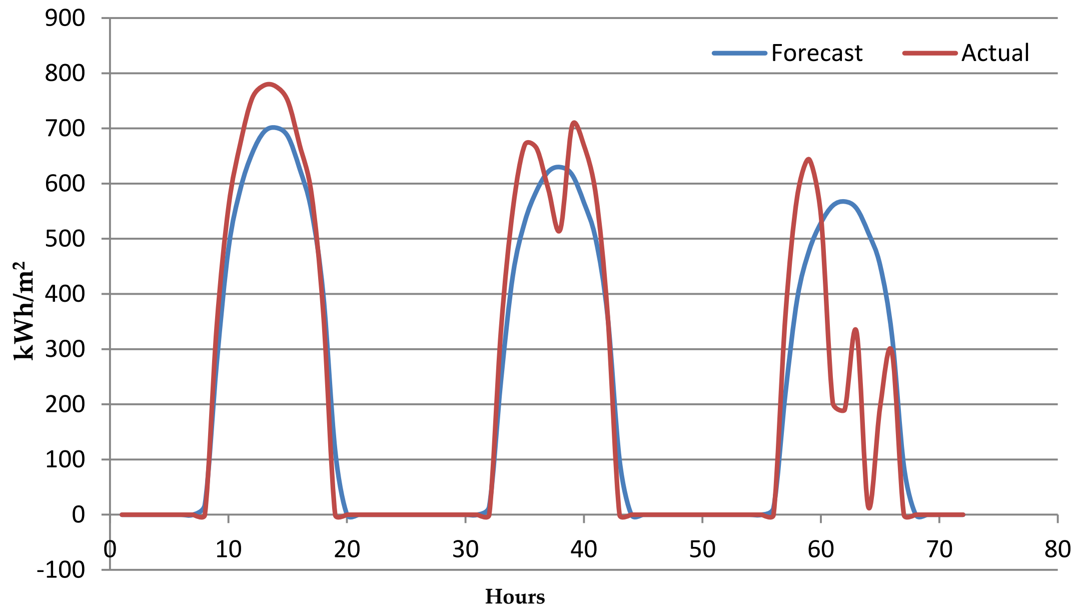

Figure 3-4: Forecasting using Maximum temperature of the day as input and Historical data (2500 days) using linear regression.

3.4 Day ahead forecasting of Electricity Price [2]

Forecasting of the electricity price (₹/MW-h) is done using a moving average model as per the formula below. Challenging part is to find the right value for α.

$$\text{Price (n+1)} = \text{Price (n)} + \alpha^{*} \{\text{Price (n)} - \text{Moving Average (n)}\}$$

As discussed in the chapter on Forecasting, this method is error prone and thus to minimize the error we have used an incremental size of the interval, which increases proportionally with time. This has proved to be useful and reduced the error to a very minimal percentage. On an average the error stands at around 12%. This error is large compared to the error give by computationally intensive techniques such as MAPE (Mean absolute percentage error) which give an error less than 5%.

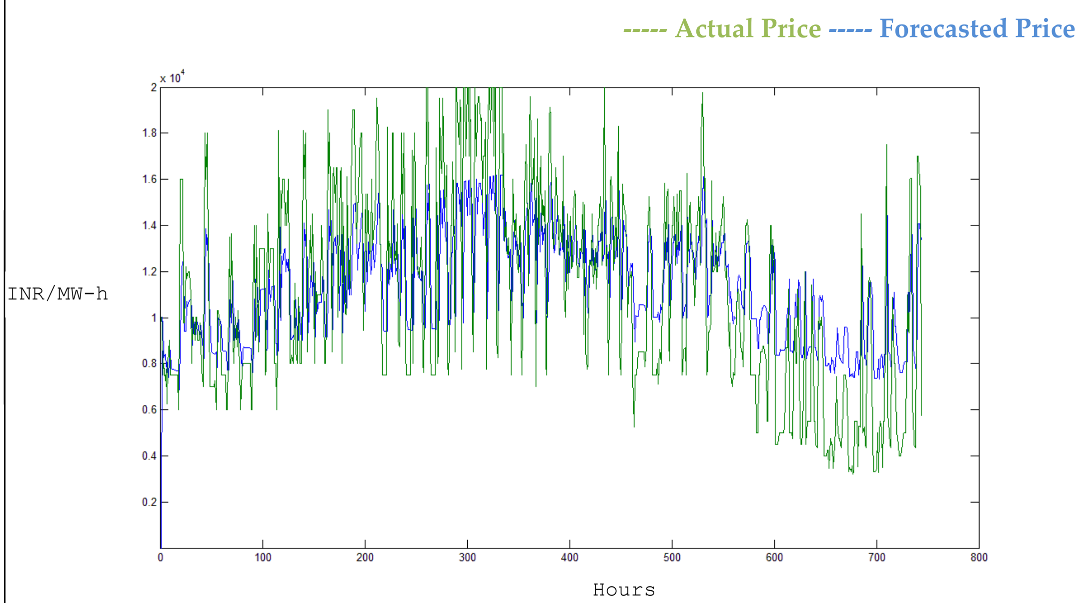

Figure 3-5: Plot showing Actual price and the Forecasted price using $\alpha = 0.5$

Figure 3-5 shows us the overlap of the actual price and the forecasted price using the incremental moving average technique. The forecast is following up the actual price but the prediction error is pretty high. Looking at the error and the price gives more evidence into what caused it happen. It is evident from the following plot (*Figure 3-6*) that there is a lot of correlation between the Actual price (Data) and the error, which means the error can further be reduced by increasing α.

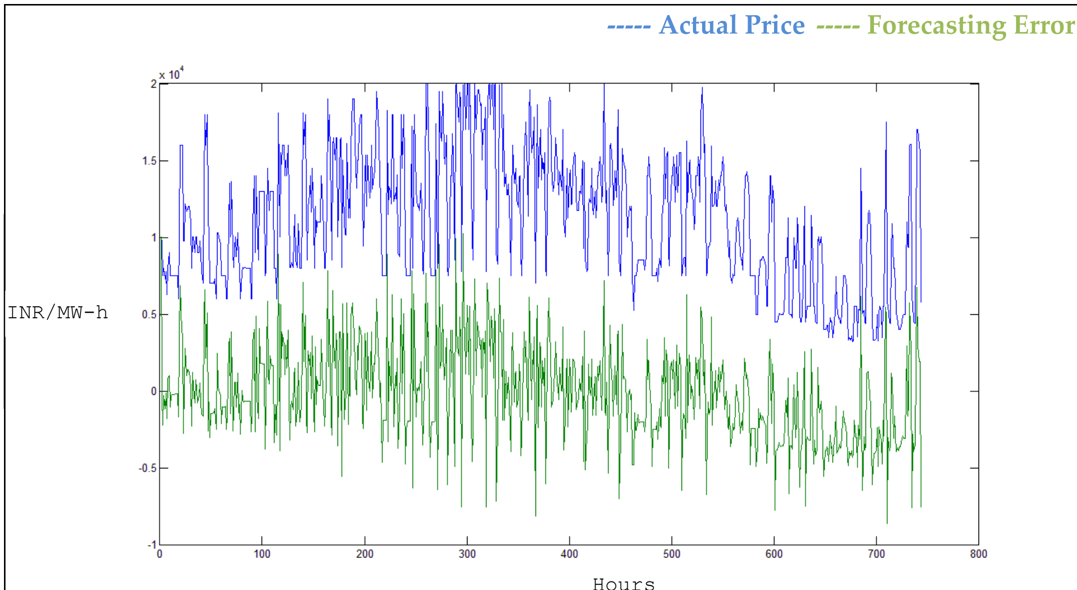

Figure 3-6: Plot showing Error and the actual price for $\alpha = 0.5$

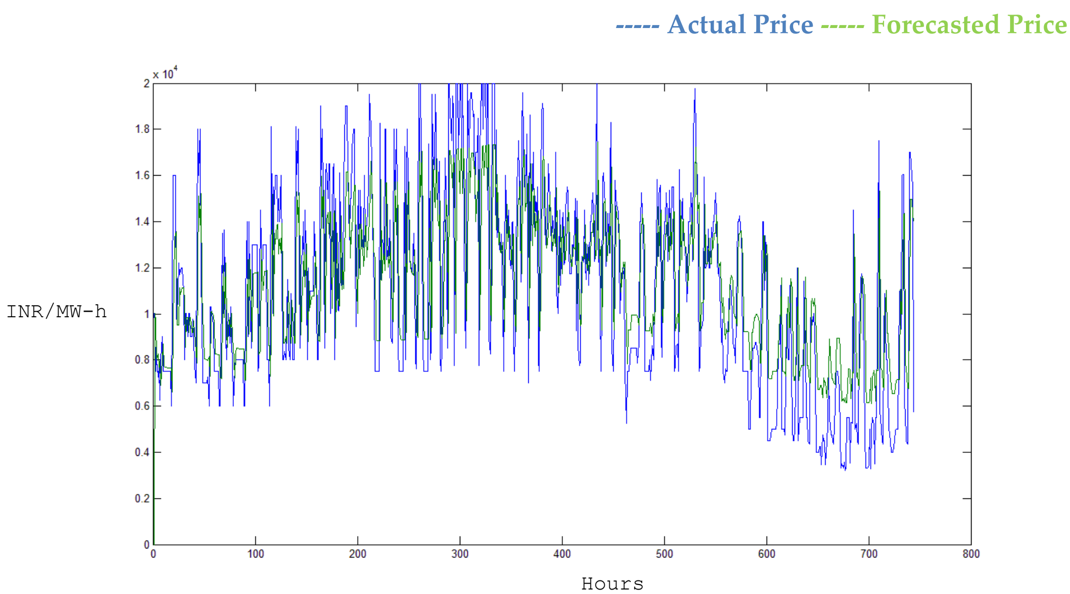

Figure 3-7: Plot showing Actual price and the Forecasted price using $\alpha = 0.65$

Similar to the plots in the previous page, it is still evident from the following plot (*Figure 3-8*) that there is a lot of correlation between the Actual price (Data) and the error, which means that there is a good chance of reducing the error by increasing α.

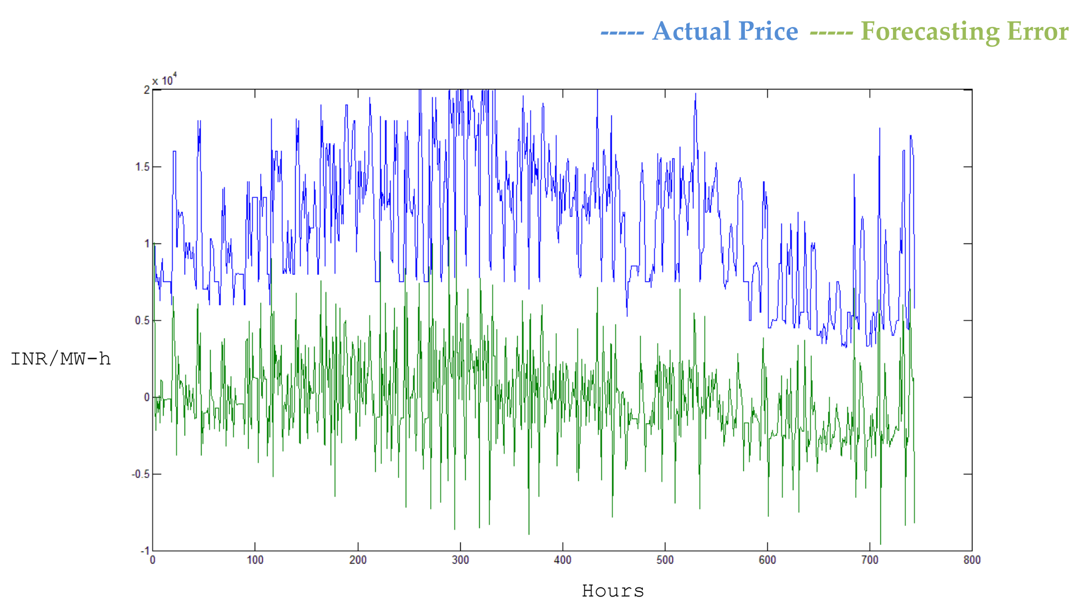

Figure 3-8: Plot showing Error and the actual price for $\alpha = 0.65$

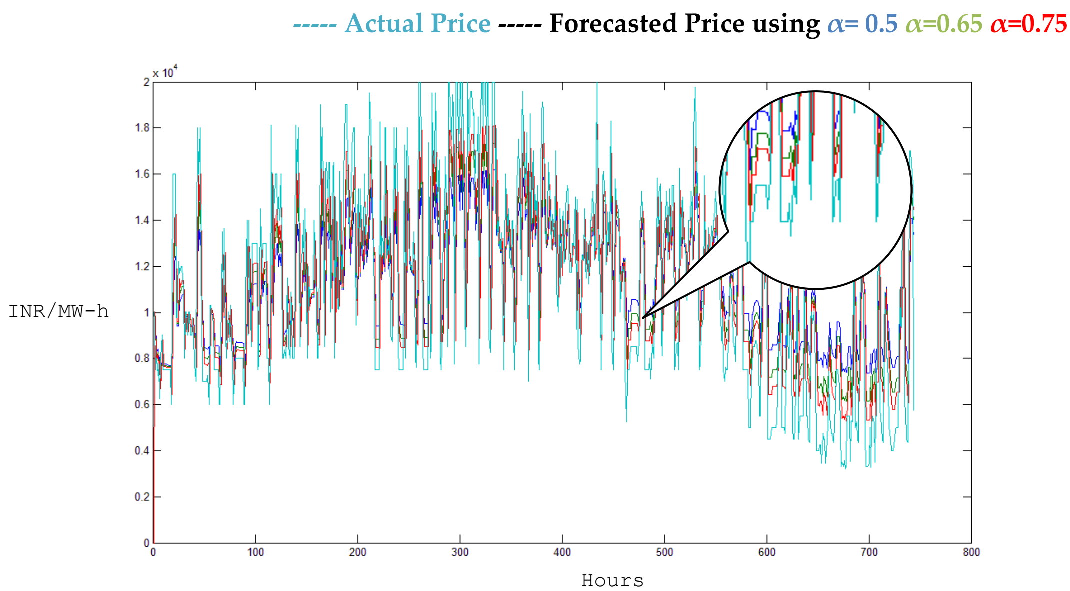

Figure 3-9: Plot showing Actual price and forecasted price for various values of α (0.5, 0.65 and 0.75)

It is clear from the above plot (*Figure 3-9*) that error is decreasing with increase in the value of α. Thus we need to find the optimal value for α which minimizes the error, which is measured by the total variance.

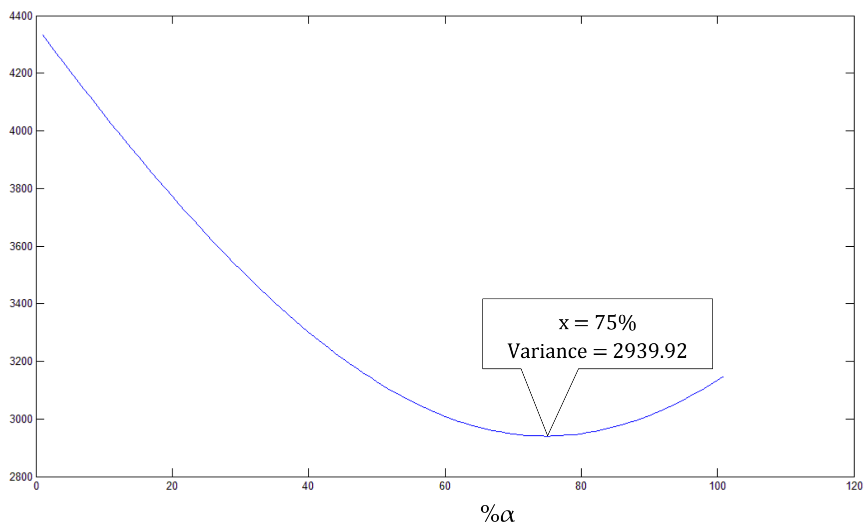

Figure 3-10: Plot of Variance of error vs α, with minimum at $\alpha = 0.75$

The plot (*Figure 3-10*) above, plotted between variance of error and α shows that the variance of error is minimum at $\alpha = 0.75$ and $\sigma = 54.221$.

CHAPTER FOUR

Energy Trading Architecture

4.1 Formulation of the Problem

Trading is done to maximize the total profit by minimizing the total cost incurred in the next 24 hours (Fundamental Cycle) and the optimal values for the current hour (hour 0) are implemented at that time.

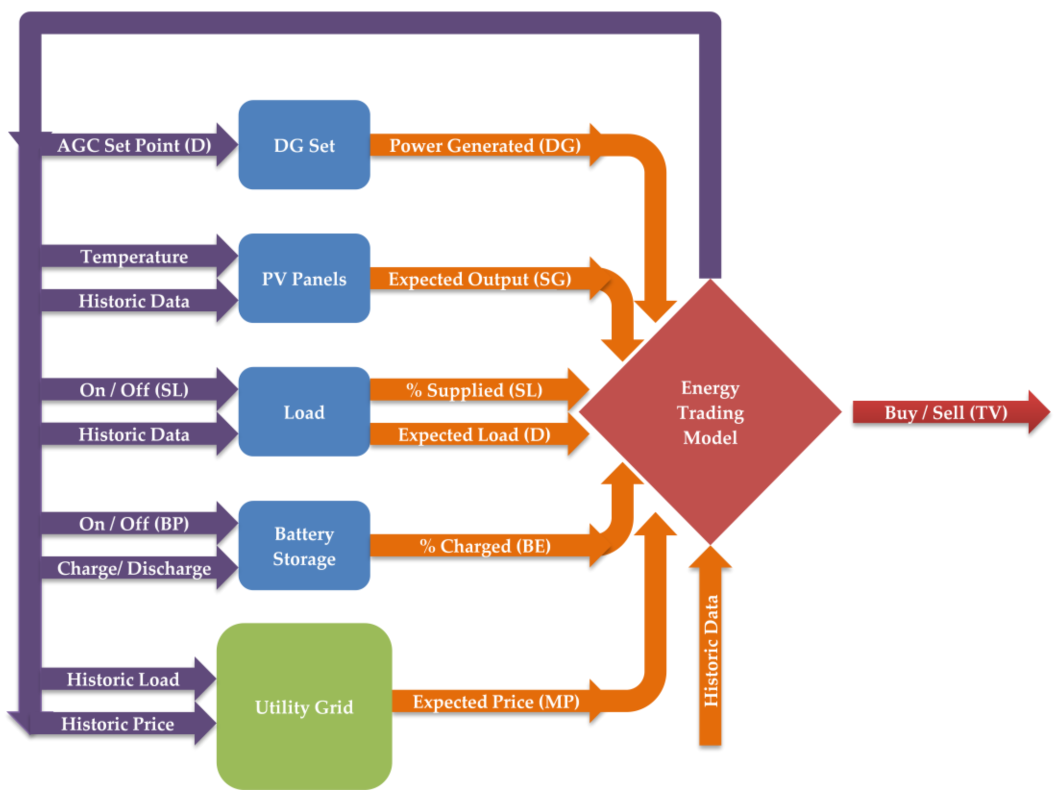

Figure 4-1: Information flow diagram of the Microgrid with arrows indicating the direction of the flow of information.

As shown in *Figure 4-1* the trading model receives data from all the sources and loads and it will use the forecasted data to make profitable trading decisions without compromising on the constraints. It will also make the decision of taking power from the main grid, Battery and the emergency Diesel Generator set. It will make sure that the schedulable load is supplied power when the price of the power is the least.

Objective is to make **profitable trading decisions**, adhering to constraints.

So, Introducing a function, $\Psi(\bar{u})$

$$\Psi_{\mathrm{n}}(\bar{u}) = \sum_{i=n+1}^{n+72} \{u_i \frac{\partial}{\partial u_i}\left\{\sum_{j=n}^{n+23} c_j\right\} - \frac{1}{2}{u_i}^2 \frac{\partial^2}{\partial {u_i}^2}\left\{\sum_{j=n}^{n+23} c_j\right\}\} \tag{4.0}$$

Where, $\bar{u}$ is a vector consisting of all the independent variables in $\sum_{j=n}^{n+23} c_j$

The output variables of the model are the independent variables associated with c_n and they are assigned the values they take at the global minimum of $\Psi_{\mathrm{n}}(\bar{u})$ within the boundary conditions by the model and there are two sets of independent variables i.e. 48 variables which can be varied to find the minimal value of the total cost. The list of equations is provided in the next page.

Table 4-1: Various variables under consideration in the METM

Hour	Grid Price	Solar Generation	Demand	Net Generation	DG Production	DG Cost	Battery Energy	Battery Power	Trade Volume	Trade Cost	Total Cost
(i)	(MP)	(SG)	(D)	(N)	(DG)	(DC)	(BE)	(BP)	(TV)	(TC)	(C)
0											
1											
2											
- -											
23											

Data obtained using Forecasting Techniques (Grid Price, Solar Generation, Demand)
Independent variables (DG Production, Battery Power)
Variables in the Objective function (Total Cost)

Independent Variables (48):

i. $[DG_0, DG_1, DG_2, DG_3 \ldots DG_{23}]$
ii. $[BP_0, BP_1, BP_2, BP_3 \ldots BP_{23}]$

Equations:

i. $N_i = S_i - D_i$
ii. $DC_i = a + b(DG_i) + c(DG_i)^2$
iii. $BE_{i+1} = BE_i + BP_i$
iv. $TC_i = TV_i \times MP_i$
v. $C_i = TC_i + DC_i$
vi. $BC_{MAX} = BE_{MAX} - BE_{SRT}$

Objective Function (Cost minimization):

i. $\sum_{i=0}^{23} C_i$

Constraints:

i. $N_i + DG_i + TV_i - BP_i = 0$
ii. $0 \leq DG_0, DG_1, DG_2, DG_3 \ldots DG_{23} \leq DG_{MAX}$
iii. $-BP_{MAX} \leq BP_0, BP_1, BP_2, BP_3 \ldots BP_{23} \leq BP_{MAX}$
iv. $0 \leq BE_0, BE_1, BE_2, BE_3 \ldots BE_{23} \leq BE_{MAX}$

NOTE: $a, b, c, BE_{SRT}, BP_{MAX}$ and BE_{MAX} are constants.

4.2 Introduction of Slack Variables

Independent variables BP_i (for i = 0, 1, 2, 3…..23) can take negative values also, hence there is a need for introducing slack variables. Let us call them X and Y such that:

i. $BP_i = X_i - Y_i$ (for i = 0, 1, 2, 3…..23) (4.1)

ii. $0 \leq X_0, X_1, X_2, X_3 \ldots X_{23} \leq BP_{MAX}$

iii. $0 \leq Y_0, Y_1, Y_2, Y_3 \ldots Y_{23} \leq BP_{MAX}$

Now, introducing slack variables has increased the number of independent variables to 72. They are:

i. $[DG_0, DG_1, DG_2, DG_3 \ldots DG_{23}]$

ii. $[X_0, X_1, X_2, X_3 \ldots X_{23}]$

iii. $[Y_0, Y_1, Y_2, Y_3 \ldots Y_{23}]$

Objective function which is to be minimized can be written in terms of independent variables is as following:

$$\sum_{i=0}^{23}\{ a + b\,(DG_i) + c\,(DG_i)^2 + MP_i(X_i) - MP_i(Y_i) - MP_i(DG_i) - MP_i(N_i)\}$$

In the matrix form it can be written as:

$$\sum_{i=0}^{23}\{ a - MP_i(N_i)\} + \frac{1}{2}[U]'[H][U] + [F]'[U] \qquad (4.2)$$

Where,

$$U_{72x1} = \begin{pmatrix} DG_0 \\ DG_1 \\ \vdots \\ DG_{23} \\ X_0 \\ X_1 \\ \vdots \\ X_{23} \\ Y_0 \\ Y_1 \\ \vdots \\ Y_{23} \end{pmatrix} \qquad H^{11}{}_{24X24} = \begin{pmatrix} 2c & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 2c & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 2c & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 2c & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 2c & 0 & 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & 2c & 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 2c & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2c & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2c & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2c & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2c & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & 2c \end{pmatrix}$$

$$H_{72x72} = \begin{pmatrix} H^{11} & | & 0 \\ - & + & - \\ 0 & | & 0 \end{pmatrix} \qquad F_{72x1} = \begin{pmatrix} b - MP_0 \\ b - MP_1 \\ \vdots \\ b - MP_{23} \\ MP_0 \\ MP_1 \\ \vdots \\ MP_{23} \\ -MP_0 \\ -MP_1 \\ \vdots \\ -MP_{23} \end{pmatrix}$$

Bounds on input variables are as follows:

i. $0 \leq DG_0, DG_1, DG_2, DG_3 \ldots DG_{23} \leq DG_{MAX}$
ii. $0 \leq X_0, X_1, X_2, X_3 \ldots X_{23} \leq BP_{MAX}$
iii. $0 \leq Y_0, Y_1, Y_2, Y_3 \ldots Y_{23} \leq BP_{MAX}$

Inequality Constraint(s):

i. $0 \leq BE_0, BE_1, BE_2, BE_3 \ldots BE_{23} \leq BE_{MAX}$

We need to get this into matrix form; hence we need to simplify it as follows:

We know that, $$BE_{i+1} = BE_i + BP_i \tag{4.3}$$

$$\Rightarrow BE_{i+1} = BE_{SRT} + \sum_{k=0}^{i} BP_i \tag{4.4}$$

$$\Rightarrow BE_{i+1} = BE_{SRT} + \sum_{k=0}^{i} (X_k - Y_k) \tag{4.5}$$

and, $$0 \leq BE_i \leq BE_{MAX} \Rightarrow 0 \leq BE_{SRT} + \sum_{k=0}^{i} (X_k - Y_k) \leq BE_{MAX} \tag{4.6}$$

$$-BE_{SRT} \leq \sum_{k=0}^{i} (X_k - Y_k) \leq BE_{MAX} - BE_{SRT} \tag{4.7}$$

Hence the inequality constraints become,

i. $\sum_{i=0}^{n} X_i - Y_i \leq BE_{MAX} - BE_{SRT}$ (*for n=0, 1, 2, 3…23*)
ii. $\sum_{i=0}^{n} Y_i - X_i \leq BE_{SRT}$ (*for n=0, 1, 2, 3…23*)

The inequality constraints also have to be expressed in the matrix form of $[C][U] \leq [D]$. Where,

$$C_{48x72} = \begin{pmatrix} 0_{24x24} & L_{24x24} & -L_{24x24} \\ 0_{24x24} & -L_{24x24} & L_{24x24} \end{pmatrix} \qquad D_{48x1} = \begin{pmatrix} BC_{MAX} \\ -- \\ BE_{SRT} \end{pmatrix}$$

L matrix in the above expression is a **unit lower triangular matrix** of appropriate dimension.

4.3 Minimizing using Matlab® and Microsoft® Excel [17][18]

We could use Matlab® for minimizing our objective function using the quadprog command. Matlab uses *Interior point convex* method for solving the problem. The results have been verified using the Microsoft® Excel which uses *Generalized Reduced Gradient* (GRG2) algorithm.

Following is the syntax for solving this problem in Matlab:

`x = quadprog(H,f,A,b,Aeq,beq,lb,ub)` solves the preceding problem subject to the additional restrictions `lb ≤ x ≤ ub`. `lb` and `ub` are vectors of doubles, and the restrictions hold for each `x` component. If no equalities exist, we set `Aeq = []` and `beq = []`.

4.3.1 Generalized Reduced Gradient Algorithm (GRG2)

This procedure is one of a class of techniques called reduced-gradient or gradient projection methods which are based on extending methods for linear constraints to apply to nonlinear constraints. They adjust the variables so the active constraints continue to be satisfied as the procedure moves from one point to another. The ideas for these algorithms were devised by Wilde and Beightler using the name of *constrained derivatives*, by Wolfe using the name of the *reduced-gradient method* and extended by Abadie and Carpenter using the name *generalized reduced gradient*. According to Avriel if the economic model and constraints are linear this procedure is the Simplex Method of linear programming, and if no constraints are present it is gradient search.

The idea of generalized reduced gradient is to convert the constrained problem into an unconstrained one by using direct substitution. If direct substitution were possible it would reduce the number of independent variables to (n-m) and eliminate the constraint equations. However, with nonlinear constraint equations, it is not feasible to solve the m constraint equations for m of the independent variables in terms of the remaining (n-m) variables and then to substitute to these equations into the economic model. Therefore, the procedures of constrained variation and Lagrange multipliers in the classical theory of maxima and minima are required. There, the economic model and constraint equations were expanded in a Taylor series, and only the first order terms were retained. Then with these linear equations, the constraint equations could be used to reduce the number of independent variables. This leads to the Jacobian determinants of the method of constrained variation and the definition of the Lagrange multiplier being a ratio of partial derivatives.

4.3.2 Interior point method [19]

Interior point methods (also referred to as barrier methods) are a certain class of algorithms to solve linear and nonlinear convex optimization problems. The interior point method was invented by John von Neumann. Von Neumann suggested a new method of linear programming, using the homogeneous linear system of Gordan (1873) which was later popularized by Karmarkar's algorithm, developed by Narendra Karmarkar in 1984 for linear programming. The method consists of a self-concordant barrier function used to encode the convex set. Contrary to the simplex method, it reaches an optimal solution by traversing the interior of the feasible region.

Any convex optimization problem can be transformed into minimizing (or maximizing) a linear function over a convex set by converting to the epigraph form. The idea of encoding the feasible set using a barrier and designing barrier methods was studied in the early 1960s by, amongst others, Anthony V. Fiacco and Garth P. McCormick. These ideas were mainly developed for general nonlinear programming, but they were later abandoned due to the presence of more competitive methods for this class of problems (e.g. sequential quadratic programming).

Yurii Nesterov and Arkadi Nemirovski came up with a special class of such barriers that can be used to encode any convex set. They guarantee that the number of iterations of the algorithm is bounded by a polynomial in the dimension and accuracy of the solution.

Karmarkar's breakthrough revitalized the study of interior point methods and barrier problems, showing that it was possible to create an algorithm for linear programming characterized by polynomial complexity and, moreover, that was competitive with the simplex method. Already Khachiyan's ellipsoid method was a polynomial time algorithm; however, in practice it was too slow to be of practical interest.

The class of primal-dual path-following interior point methods is considered the most successful. Mehrotra's predictor-corrector algorithm provides the basis for most implementations of this class of methods

The primal-dual method's idea is easy to demonstrate for constrained nonlinear optimization. For simplicity consider the all-inequality version of a nonlinear optimization problem:

Minimize $f(x)$, subject to $c(x) \geq 0 \;\; x \in \mathcal{R}^n \, , c(x) \in \mathcal{R}^m$ (4.8)

The logarithmic barrier function associated with (4.8) is

$$B\,(x, \mu) = f(x) - \mu \sum_{i=1}^{m} \ln(\, c_i(x)) \quad (4.9)$$

Here μ is a small positive scalar, sometimes called the "barrier parameter". As μ converges to the minimum of $B\,(x, \mu)$ should converge to a solution of (4.8).

The barrier function gradient is

$$g_b = g - \mu \sum_{i=1}^{m} \frac{1}{c_i(x)} \nabla c_i(x) \quad (4.10)$$

Where, g *is* the gradient of the original function $f(x)$ and ∇c_i is the gradient of c_i.

In addition to the original ("primal") variable x we introduce a Lagrange multiplier inspired dual variable $\lambda \in \mathcal{R}^m$ (sometimes called "slack variable").

$$\forall_{i=1}^{m} c_i(x)\, \lambda_i = \mu \quad (4.11)$$

(4.11) is sometimes called the "perturbed complementarity" condition, for its resemblance to "complementary slackness" in KKT conditions.

We try to find those $(x_\mu \, , \lambda_\mu)$ which turn gradient of barrier function to zero.

Applying (4.11) to (4.10) we get equation for gradient:

$$g - A^T\lambda \tag{4.12}$$

Where, matrix A is the constraint $c(x)$ Jacobian.

The intuition behind (4.12) is that the gradient of $f(x)$ should lie in the subspace spanned by the constraints' gradients. The "perturbed complementarity" with small μ (4.11) can be understood as the condition that the solution should either lie near the boundary $c_i(x) = 0$ or that the projections of the gradient of g on the constraint compliment $c_i(x)$ normal should be almost zero.

Applying Newton's method to (4.11) and (4.12) we get an equation for (x_μ, λ_μ) update (p_x, p_λ):

$$\begin{pmatrix} W & -A^T \\ \Lambda A & C \end{pmatrix} \begin{pmatrix} p_x \\ p_\lambda \end{pmatrix} = \begin{pmatrix} -g + A^T\lambda \\ \mu - C\lambda \end{pmatrix} \tag{4.13}$$

Where, $W$is the Hessian matrix of $f(x)$and Λ is a diagonal matrix of λ

Because of (4.8) and (4.11) the condition, $\lambda \geq 0$ should be enforced at each step. This can be done by choosing appropriate α:

$$(x, \lambda) \rightarrow (x + \alpha p_x, \lambda + \alpha p_\lambda)$$

CHAPTER FIVE

Energy Trading in a Microgrid

5.1 Trading and its advantages

Using the energy trading model drastically reduces the over costs and increases the bottom-line considerably. We have taken a case study with near – real time values and simulated it with both, the model operating on it and without the model operating on it.

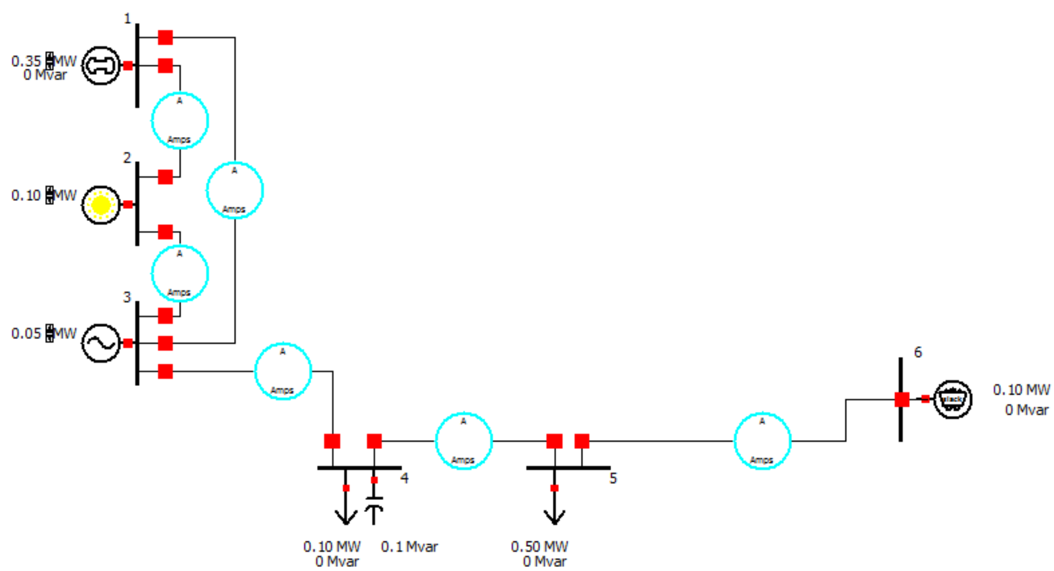

Figure 5-1: Screenshot of the model under consideration in Power World® Simulator

The model has two sources of generation, they are:

- Solar panels with a maximum generation of 500 kW
- Diesel generator with a maximum generation of 300 kW, with the cost generation function: $DC\ (₹/h) = a + b\,(DG) + c\ (DG)^2$ (5.1)

  Where,

$$a = 200\ ₹/h$$
$$b = 10\ ₹/\ kW\text{-}h$$
$$c = 0.005\ ₹/\ (kW)^2\text{-}h$$

The model also has a super storage facility (Battery) with maximum energy capacity (BE_{MAX}) of 500 kWh and maximum power (BP_{MAX}) of 200 kW.

There are two sources of revenue, one from trading and other from consumers in the Microgrid who are charges and fixed rate of ₹ 8 / kW-h (all the data used in this project is from S1-S2 regions of India and hence consumer charge is also reasonably fixed at ₹ 8 / kW-h)

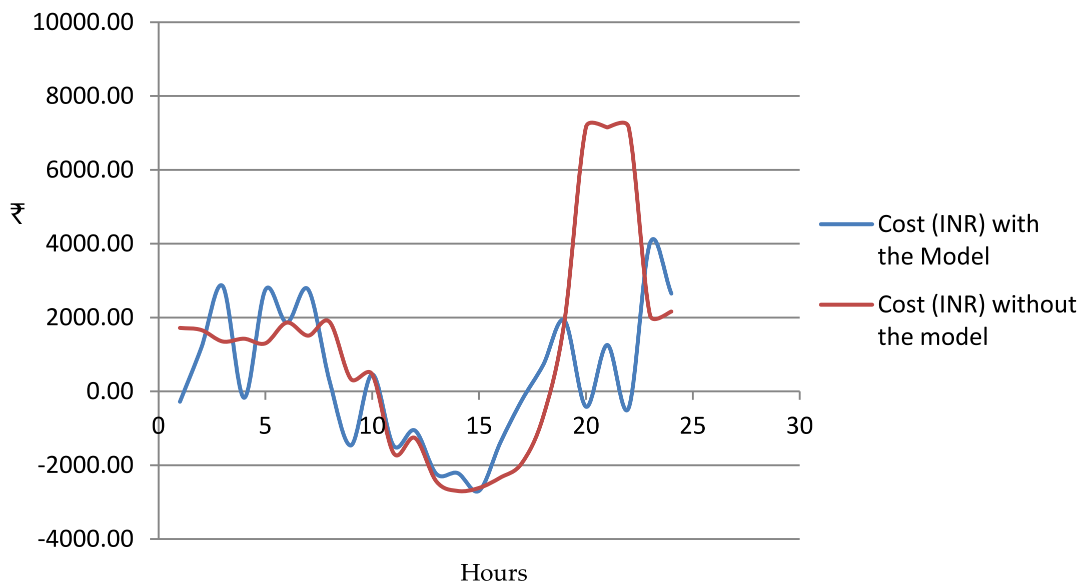

Figure 5-2: Plot showing hourly cost incurred after trading during a day (24 hours)

Advantages of having a trading model in place are clearly visible from the plot above (*Figure* 5-2). The area below the graph gives the total cost incurred in a day after trading. The trading model makes optimal trading decisions and reduces the cost by over 60%.

Table 5-1: *Balance sheet of the Microgrid under consideration, with and without METM*

	With METM	Without METM	Change
Total cost	8607.99	25497.63	**-66.24%**
Excess charge	0.00	0.00	**0%**
Revenue	35126.88	35126.88	**0%**
Net Income	**26518.89**	**9629.25**	**175.40%**

*METM = Microgrid Energy Trading Model

The results are surprising but we have to remind ourselves that we did not take into consideration the losses in charging and discharging the battery and also the usage cost of the battery. The life of a battery depends on its usage; excessive usage will reduces the life of the battery at a very high rate. Also, the cost of capital on such a high investment will considerably reduce the return on investment (ROI). But, such a high increase in the bottom-line is worth discussing as there is a lot of research going into improving the storage devices which have a very long lifetime and a very high efficiency in converting it o electricity again. Let us go a step further and analyze how the model makes such a high profit. We can make some inferences from *Figure 5-3, 5-4.* Where we can see the generation curves and also the trading decisions the model has taken to increase the bottom line.

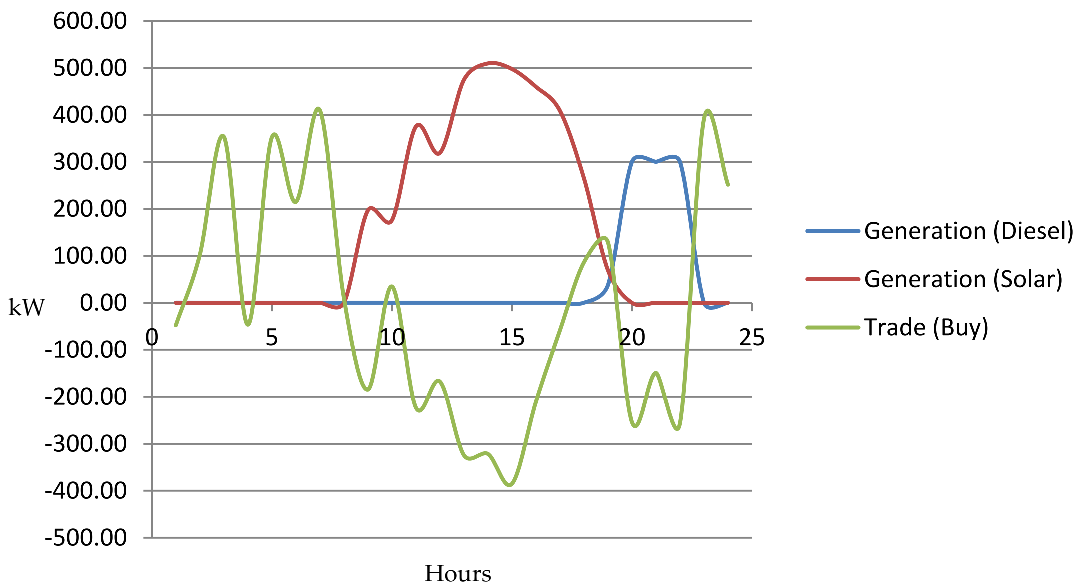

Figure 5-3: Plot giving the details of hourly generations from Diesel Generator, Solar Panels and also hourly trade volumes

It is clear from the above graph (*Figure 5-3*) that Microgrid Energy Trading Model has bought power from the utility grid when the net-generation is negative, and has sold power to the utility grid when there is excess of power in the Microgrid. But, this is very intuitive and simple and the working of the model is not very clear from the above plot, i.e. even without the model nothing different would have happened but what is counter intuitive from the plot is that it sold power it generated using diesel generator and at the same time the net generation was negative. That means the power was sourced from the storage device, but what compelled the trading model to take that decision can be understood from the plot showing the usage of battery and the hourly market price.

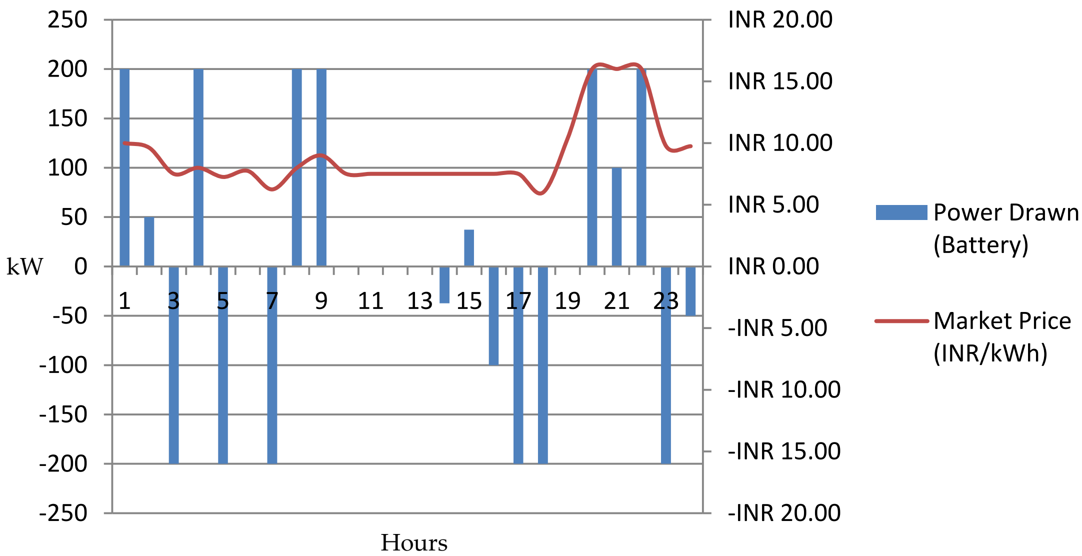

Figure 5-4: Plot showing the battery usage and the Market price for every hour

Figure 5-4 gives a better idea of working of the METM. The model charged the battery when the market price was low and sold it when the Market price was relatively high. Looking at both the plots together gives a much better idea of what really happened. From hour 20-22 (peak time) Market price went up to around 16 ₹/kW, making the use of Diesel generator with the incremental cost (b) around ₹10/kW economically viable. Hence, the Trading Model sold power from the battery and also sold the power generated using the Diesel generator to reach a local maximum in trade volume and to make maximum profits. This was possible only because it could see the opportunity of making such profits before hand and charge the battery hours in advance when the cost of power was considerably less, i.e. cheaper than the diesel generator also and seized the opportunity of making such high profits. The detailed working of the model and the trading decisions it has taken are shown in the table next page (*Table 5-2*).

Table 5-2: Simulated results of the Microgrid under study with and without the trading model

Hour (i)	Market Price (MP) *INR/kWh*	Demand (D) *KW*	PV Panel Generation (SG) *kW*	Diesel Generation (DG) *kW*	DG Production Cost (DC) *INR*	Battery Power (BP) *kW*	Battery Energy (BE) BE_{SRT}=250	Trade volume *buy* (TV) *kW*	Hourly cost with METM (INR)	Hourly cost without METM (INR)
MAX			**500**	**300**		**200**	**500 kWh**			
0	10.00	151.92	0.00	0.06	200.60	200.00	50.00	-48.14	-280.83	1719.29
1	9.63	151.92	0.00	0.00	200.00	50.00	0.00	101.92	1181.01	1662.28
2	7.51	153.40	0.00	0.00	200.00	-200.00	200.00	353.40	2852.49	1351.36
3	8.00	153.28	0.00	0.00	200.00	200.00	0.00	-46.72	-173.80	1426.38
4	7.26	151.89	0.00	0.00	200.00	-200.00	200.00	351.89	2754.17	1302.49
5	7.75	214.57	0.00	0.00	200.00	0.00	200.00	214.57	1863.11	1863.11
6	6.25	209.62	0.00	0.00	200.00	-200.00	400.00	409.62	2760.63	1510.40
7	8.00	210.27	0.00	0.00	200.00	200.00	200.00	10.27	282.18	1882.21
8	9.00	211.68	196.70	0.00	200.00	200.00	0.00	-185.02	-1465.32	334.79
9	7.51	210.24	175.70	0.00	200.00	0.00	0.00	34.54	459.43	459.43
10	7.51	152.24	375.20	0.00	200.00	0.00	0.00	-222.96	-1474.65	-1674.65
11	7.51	151.16	319.20	0.00	200.00	0.00	0.00	-168.04	-1062.14	-1262.14
12	7.51	150.12	474.60	0.00	200.00	0.00	0.00	-324.48	-2237.14	-2437.14
13	7.51	150.56	509.60	0.00	200.00	-37.29	37.29	-321.75	-2216.64	-2696.73
14	7.51	149.58	497.70	0.00	200.00	37.29	0.00	-385.41	-2694.81	-2614.72
15	7.51	149.20	459.90	0.00	200.00	-100.00	100.00	-210.70	-1382.55	-2333.64
16	7.51	149.96	408.80	0.00	200.00	-200.00	300.00	-58.84	-241.89	-1943.90
17	6.00	151.22	265.30	0.00	200.00	-200.00	500.00	85.92	715.47	-684.42
18	10.38	235.32	69.30	37.61	583.19	0.00	500.00	128.41	1915.61	1915.61
19	16.01	246.01	0.00	300.00	3650.00	200.00	300.00	-253.99	-416.58	7153.05
20	16.01	250.52	0.00	300.00	3650.00	100.00	200.00	-149.48	1256.81	7151.51
21	16.01	243.72	0.00	300.00	3650.00	200.00	0.00	-256.28	-453.21	7153.05
22	9.76	191.17	0.00	0.00	200.00	-200.00	200.00	391.17	4016.51	2065.17
23	9.75	201.28	0.00	0.00	200.00	-50.00	250.00	251.28	2650.14	2162.61
								Total cost	**8607.99**	**25497.63**

CONCLUSION

The Microgrid Energy Trading Model (METM) built using multiple coding languages and applications is has achieved very good results. In the case study, where we have assumed multiple sources of generation and a storage facility, it has reduced the net costs incurred by over 60% by trading efficiently and making maximum use of the storage facility. It has also increased the bottom-line by over 175%, this is a little surprising but once we take losses in charging and discharging into consideration it will reduce to a little over 100% increase.

In addition to increase of profits and increase in the Return on Investment (ROI), it also reduces the carbon dioxide emissions thus producing clean energy. A typical 300 kW Diesel Generator produces with a load factor of 20-50% produces approximately 0.8 kg of CO_2 for every kW-h generated. With the METM in place the Diesel Generator in the Microgrid produces approximately 900 kW-h less than what it produces without the METM. Which means the model reduces CO_2 emissions by 720 kg/day.

Future Scope:

i. More accurate and efficient programs can be built and integrated with the model we have built, to have better forecast and reduce the risk involved in trading.
ii. Prediction of the cloud movement would give very accurate forecast of solar energy which would increase the security of the system
iii. Sources of generation could be increased and renewable sources like wind, biogas etc can be added
iv. Life cycle cost of storages can be inculcated into the model which would give accurate return on investments.

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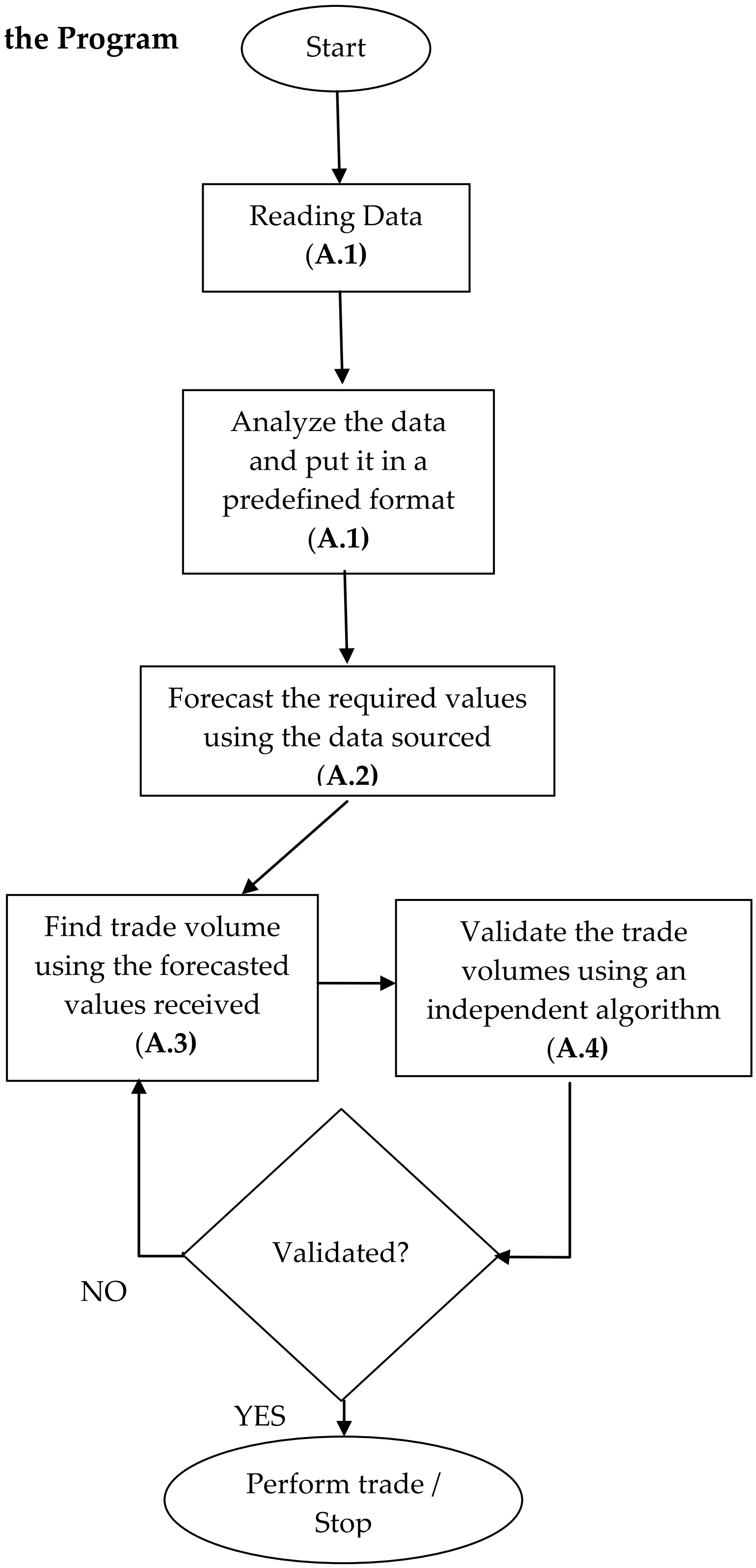
APPENDIX A

Working of the Program



APPENDIX B

A.1 Program for importing data from web and analyzing it

<Microsoft Excel Visual Basic for Applications>

```
Sub Macro ()

    Dim strString As String
    Dim strString1 As String
    Dim month As Integer
    Dim year As Integer
    Dim index As Integer
    Dim index1 As Integer
    Dim index2 As Integer
    Dim index3 As Integer
    index3 = 1


For year = 2 To 8                         'importing data
                For month = 1 To 12
                Sheets("Sheet1").Select
                If month < 10 Then strString1 = "0" & month Else
strString1 = "" & month
                strString = "-200" & year
                    With ActiveSheet.QueryTables.Add(Connection:=
_

"URL;http://www.tutiempo.net/en/Climate/Madras_Minambakkam/" &
strString1 & "" & strString & "/432790.htm" _
                    , Destination:=Range("$A$1"))
                    .Name = "432790_1"
                    .FieldNames = True
                    .RowNumbers = False
                    .FillAdjacentFormulas = False
                    .PreserveFormatting = True
                    .RefreshOnFileOpen = False
                    .BackgroundQuery = True
                    .RefreshStyle = xlInsertEntireRows
                    .SavePassword = False
                    .SaveData = True
                    .AdjustColumnWidth = True
                    .RefreshPeriod = 0
                    .WebSelectionType = xlSpecifiedTables
                    .WebFormatting = xlWebFormattingNone
                    .WebTables = "3"
                    .WebPreFormattedTextToColumns = True
                    .WebConsecutiveDelimitersAsOne = True
                    .WebSingleBlockTextImport = False
                    .WebDisableDateRecognition = False
                    .WebDisableRedirections = False
                    .Refresh BackgroundQuery:=False
                    End With
```

```
                    Columns("E:O").Select    'removing irrelevant
data
                    Selection.Delete Shift:=xlToLeft
                    Sheets("Sheet2").Select
                    ActiveCell.FormulaR1C1 = "=MAX(Sheet1!C)"
                    Range("A1").Select
                    index = Worksheets("Sheet2").Cells(1, 1)
                    index1 = index + 2
                    index2 = index + 3
                    strString = "A" & index1
                    strString1 = ":D" & index2
                    Sheets("Sheet1").Select
                    Range("" & strString & "" & strString1 &
"").Select
                    Selection.ClearContents
                    index1 = index + 1                  'copying
data onto sheet 3
                    strString1 = ":D" & index1
                    Range("A2" & strString1 & "").Select
                    Selection.Copy
                    strString = "A" & index3
                    Sheets("Sheet3").Select
                    Range("" & strString & "").Select
                    ActiveSheet.Paste
                    Sheets("Sheet1").Select
                    index3 = index3 + index

                  Next month

      Next year


End Sub
```

APPENDIX C

A.2 Code for Least variance Moving Average model:

< Matlab>

```
s(1)=data(1);
for i=2:744
  s(i)=data(i)+s(i-1);
end
for i=1:744
  ma(i)=s(i)/i;
  diff(i)=data(i)-ma(i);
end
j=0:0.01:1;
for k=1:101
    for n=2:744
    futp(n)=ma(n-1)+ j(k)*diff(n-1);
    error(n)=data(n)-futp(n);
    end
    stdv(k)=sqrt(var(error));
end
```

APPENDIX D

A.3 Code for building the trading model:

<Microsoft Excel Visual Basic for Applications>

```
Sub Macro2()
'
' Macro2 Macro
'

Dim stra As String
Dim strb As String
Dim i As Integer
Dim j As Integer
Dim delay As Integer

    For i = 3 To 26
        'i = 3
        j = i + 23
        a = "" & i
        b = "" & j
        SolverReset
        For delay = 1 To 3
            SolverReset
            SolverAdd CellRef:="$F$" & i & ":$F$" & j & "",
Relation:=1, FormulaText:="300"
            SolverAdd CellRef:="$F$" & i & ":$F$" & j & "",
Relation:=3, FormulaText:="0"
            SolverAdd CellRef:="$I$" & i & ":$J$" & j & "",
Relation:=1, FormulaText:="200"
            SolverAdd CellRef:="$I$" & i & ":$J$" & j & "",
Relation:=3, FormulaText:="0"
            SolverAdd CellRef:="$L$" & i & ":$L$" & j & "",
Relation:=1, FormulaText:="500"
            SolverAdd CellRef:="$L$" & i & ":$L$" & j & "",
Relation:=3, FormulaText:="0"
            SolverOk SetCell:="$O$" & i & "", MaxMinVal:=2,
ValueOf:="0", ByChange:="$F$" & i & ":$F$" & j & ",$I$" & i &
":$J$" & j & ""
            SolverSolve True
        Next delay
    Next i
End Sub
```

APPENDIX E

A.4 Code for importing data and validating the results:

<Matlab>

```
function importfile(fileToRead1)
%IMPORTFILE(FILETOREAD1)
%  Imports data from the specified file
%  FILETOREAD1:  file to read

% Import the file
sheetName='data';
[numbers, strings, raw] = xlsread(fileToRead1, sheetName);
if ~isempty(numbers)
    newData1.data =  numbers;
end
if ~isempty(strings)
    newData1.textdata =  strings;
end

if ~isempty(strings) && ~isempty(numbers)
    [strRows, strCols] = size(strings);
    [numRows, numCols] = size(numbers);
    likelyRow = size(raw,1) - numRows;
    % Break the data up into a new structure with one field per
column.
    if strCols == numCols && likelyRow > 0 && strRows >=
likelyRow
        newData1.colheaders = strings(likelyRow, :);
    end
end

% Create new variables in the base workspace from those fields.
vars = fieldnames(newData1);
for i = 1:length(vars)
    assignin('base', vars{i}, newData1.(vars{i}));
end


%   Constructing the required matrices for scheduling
%   Defining Constants
a = 0.5;
b = 10;
c = 0.005;
DGmax = 300;
BPmax = 200;
```

```
BEmax = 500;
BEsrt = 200;
BCmax = BEmax - BEsrt;

%   Construction of the H matrix
H = zeros(72);
for i=1:24
    for j=1:24
        if i==j
        H(i,j)=2*c;
        end
    end
end

%   Construction of the F matrix
for i=1:24
    F(i) = b-data(i,1);
end
for i=25:48
    F(i) = data(i-24,1);
end
for i=49:72
    F(i) = -data(i-48,1);
end

%   Construction of L 24x24 matrix
L = ones(24);
for i=1:24
    for j=1:24
        if j>i
            L(i,j) = 0;
        end
    end
end

%   Construction of C matrix
for i=1:24
    for j=1:24
        C(i,j)=0;
        C(i+24, j)=0;
        C(i, j+24)= L(i,j);
        C(i+24,j+24)= -L(i,j);
        C(i,j+48)=-L(i,j);
        C(i+24,j+48)=L(i,j);
    end
end

%   Construction of D matrix
for i=1:24
```

```
    D(i)= BCmax;
    D(i+24)= BEsrt;
end

%   Construction of m and M matrices
for i=1:72
    M(i)=DGmax;
    m(i)= 0;
end
for i=25:72
    M(i)=BPmax;
    m(i)= 0;
end

%   Evaluation of the problem
U = quadprog(H,F',C,D',[],[],m',M');

%   Construction of resultant matrix
for i=1:24
        DG(i,1)=U(i,1);
        X(i, 1)= U(i+24,1);
        Y(i, 1)= U(i+48,1);
        BP(i, 1)= X(i, 1) - Y(i, 1);
```

Biodata

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