SELF-ORGANIZATION AND COMMUNICATION NETWORKS FOR MICROGRIDS

By

CHINMAY SAVE

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Written by Chinmay Save

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Prof. Frank Barnes

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Prof Tim Brown Prof Lijun Chen

Date: ______________

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Self-organization and communication networks for microgrids

Thesis directed by Prof. Frank Barnes

Abstract

Microgrids play an important role in deployment of smart grids by providing means for integration of renewable sources in electrical grid, reducing carbon footprint as well as lessening the load on utility. As the smart grid is being deployed, the nodes participating in electrical grids are becoming "smarter", thus an effective communication network needs to be in place for exchange of information between these nodes. Self-organizing electric grid will help overcome faults, power outages and will facilitate in effective distribution of electricity. This thesis is investigates wireless communication network protocols and network design for intra as well as inter microgrid communication. This work also investigates a feasibility of exchange of electricity between microgrids and develops an algorithm to self-organize an electrical grid is also provided.

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CHAPTER I

INTRODUCTION

Often depicted as the “biggest machine in the world” the North American electrical grid is a complex integrated network running for millions of miles across the United States and Canada. The grid is like a hub and spoke system [1], with large central power plants at the center providing power to millions of users. There are more than 300,000 miles of transmission line, which are 110KV or above, and more than 5.2 million miles of local distribution lines. Considering the vastness and complexity of the electrical system, the grid is surprisingly old and prone to failures. The average age of equipment in the grid is more than forty years and according to a recent study the American electric grid is 50% more prone to failure than electric grids in Japan and Europe [2]. A way to improve this situation is making current grid “smarter” by implementing new technologies. Smart grid technology is about integrating new innovations in the old infrastructure. New ideas such as superconductors, nanosensors and renewable energy sources can make significant difference to the stability of today’s grid. However, initial high installation cost and costly research are hindering the progress of smart grid. According to Lou Rana, President of Con Edison, even though one can improve the performance of electrical grid and make it more reliable by simply replacing the old copper wires with new ones, it would be a temporary solution. The United States is expected to increase its power consumption by 29% [2] by year 2030 and current infrastructure will surely not be able to support such increase in load, which makes implementing smart grid a necessity.

A part of adopting smart grid is integration of renewable power sources in the traditional grid. However, it is not feasible to integrate renewable energy resources in hub and spoke fashion, since renewable sources usually carry high initial investment and can be little capricious in generation to be reliably used on such a large scale [3]. Distributed energy resources (DER) could help integrate renewable energy in the traditional grid. DERs produce electricity locally with the help of renewable sources, such as wind and solar, at a small scale and facilitate the needs of local consumers. Microgrids link multiple DERs in a small network serving some or all the needs of the participating users [4]. Microgrids facilitate in reducing the electricity cost, increase energy efficiency and are useful in overall betterment of the environment.

Incorporating microgrids in the traditional electric grid has technical as well as regulatory challenges. Controlling voltage, phase and frequency levels with multiple renewable sources is challenging. Also constantly switching from islanded mode to grid connected mode while maintaining the quality of electricity is difficult. In case of regulations, not all microgrids are owned by a utility. Some microgrids are owned by private parties and integrating those microgrids with correct tariff and desired power quality is not easy [2]. Until now, microgrids are usually treated as a back-up. Whenever the utility faced power outage, microgrids are in place to ensure electricity supply to consumers. Microgrid supplies electricity only to the customers residing in that particular microgrid and inter-microgrid power exchange is not done. In the past, microsources (MS) in a microgrid did not produce enough electricity to sustain other microgrids as well, but as more and more sources are being fused in microgrid, exchanging electricity between microgrids is a definite possibility [5].

Communication between the nodes in an electric grid network would be greater once smart grid is deployed. This would require a transport network capable of handling traditional utility power delivery information along with the large amount of new data generated by the new “smart” nodes. Depending on the location of node and type of data, smart grid communication is a mixture of different technologies such as power line communication, fiber optic communication, SCADA as well as wireless. Microgrids will have similar requirements as a smart grid and would require a robust communication network in a microgrid so that DERs, loads and storage units can work effectively in tandem.

This thesis investigates possible protocols that are suitable for wireless communication within a microgrid as well as for the messages that need to be exchanged between nodes and microgrid controller so that microgrid would be able to work effectively and communicate its status to other microgrids and utility. Furthermore, the thesis will also dwell into the possibility and feasibility of using a self-organizing algorithm to organize a group of microgrids using the information gleaned from microgrid controller so that power can be exchanged between them and the load on utility is further reduced.

CHAPTER II

RELATED WORK

Before looking into the communication network and self-organization of the grid, this section investigates the work done on the microgrid and communication networks. This section also discusses various self-organizing algorithms that are useful in self-organizing electric grid.

2.1. Microgrids

In recent years research on microgrid has picked up pace as focus on incorporating greater amount of renewable sources has increased. There has been a lot of research on microgrids, its working, control mechanisms as well as usefulness of a microgrid in overall smart grid. In a paper, “Microgrid Controls and Operation” by Farid Katiraei et al. [4], various components of microgrids along with the type of controls that are required for those controls are discussed in great detail. The paper describes voltage droop control that describes how quality of power can be maintained. This paper also addresses the nodes which should be part of microgrids, which is relevant to the work done in this thesis. Apart from the paper mentioned before several papers such as a white paper on Centralized and Distributed Power Systems published in power systems engineering research center and energy manager design for microgrids by Ryan Firestone and Chris Marnay [6] depict the role of controller as well as the overall working of microgrid. The latter, especially describes the messages exchanged within a microgrid as well as between microgrids in a great details. There is other excellent literature available for understanding working of microgrid and smart grid in IEEE. Another paper “Sustainable virtual utilities based on a microgrid” describes the integration renewable sources in microgrids [7].

2.2. Communication networks

This section pertains to the communication networks. Communication networks have been researched for a long time. This section looks at various protocols and network structures. There is a lot of excellent literature on the communication protocols as well as their various applications. A work by Josh Gans, et al. titled “Wireless communication”, explains the working of wireless networks, spectrums used and as well as the economic aspects of wireless communication. This paper is excellent in terms of setting up a firm base for further development of wireless communication [8].

This thesis also looks into the various communication protocols available. ZIGBEE, Wi-Fi, Bluetooth, Z wave, Ultra wide band, Radio Frequency (RF) have been extensively researched and compared with one another in various situations. A paper, “A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZIGBEE, and Wi-Fi”, by Jin-Shyan Lee compares ZIGBEE, Bluetooth, Wi-Fi and Ultra Wideband protocols [9]. Although these protocols have never been compared for a microgrid communication, the data available is wide-ranging enough so that the performance of these protocols can be simulated for a microgrid.

In case of communication in microgrid, a communication framework in multi-agent [11] system depicts the communication that can take place in an islanded microgrid in great detail. Another paper, “Autonomous control in microgrid”, details the possible automation in microgrid. Another paper, “Wireless Communication and Networking Technologies for Smart Grid:Paradigms and Challenges”, by Xi Fang [12] discusses the communication network technologies that can be employed in smart grid. This paper is especially important as it gives an idea regarding the technologies that are suitable for microgrid.

2.3. Self-organizing algorithm

Although a network of microgrid has never been self-organized, there are a lot of self-organizing algorithms available. Some self-organizing algorithms are specifically developed for a communication network and others are more general. Algorithms such as self-organizing maps (SOM) [13] can be a useful option to be considered in self-organizing electric grid. Another paper on this technique is, “Self-organizing Broad-Band Transport Networks”, by Wayne Grover [14]. This work describes a self-organizing algorithm that is used for a wireless communication network.

Thus in conclusion, it has been observed that there has been a lot of material on communication network protocols and on microgrids, however limited research has been done on protocols that are suitable for microgrid communication as well as possibility of self-organizing a wireless network.

CHAPTER III

ELECTRIC GRID AND MICROGRID

Before designing a communication network for the system, it is important to understand the system itself along with its constraints. This chapter looks into electrical grid and microgrid structure and constraints that the communication network will face due to this. The first section of the chapter explains general electrical grid and how electricity is currently supplied to various consumers from the generators. The next section of the chapter investigates structure of a microgrid and how distributed generators and storage units come together to form an alternate means of power supply.

3.1. Electric grid structure

Electric grid is divided in three components, Electric generation, electric transmission grid and electric distribution grid [15]. As the name suggests, electric generation consists mainly of power plants. The power plants are at the center of the network in traditional grid as the power is generated at these locations. These plants reside near water sources (for hydroelectric power plants) and away from populated regions, as electricity has to be carried over long distances electric power is stepped up to a higher voltage at electric generation stations.

Electrical transmission grid carries high voltage electricity from the power plants to different substations. Transmission grid carries electricity over long distance often crossing the state boundaries [16] to supply electricity to distribution stations.

Distribution grid connects customers to the substation. Voltage is stepped down at this level before supplying it to customers. Distribution lines carry electricity to the consumers.

Microgrids reside in the distribution grid as they generate electricity near customers and supply it to local loads. Each substation serves primarily to a certain area, although nearby substations can also reach the consumers, they are treated as a back-up in case of failure.

Following Figure depicts structure of electric grid:

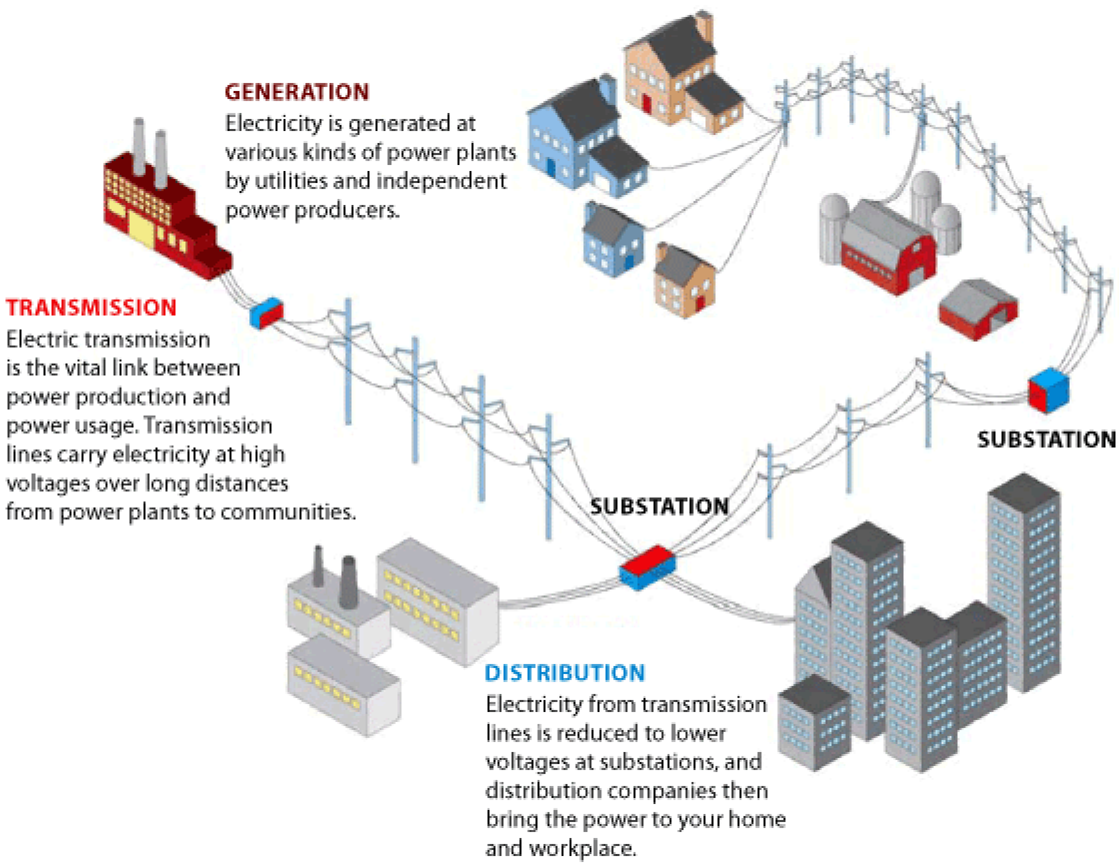


Figure 1. Electrical grid structure [19]

Thus electrical grid is structured like a hub and spoke with redundant lines to avoid single point of failure. A substation is usually designated to serve multiple neighborhoods and encompasses several microgrids.

3.2. Microgrid

Microgrid is a concept where loads are supplied power from local generators eliminating need of a central dispatch. A microgrid is typically used to supply electricity to a small localized area, typically a neighborhood. As the generators are small and localized, microgrid can be very efficient and flexible. Traditionally, microgrids are used like an uninterruptable power supply (UPS) system. When the power quality from main grid is reduced or power from central grid is insufficient, these localized generators supply power to fulfill the demand. In this thesis, we look into possible ways to use microgrids as a primary source and thus reducing the load in electric grid. Microgrid operates in two modes:

1. Grid connected mode
2. Island mode

In grid connected mode, the utility grid is active and the switch connecting the microgrid to main grid is closed. In this case microgrid draws power from main grid. In this mode the distributed generators are not used or being used as a secondary source to support the main grid at the time of peak load. In the second mode, island mode, the switch connected to the main grid is open and electricity is supplied by the individual sources. The feeders in microgrid are supplied electricity by the micro-sources.

A typical microgrid is structured as shown in the figure below:

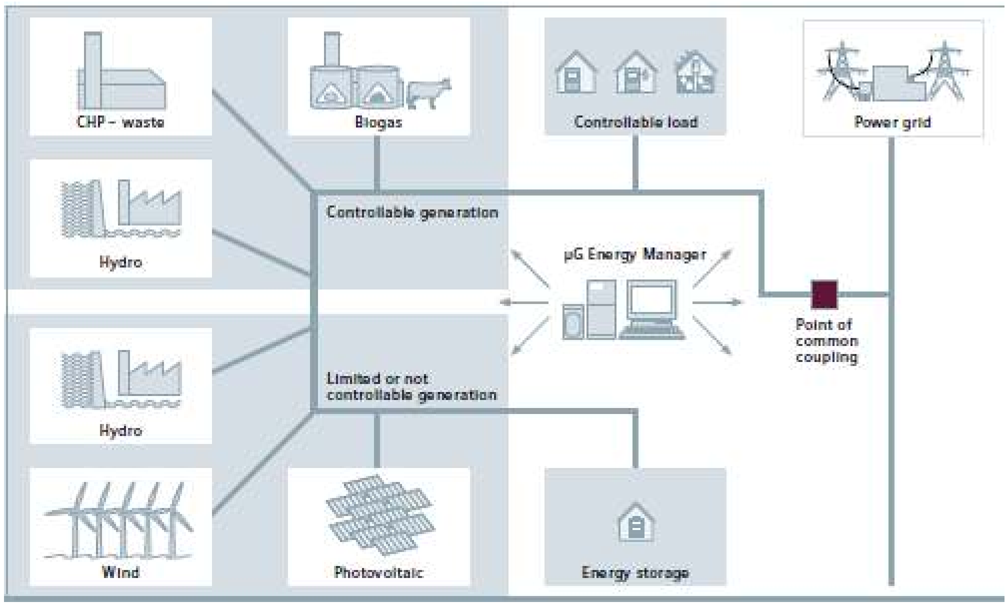


Figure 2. Structure of a microgrid [20]

The Microgrid is connected to main power line via a transformer. There is a feeder in the microgrid to distribute electricity. Load (households, factories etc.), power generators (solar panels, wind power generation) and power storage elements (batteries) are connected with to each other via feeder. Ideally, the generators will provide power to the load and microgrid will store surplus power in batteries, so microgrid will work independently from main grid and will always remain in island mode. If electricity required by the load is greater than the amount of electricity generated by the local sources then the microgrid takes power from main grid and then microgrid will be in grid connected mode.

Thus microgrids are capable of producing localized power and reduce the load on utility to certain extent. However if one has to consider transferring electricity between microgrids, it would either require special constructions or permission from utility to use its infrastructure. Although one can consider using utilities infrastructure over short distances, doing so over larger distances would be a technical as well as regulatory challenge.

In conclusion, one understands from this chapter that the microgrids are at distribution grid level in electric grid. As microgrids cover a small area, usually a neighborhood, a single substation encompasses more than one microgrid. In terms of electrical connections, it would be difficult to transmit power from microgrid to microgrid that are separated by substations unless there is a parallel transmission line and such construction is expensive. Thus, in order to minimize such constructions a self-organizing network should be in place that understands the electrical constraints. Also, in order to improve coordination within as well as between microgrids a sound communication network should be developed.

The remaining chapters will answer the problems presented above. The next chapter will look into communication network and then this thesis will develop an algorithm based on the communication network to self-organize an electrical grid to certain extent.

CHAPTER IV

COMMUNICATION NETWORK FOR MICROGRID

This chapter looks into communication network present in electrical grid and develops a communication network for microgrid communication. The chapter investigates the communication network requirements for information exchange between microgrids as well as within a microgrid. The chapter shortlists protocols suitable for the communication in microgrid and compares those protocols on the basis of several parameters such as bandwidth, security and cost, to come up with the most suited protocol for communication.

Before developing a communication network for microgrid, though, it is important to understand the communication network for the electric grid and the protocols used in it as this will help in narrow down the protocols for the microgrid communication.

4.1. Communication network for electric grid

Incorporating information technology and communication with electrical grid is an important aspect of development of smart grid. In smart grid operation and management, reliable communication plays a very vital role. A solid communication network is an integral part along with the sensing, metering and energy monitoring technology development.

Smart grid communication can be layered in following segments:

1. Information technology layer
2. Communication Layer
3. Energy systems layer.

Information technology layer predominantly deals with the operations of smart grid. It looks after the controls of the generators as well as consumers. Information technology layer takes care cloud connectivity, software that enables better control and operation of smart grid. This is essentially the IT layer of smart grid technology [16].

Communication layer, as the name suggests, looks after the communication between information technology layer and energy system layer. Communication layer will facilitate various means of communication depending upon the area and the nodes in contention. This aspect of communication layer will be elaborated in sections to follow. Communication layer is divided in various networks depending on distance and the section of electrical grid in contention.

Finally, the energy system layer looks after the electrical connections and actual transfer of electricity. Energy system layer pertains to the electrical grid structure mentioned before. Electrical system looks after the supply of electricity to the consumers. It also sends the required information to the information technology layer via communication network.

4.1.1. Communication layer

As mentioned before, communication layer of a smart grid deals with the communication technologies in electric grid. The technology used for communication varies with the type of nodes in contention as well as the area of the network. By looking into different technologies that are feasible for different type of networks one can shortlist the protocols that are most suited for microgrid communication. Communication layer, like electrical grid, is divided in roughly four categories depending on the size of the network. The categories are:

i. Customer Premise Network

ii. Neighborhood area network

iii. Access area network

iv. Backhaul network

Figure 3 describes the communication network for an electrical grid with different existing sub-networks. If one moves from left to right, the figure shows how communication networks change with size and how different protocols are employed for the communication purposes.

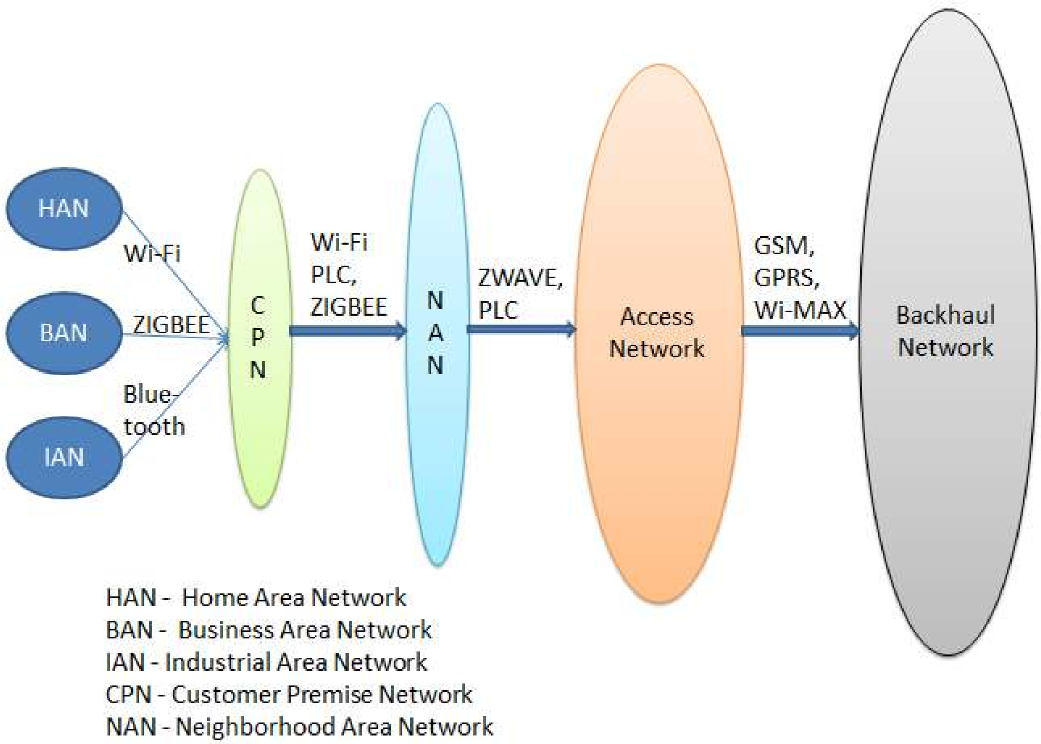


Figure 3. Smart grid communication network

Customer Premise Network (CPN): As the name suggests, this type of network consists of several customer nodes. This network will forward information to the local accumulator who in turn will connect to the Neighborhood Area Network (NAN). This network is small with area of around 100sqm. Wireless technologies such as ZIGBEE, WI-FI and Bluetooth are effective for this network. Some utilities divide this network further in Home Area Network (HAN), Industrial Area Network (IAN) and Business Area Network (BAN). Each network has different power requirements and consumption pattern. CPN coexists with the distribution grid.

Neighborhood Area Network (NAN): This network groups CPNs and local generators as well as storage units. In short, this type of network encompasses one or more microgrid. This network is spanned over 100-500sqm. Technologies such as Wi-Fi, RF mesh as well as WI-max are effective for this type of communication.

Access Area Network (AAN): This type of network connects several NANs to a substation. This network is responsible to connect electric grid at distribution level. This network can be used to exchange information between microgrids. Communication methods such as radio links and power line communication (PLC) are two effective technologies for this type of network.

Backhaul Network (BN): This network is equivalent to electrical grid's transport network. Backhaul network connects substations and power plants. This network connects electrical grid at transmission as well as generation level. Microwave communication and fiber communication are two effective methods for communicating in this network as this network carries large and critical data.

Among the various networks described in above mentioned section, CPN and NAN are comparable with the size of a microgrid, thus the protocols implemented in these networks can work for microgrid communication.

Table 1 denotes the comparison of various communication protocols from CPN and NAN, their data rate and range for their potential application in microgrid.

Table 1. Comparison of different protocols

Protocol	Data rate	Coverage
Bluetooth	721Kbps	10-30m
Wi-Fi	1-54Mbps	100m
Z-wave	10-40Kbps	30meters
ZIGBEE	250Kbps	100 meters
GPRS	14.4Kbps	1-10Km
Wi-MAX	4-46Mbps	Up to 50Km

A study in Vienna [17] has concluded that ideal data rate for microgrid is near 1Mbps. For a protocol to be considered for microgrid communication, the data rate should be at least 70% percent of required 1Mbps, which is 700Kbps. Based on the requirement, the most suitable protocols for microgrid communication will be Bluetooth, WI-FI and ZIGBEE. In the next chapter the communication network within a microgrid and inter microgrid as well as topologies for the network will be explored.

4.2. Intra-microgrid communication

Microgrids are part of Customer Area Network and Neighbor Area Network. The communication network for a microgrid is not bigger than several 100 meters. Thus according to the Table 1 in Chapter 3, the most suitable wireless technology for intra-microgrid communication is either Wi-Fi (IEEE 802.11), ZIGBEE (IEEE 802.15.4) or Z-wave. There are other wireless technologies such as Bluetooth which have several 100 meters range, but considering the development in ZIGBEE and Wi-Fi for smart grid communications [12][18][19], these two technologies are definitely the most promising.

Following sections compare the three protocols based on various parameters and come up with the best suitable protocol for intra-microgrid communication. The protocols will be compared based on topology, security, bandwidth available, transmission time and installation costs.

4.3 Intra-microgrid communication network design

4.3.1. Topology

Placement of nodes in microgrid is random and unique to each microgrid. One cannot predict where and how many loads and generators are going to be present in a particular microgrid. For a wireless network, each node will sense presence of other node in its range and form a link for potential communication, thus the physical topology of microgrid communication network would be a full-meshed topology. Following figure shows a full meshed topology depicting placement of various nodes:

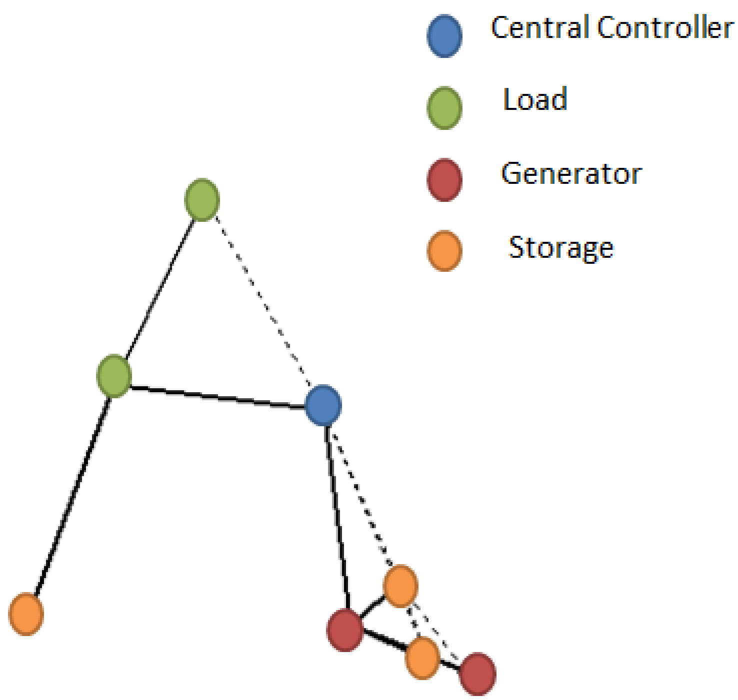


Figure 4. Physical topology

In microgrids, the participating nodes rarely communicate with each other. Most of the communication occurs between the microgrid controller and the nodes. Thus it is logical to place the controller at the “root” of the network. The communication should be from the root to other nodes with minimum number of hops to reduce the traffic, thus the networks should be logically structured as a tree. Following figure shows logical topology of microgrid.

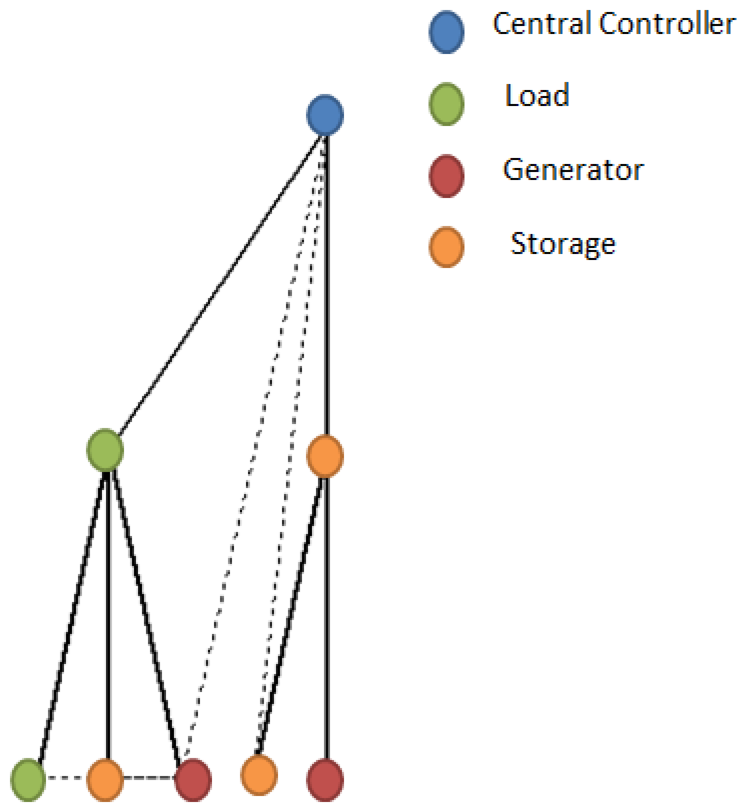


Figure 5. Logical topology

4.3.2. Bandwidth

Communication in microgrid is not bandwidth intensive. The messages exchanged between the controller and nodes are mostly data, which means very high-speed links is not a necessity. In fact according to a study in University of Vienna [17], a bandwidth of 1Mb should be enough for communication in a microgrid.

4.3.3. Security

Security is an important factor that needs to be addressed since sensitive information such as customer's billing and personal information, status of the generators etc. that will be exchanged. Thus the protocol that will be implemented needs to have some form of encryption to ensure the integrity and confidentiality of the data [20]. We will therefore compare the protocols in terms of security.

4.3.4. Transmission delay

Extensive research has been done on the messages that need to be exchanged between microgrid controller and the nodes. Control systems such as Zeus and Jade have well-defined types of messages. Researchers in TU Vienna [17] have looked into the latencies that are acceptable for various types of messages in a microgrid. Table 2 enlists the messages that need to be exchanged between microgrid controller and nodes and depicts the acceptable latencies in a network for communication in a microgrid. The message with highest priority and lowest latency requirement is error message sent by the nodes. Error messages are predominantly of 2 types, a critical error message (requiring latency of 1 sec) and a non-critical error message (requiring latency of 5 sec). Other than error messages, the other type of messages are information (load, power generation etc.), values (voltage, current, billing info etc.) as well as commands (switch on, switch off etc.)

Table 2. Message and corresponding delays

Messages	Acceptable Delay (Sec)
Error (High priority)	1
Error (Low priority)	5
Information (High)	5
Information (low)	10
Values (voltage, current etc.)	2
Values (consumer)	30
Command	2

4.3.5. Cost

Apart from the technical requirements, it is also useful and important to look into the cost of installing a communication network in a microgrid. Since microgrid has heavy initial investment [16], it would be accommodating to develop wireless network with minimum amount of investment.

4.4. Bluetooth (IEEE 802.15.1)

Bluetooth is a radio based wireless technology which is low cost and small range and is mainly applied in Wireless Personal Area Network. This technology is primarily aimed at replacing cables in computer peripherals and cellphone devices. Maximum possible range for this protocol is 10-30m, which is sufficient to be considered as a possible protocol for microgrid. Bluetooth can support data rate up to 746Kbps. Bluetooth has two topologies, piconet and scatternet. In piconet, Bluetooth protocol elects a node a master and other devices act as slaves, which is similar to the microgrid network with central controller acting as master sending commands and other nodes acting as slaves. Scatternet is combination of multiple piconets together where a device can be slave in more than one network. Scatternet will not be very useful in intra-microgrid communication; however one can definitely use piconet. Bluetooth devices have a 16 bit CRC encryption for integrity and confidentiality of data. Bluetooth routers cost around $80-$100 and repeater cost around same which means that the cost of installing machine will be higher since there will have to be multiple repeaters.

4.5. ZIGBEE (IEEE 802.15.4)

IEEE 802.15.4 is the standard followed by ZIGBEE, which is essentially a protocol for Home Area Network (HAN). ZIGBEE however has evolved in many flavors, which include ZIGBEE for smart grid [12] which has better range compared to ZIGBEE for HAN. ZIGBEE provides self-organized, multi-hop reliable communication. The network topology for ZIGBEE is similar to that of Bluetooth consisting of a master and number of slaves, thus this topology as well is suitable for microgrid communication. ZIGBEE has three types of devices, ZIGBEE controller (master), ZIGBEE router (semi-intelligent device) and ZIGBEE sensor (unintelligent end node). ZIGBEE controller costs $469 and ZIGBEE nodes and routers cost around $ 250 but since ZIGBEE's range is 100m the overall cost of the network may be less than the Bluetooth.

4.6. IEEE 802.11 (Wi-Fi)

IEEE 802.11 or Wi-Fi is a very widely used network protocol. This protocol has a range of around 100m. A common topology of IEEE802.11 is a full-meshed network which can easily be modified into the desired tree topology for intra-microgrid communication. As long as the devices are in the range, Wi-Fi can form a Local Area Network (LAN) without pre-planning and can elect a Basic Service Set (BSS) as a master. Wi-Fi supports 32bit CRC encryption which is better than the one supported by ZIGBEE and Bluetooth. There are a lot of options in terms of 802.11 devices as this protocol is so widely used. Wi-Fi routers cost around $150 which is cheaper than ZIGBEE and Wi-Fi has similar range which makes it an ideal protocol to use for microgrid communication. The only disadvantage of deploying this protocol is potential inter-channel interference from other devices using same protocol and channels.

Table 3 describes a comparison of above mentioned protocols in terms of different parameters such as range, bandwidth, security and frequency band. This information is useful while simulating the protocols for microgrid.

Table 3. Intra-microgrid communication protocols

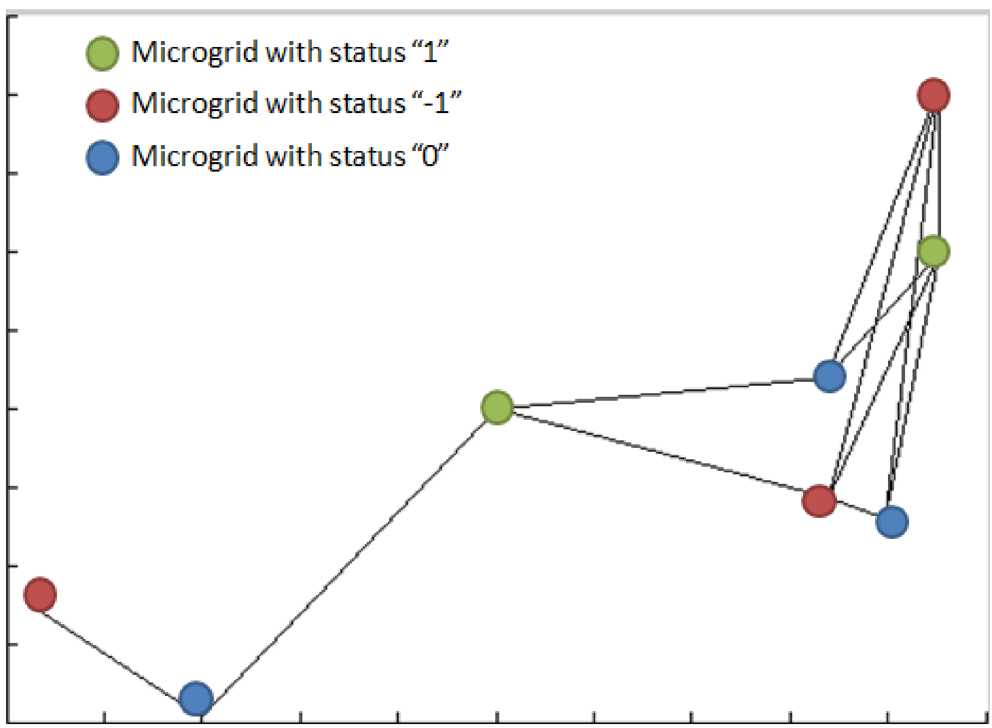
Parameter	Bluetooth	ZIGBEE	Wi-Fi
Frequency Band	2.4GHz	2.4GHZ	2.4GHz
Range	10m	**10-100m**	**100m**
Channels	**79**	16	14
Topology	Tree	Tree	Mesh
Data Protection	16 bit CRC	16bit CRC	**32 bit CRC**
Data Rate	1 Mb/s	250Kb/s	**54Mb/s**

4.7. Inter-microgrid communication

This section will look into inter-microgrid communication. Distance between microgrids can vary from several hundred meters to many miles, thus the protocol one is going to use should be able to communicate over long range. The network itself will be ad-hoc as there will not be a central controller present in the system.

4.7.1. Network design

As mentioned before, the inter microgrid network will be ad-hoc. Thus microgrids will have to communicate with each other and form a network. This ad-hoc network will be a meshed network opposed to the tree topology employed in intra-microgrid communication. Following figure shows a typical ad-hoc network between microgrids



6. Inter-microgrid network topology

The states of the microgrids will be elaborated later in the paper.

4.7.2. Protocols for inter-microgrid communication

Considering the range required for inter-microgrid communication and keeping in mind limited bandwidth utilization, either GPRS, Wi-Max or power line communication protocols can be used for this purpose.

GPRS uses cellphone tower infrastructure for communication and can offer bandwidth up to 16 Kbps. Power line communications uses AM modulation to insert information in the electric waves and the message can be sent at data rate of around 1 Mbps over several kilometers. Both methods have good range and adequate bandwidth to facilitate the needs of communication network.

In conclusion, this chapter has looked into the possible protocols and network that will support intra-microgrid communication as well as inter-microgrid communication. It was observed that for intra-microgrid communication, tree topology is most suitable and for inter microgrid communication a meshed topology is suitable. Protocols that can work for intra microgrid communication are ZIGBEE, Wi-Fi and Bluetooth, whereas the protocols for inter microgrid communication are GPRS or Power Line Communication.

CHAPTER V

SELF-ORGANIZING MICROGRID NETWORK

This section of the thesis investigates the methods to self-organize electrical grid using suitable self-organizing communication algorithm. The initial section of the chapter lists the benefits of self-organizing electrical grid and potential challenges in doing so. The later part of the chapter looks into a possible algorithm to do so as well as evaluate the results from such self-organization.

Distance between microgrids can vary between several hundred meters to several miles, so inter-microgrid communication occurs over radio links or over power line communication. Radio links are used by utility for communication between substations and power line communication is an emerging technology where communication messages can be sent over transmission lines. Microgrids are more or less independent entities and communication between them fairly limited. Communication network for the inter-microgrid communication is a fully meshed ad-hoc.

5.1. Benefits of self-organizing electric grid

Communication between microgrids is relatively straight-forward and minor unless there is a possibility of exchanging electricity at a lower cost than utility. To exchange electricity, one will have to re-organize the grid in a way that one microgrid will act as a generator and other a load. Thus, self-organizing the electric grid is beneficial. It will mean that certain sections of the electrical grid will get electricity of renewable sources which will result in reduction of overall load on microgrid. Thus microgrids would play a more active role in electrical grid. Using microgrids we can also reduce the carbon footprint and lessen the pollution caused by power plants and finally, as the sources are localized, in case of power outage the electric grid can be re-organized to ensure power supply to consumers.

5.2. Challenges in self-organizing electric grid

Self-organizing microgrids network faces technical as well as legal challenges. Electric grid continuously carries electricity from utility hence it is important to ensure that the utility power supply is isolated before microgrid starts providing power to load. If either supply is not isolated then it may cause back-currents which are detrimental to the equipment.

The isolation of one supply from another is done at point of common coupling (PCC). The point of common coupling is a switch which opens and closes allowing either microgrid or utility to connect to load. But PCC works for only one microgrid. Opening and closing a PCC will not facilitate the exchange of electricity between microgrids. In order to ensure that the exchange of electricity takes place between microgrids, one would need to modify the design of substation so that substation can route electricity between microgrids or one would have to add additional lines between microgrids and change the logical connections each time there is a different microgrid with excess electricity. Adding additional lines is costly (almost $5 per feet) and utility is unlikely to change the structure of substation for privately owned microgrids. Thus it is challenging for microgrids to exchange electricity.

This thesis will look into the latter solution of installing parallel transmission lines and reorganizing the grid between microgrids. However, installing transmission lines is cost prohibitive thus exchange of electricity can be effective and feasible for microgrids which are near each other, with realistic opportunity to build a power line between the two. However, exchange and self-organization of the grid becomes very tricky between microgrids residing in different substations. This is due to the fact that there is no real point of common coupling to disconnect electricity coming from utility and provide a path to exchange of electricity between microgrids. Also, it is not feasible to create an independent network of several miles as the cost of laying such a network will far exceed the potential benefits from it. And finally, the utility will not be very compliant to let locally generated power travel via its grid. Due to these reasons, currently it is not feasible to self-organize microgrid network more complex than a microgrid network within a single substation.

Typically a substation will not have more than 7-8 microgrids and we will assume that a separate transmission line is constructed between microgrids within 5 Km from each other. As this network will consist of maximum 7-8 nodes, using complicated algorithm such as self-organizing maps to reorganize the grid may not be necessary, as a relatively simple self-organizing algorithm such as modified OSPF will be as effective.

Thus we will implement a modified version of OSPF where nodes will elect designated and back-up designated stations to provide them power in case of shortage. The algorithm will be designed keeping in mind the constraints of common coupling of electrical grid.

5.3. Deciding the state of a microgrid

The state of a microgrid is determined on the basis of amount of power it has predicted to generate, amount of predicted load and reserve battery supply remaining in the grid.

The amount of real power generated is calculated by the voltage, current and the phase angle sent by the generators. This power is converted in KWH. Predicted power consumption is based on the previous data and before microgrid goes online, the system makes sure it has at least 40% back-up storage. From this information, microgrid propagates its state to other microgrids. State “1” denotes that the microgrid has sufficient electricity and can lend it to any microgrid requiring it at a pricing better than that offered by utility. State “0” signifies that microgrid will be able to sustain itself but no other microgrids and state “-1” means microgrid will require electricity from others.

If the status alone is not sufficient for a microgrid to decide if it can lend power to other microgrid or not then the microgrid will send or ask for additional information such as the voltage of operation, current, phase angle as well as peak load that it can handle. As a microgrid knows the amount of active and reactive power from the received voltage, current and phase angle; a microgrid can gauge the quality of power before connecting to the other microgrid. If the amount of reactive power is greater in the microgrid supplying electricity then other microgrid may reject that service and proceed to use main grid which guarantees certain quality of service.

5.4. Algorithm to self-organize a microgrid network

This section of the paper looks into developing a suitable algorithm for organization of microgrids. The algorithm is similar to OSPF routing. Initially each microgrid sends out a package to make their presence felt. Along with this packet they send their status. The status is determined by the amount of electricity they are estimated to generate, amount of load on and charge in battery. The status can be 1, 0 or -1. “1” denotes that the microgrid is not only capable of sustaining itself but it also has enough spare electricity to provide support to other microgrids. 0 shows that the microgrid can support itself and has some spare electricity but it is not enough to support other microgrid. And -1 shows that the microgrid requires electricity. Once all microgrids receive this status from other microgrids, depending on their condition, they either become backup designated station or designated station. All microgrids in state “1” can become designated stations to those in state “-1”. All microgrids in state “0” can become back-up designated stations to those in state “-1”.

If a microgrid, whose state is -1, is short of electricity then it reaches out to its designated station for electricity. If designated station has sufficient electricity, then it provides it to the microgrid. If the designated station does not have enough electricity then it looks for electricity to its back-up designated station. If all fails then the electricity deficient microgrid connects to main grid for power.

Here is an algorithm depicting the process of selection of designated and back-up designated microgrids. The algorithm also explains the communication that occurs between the stations in the process of selection.

1. Each microgrid will check its status.
2. If the status is 1, it will do nothing.
3. If the status is 0 then it will look for closest microgrid with status 1; that microgrid will be the designated station for that grid.
4. If the status is -1 then the microgrid will look for a grid with status 1; that grid will be the designated station for the grid. And this microgrid along with the associated back-up designated microgrid will supply electricity.
5. In case of deficiency in power, a microgrid will reach out to its designated microgri
6. If electricity from designated microgrid is not sufficient then designated microgrid will go to back-up designated microgrid.

Thus this algorithm will self-organize the grid considering the electrical connections' limitations. The final self-organized network can be used to modify the grid temporarily so that one can exchange electricity between microgrids.

CHAPTER VI

SIMULATION AND RESULTS

The algorithms and scenarios described above are simulated in MATLAB. MATLAB provides a suitable platform and versatile visual outputs to aid the research. Other platforms such as NS2 are also suitable for such simulations.

6.1. Intra-microgrid communication simulation

In intra-microgrid communication simulation physical as well as logical topologies are simulated. Physical topology is a meshed topology with nodes connecting to all or most of the nodes in their range. Logical topology is tree topology; it depicts the flow of data from controller to nodes.

Initially nodes are placed randomly as one cannot predict where load is going to be or which area within the microgrid is most suitable to generate and/or store electricity. This simulation is with 7 microgrid nodes, in which there are 3 microsources, 3 loads and one storage unit. The eighth node in the simulation is a controller, which takes information from microgrid nodes and also communicates with other microgrids. The controller is denoted by "1" in the figure below.

Figure 7 shows the simulation of microgrid network:

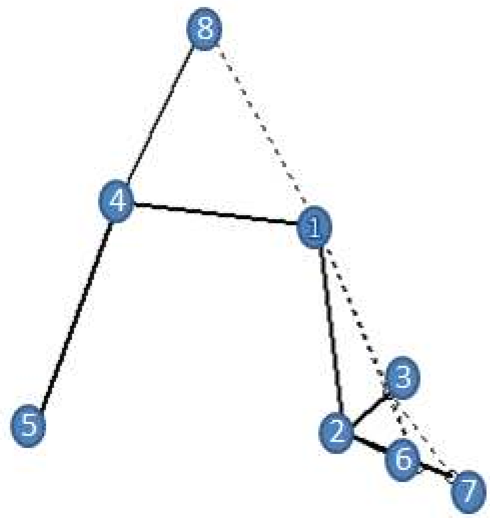


Figure 7. Physical topology

In this topology, nodes have connections with each other as well as with the controller. Solid lines depict the path that goes to controller, whereas dotted lines show the connection between two nodes. The dotted line paths serve as back-up routes.

Logically the communication network will have a tree-like structure as shown in the figure 8:

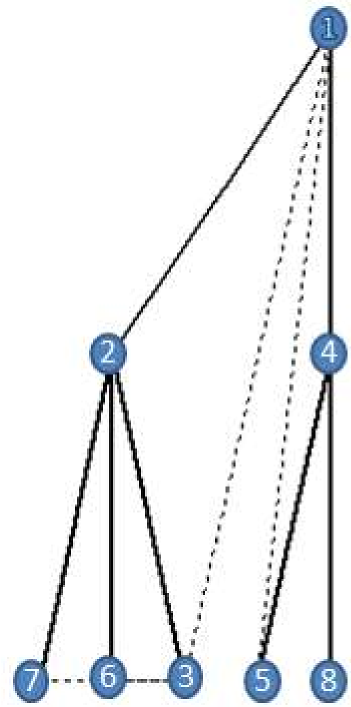


Figure 8. Logical topology

The controller first must know where all the nodes are and their respective statuses. Using routing protocol, the controller gathers knowledge regarding other nodes. All other nodes also know about the position each node.

Once all the information is exchanged between the nodes, the controller keeps track of placement as well as link path to each node. The nodes themselves are only aware of the next hop. Figure 9 shows the information stored by controller on the packets.

```
info =

         0  500.0000  500.0000    2.0000    5.0000         0
    1.0000  525.2925  306.8304    3.0000    4.0000    1.0000
    2.0000  627.0985  265.1894         0    3.0000    2.0000
    5.0000  312.3440  522.6948    2.0000    3.0000    1.0000
    6.0000  394.5006  691.5913         0    2.0000    2.0000
    3.0000  569.3237  343.2188         0    4.0000    2.0000
    4.0000  594.9357  273.9462         0    4.0000    2.0000
    7.0000  235.7673  314.0590         0    1.0000    2.0000
```

Figure 9. Matrix stored in controller

First column is node id, using this we can identify various nodes. Column 2 and 3 are the physical coordinates of the nodes. The controller is at (500,500), which is center of microgrid. The next column is number of children node. This helps in determining if the request be forwarded or not. The next column is number of neighbors and final column is the level. Level is used determine the depth. Level 0 is the root; level 1 is one hop away and so on.

The overall network information is stored in following matrix. The matrix is named tneighbor and is shown in the figure below:

```
tneighbor =

    -1     2     4    -1
     1     3     6     7
     2    -1    -1    -1
     1     5     8    -1
     4    -1    -1    -1
     2    -1    -1    -1
     2    -1    -1    -1
     4    -1    -1    -1

>>
```

Figure 10. tneighbor matrix

The first column in the matrix is for parent neighbor, -1 signifies that the node is root. The next 3 columns denote the children and the value in the column is the node id of the child. This matrix is used to get an idea of what node is connected to which node.

The controller is placed at the root of the communication network and it sends out the three requests (request for battery, electricity generation and electricity consumption). The information is gathered. Figure 11 depicts the requesting and gathering process.

```
Request to information signal sent to node
     2

Request to information signal sent to node
     4

Request to information signal sent to node
     3

Request to information signal sent to node
     6

Request to information signal sent to node
     7

Request to information signal sent to node
     5

Request to information signal sent to node
     8

Information sent to root by node by loads
Information sent to root by node by storage
Information sent to root by node by genrators
```

Figure 11. Communication simulation example

In response the nodes will send information to the controller. Controller polls each node for information, and each node sends its respective information. The polling process is done from the closest node to the node farthest away. As shown in the figure above, node 5 takes much more time to send information than the node 7 and 8. The reason of this delays is due to the fact that node 5 is greater number of hops away than nodes 7 and 8. The controller gathers and stores this information. Once the controller has acquired the information, it makes a decision whether it can support the load for next iteration. If it can then the status of the microgrid is 0 and if it cannot then status is -1. If the microgrid has surplus energy and it can distribute the electricity to other microgrids then the status is 1. As mentioned before, this poling is done every 15 minutes to check the status of the nodes. If during the 15 min interval the predicted generation or load changes drastically then that node will send an error signal which will result in controller requesting for alternate means of power source (either from storage units or utility).

6.2. Latency calculations for different protocols

This section depicts the performance of various protocols when simulated for the given microgrid. The microgrid in contention in this case is the one described previously. As mentioned in the previous section, average payload per message is 20 bytes for microgrid communication. Different latencies are mentioned in the table in the previous section. In order to calculate the latency following formula will be used:

$$Ttx = \left(Ndata + \left(\frac{Ndata}{NmaxPld * Novhd}\right)\right) * Tbit + Tprop$$

Where,

T_{tx} is transmission time

N_{data} is data size

N_{maxpl} is maximum payload

T_{bit} is bit time

T_{prop} is propagation delay.

From the above equation, following graph is generated comparing transmission delays for various protocols.

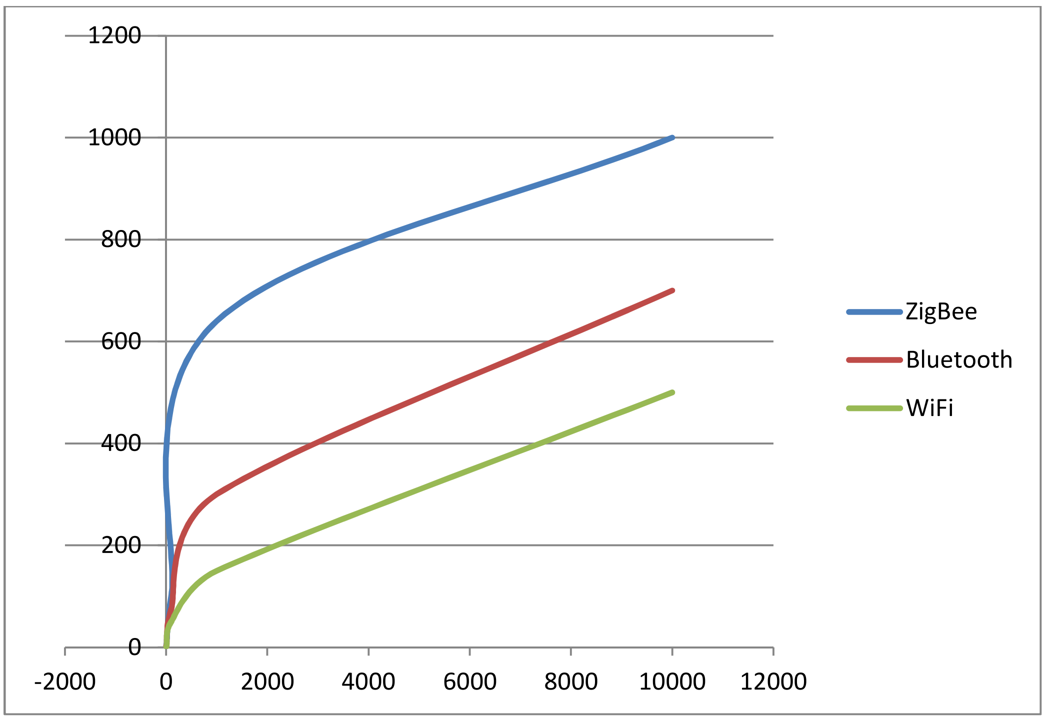


Figure 12. Transmission time calculation comparison

Thus we can see that all protocol have satisfactory transmission time for microgrid even in case of high priority packets, which means that all of the above protocols will be well suited for the intra-microgrid communication.

So, in case of intra-microgrid communication, Wi-Fi, ZIGBEE and Bluetooth will perform satisfactorily. However their cost of installation may vary.

6.3 Estimation of cost of installation

Depending on the range and cost of router, one can simulate the potential cost of installing a network. This will be beneficial in deciding which protocol should be preferred for intra-microgrid communication, since until now Bluetooth, ZIGBEE and Wi-Fi are viable.

Bluetooth has maximum range of 30m and for the 6 node network in contention; the total range that needs to be covered is approx. 2250m. As each router and repeater cost $80, the total cost will be $6480.

ZIGBEE has a controller with cost of $469 and other nodes cost $250 but ZIGBEE gas range of 100m. Thus the total cost will be $7969.

For Wi-Fi, each router costs around $150 and it has range similar to ZIGBEE, thus the cost of installation is $4500.

Considering overall parameters for intra-microgrid communication network as well as the cost of installation, Wi-Fi is the most wireless suitable protocol between 802.11, ZIGBEE and Bluetooth.

6.4. Simulation of loads and distributed generators

A microgrid is made up of load nodes and generator nodes. In order to test the communication network and the performance of the algorithm, a simulation of microgrid loads and generators is required. A challenge in sending information is to obtain actual information on these nodes since the load and distributed generator information is usually proprietary and not easily accessible. In order to obtain actual numbers, this thesis has reverse engineered and extrapolated the data from the graphs available. This thesis has used a household load variation pattern to vary the loads experienced by microgrid. For generators, this thesis has considered three renewable sources; solar energy, wind and biogas. Once installed, biogas can produce energy at a constant rate but for solar and wind information has to be extrapolated.

6.4.1. Obtaining data on load

According to mpower [30] per hour consumption in California depending on the type of load will look as follow:

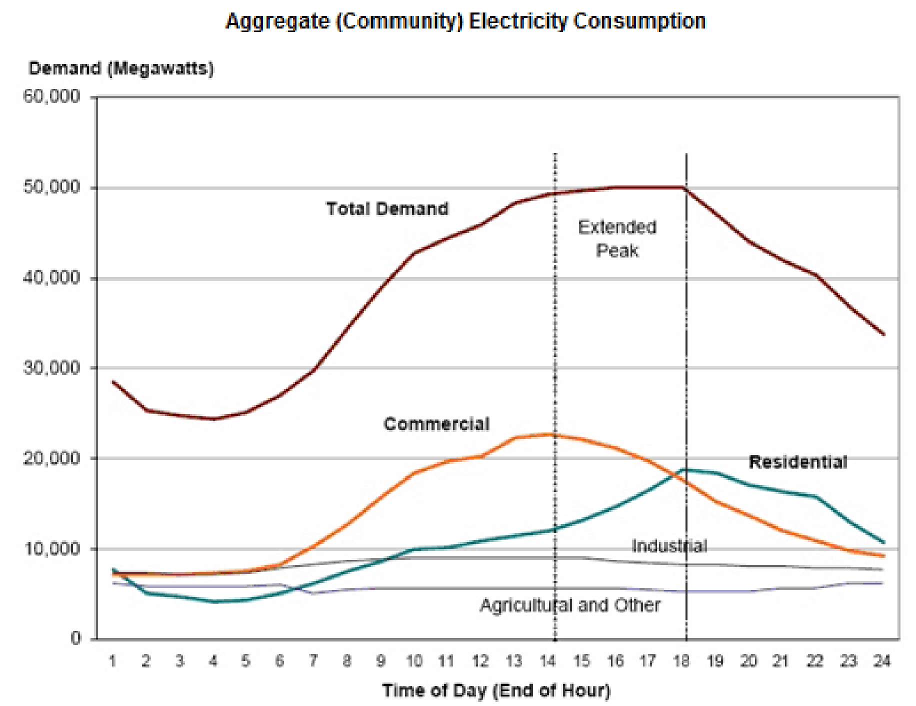


Figure 13. Variation in load over 24 hrs.[30]

As one can see, commercial and residential demands are different. Commercial demand peaks at office hours and residential demand peaks in the evening when everyone is home. Using this curve and typical monthly charges per household, we were able to find approximate hourly consumption per house hold. After that we increased the power to incorporate heating during winter. This increase was based on a survey done by the US government [16]. Following graph depicts the hourly consumption for a typical household during summer as well as winter.

6.4.2. Calculating solar power generation

Solar power can be generated only during the period when sun is out and amount of power generated depends on the intensity of sunlight and efficiency of generators. According to, "Renewable and efficient Electric Power Systems", average energy generated per square meter per day is 5.5 KWH [15] in California. Assuming that sunlight is received for about 10hrs, we extrapolated this number into a bell curve with intensity of solar energy increasing till sun reaches its apogee and decreasing after that. We assume Photovoltaic cell efficiency to be 15% and inverter efficiency to be 70%. Then, the amount of electricity produced is given by:

$$\text{Electricity (KWH)} = \frac{\text{PV efficiency} * \text{inverter effciency} * \text{energy per sqm} * \text{Area covered} * \text{area covered}}{1000}$$

Figure 14 shows variation in solar power generation over 10 hrs. With 100sqm area covered by solar panels,

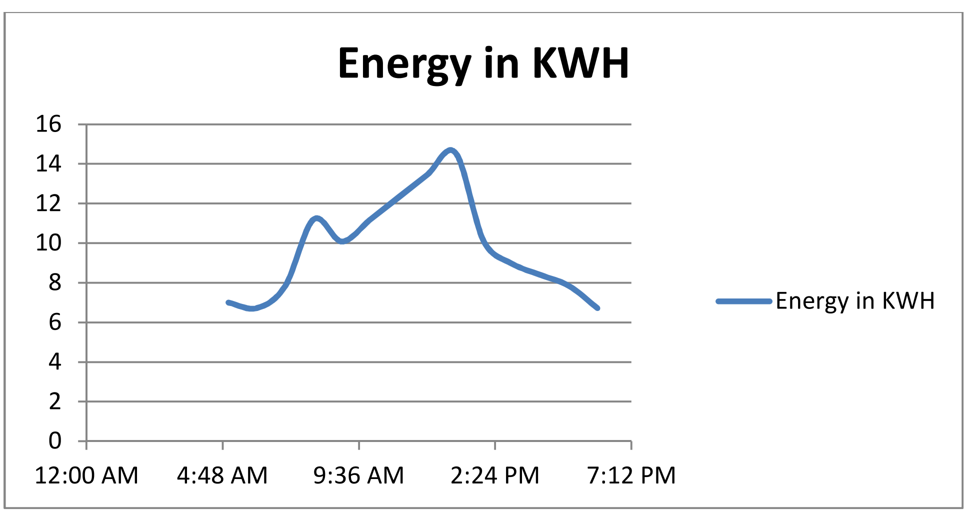


Figure 14. Variation in electricity from solar energy

It should be noted that this simulation is done strictly to have a virtual solar generator. This model is not very accurate as it does not consider the changes in weather and the angle at which solar panels are placed. This model however gives realistic numbers to test the self-organizing algorithm.

6.4.3. Calculating wind power generation

Wind power generation depends on the speed of wind, blade span and efficiency of generators. In order to get the data on wind speed, this thesis has used wind speed graphs provided by NIST [28] for various regions in the United States. Following formula is used to calculate wind power generation. Wind energy is estimated using following formula:

For a blade with diameter d, wind speed v, the estimated electricity generation is given by,

$$\text{Electricity (KWH)} = \frac{\pi d^2 * v^3 * number\ of\ turbines * efficiency\ of\ inverter}{1000}$$

As in case of solar generation, the numbers generated are not very accurate but they help in simulating the effect of having wind power source in a microgrid.

6.4.4. Deciding the state of microgrid

We have created a matrix system to determine if a microgrid is capable of sustaining on its own. This state definition matrix will be beneficial in self-organizing the grid for efficient electricity transfer. Following figure shows the interface where we can check the status of microgrid. The state definition is just a combination of total predicated power from generators and predicted load on a microgrid.

Another aspect to be considered is whether the cost of electricity is better than that provided by utility or not. However, this is not considered in this thesis and it is assumed that the cost of electricity is always either better or equal to that of utility. Thus, column 3 is always green.

Amount of predicted real power	Predicted power consumption	Better than Utility pricing	Status
22	23	● 1	✗ -1
21	20	● 1	✓ 1
15	30	● 1	✗ -1
28	22	● 1	✓ 1

Figure 15. Microgrid state

This matrix has predicted generated power, predicted load and a field that compares pricing with utility to see if its better or not. If predicted generated power is greater than load and the pircing is better than utility pricing then the microgrid is in status "1", if the load is greater than the power generated then the status is "-1".

6.5. Self-organizing example

Self-organizing algorithm can be run in various circumstances. Following figure depicts a network of six microgrids in close proximity. These microgrids initially have electrical interconnections shown by the solid line.

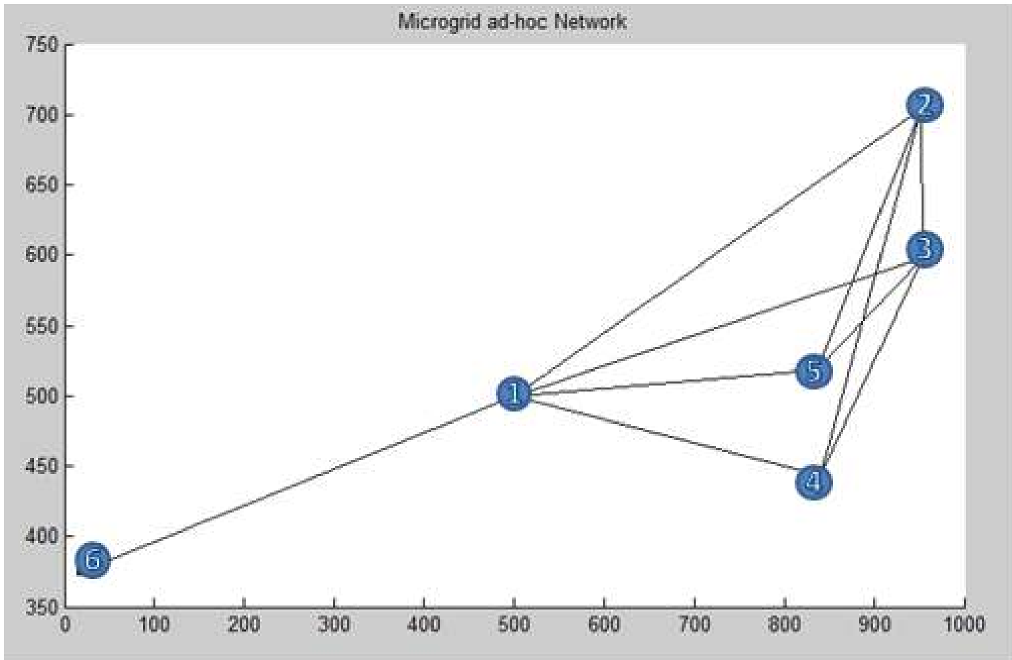


Figure 16. Initial connections of a self-organizing network

Each microgrid tries to connect with as many microgrids as possible and the overall electrical network follows the rules mentioned while developing the network so that no node is left out and all the microgrids have some means to reach each other if required. For this simulation, table 4 describes the states of the microgrid along with the type of local power sources that are available:

Table 4. State table for self-organizing simulation

Node	Power sources	State
1	80sqm of solar panels	-1
2	Biogas, 300sqm solar panels	1
3	None	-1
4	Microturbine	0
5	400sqm of solar panels	0
6	50 Wind turbines of diameter of 2m	-1

Once microgrids broadcast these states, using the self-organizing algorithm mentioned above the electrical grid is self-organized. The self-organized grid looks as follows:

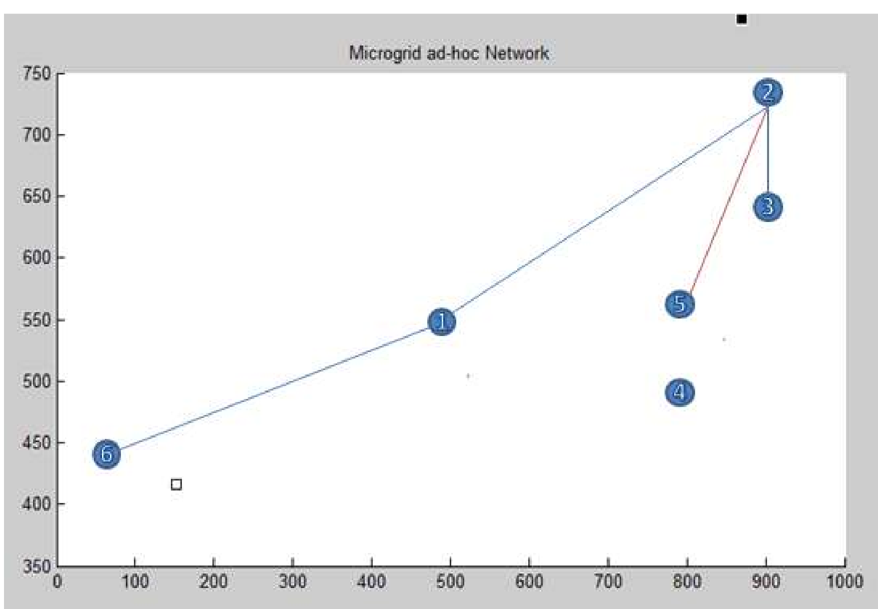


Figure 17. Self-organized network

As shown in the figure above, node 2, which has excess electricity is connected with the microgrids that require electricity and node 5 acts as a back-up designated station to node 2. Node 4, which can fulfill its own requirement, is left out of the network and will be requested to connect only if both node 2 and 5 don't have enough electricity. Figure 18 shows the request and supply pattern for the given network.

```
1 Requests power from designated node 2
node 2 provided electricity to the node 1
3 Requests power from designated node 2
node 2 provided electricity to the node 3
6 Requests power from designated node 2
node 2 provided electricity to the node 6 with help of back-up designted station 5
```

Figure 18. Simulation snapshot

This algorithm can work on a large network as well but it probably will not be as efficient. Technologies such as biologically inspired self-organizing network [16] and self-organizing maps [17][18] will probably be more efficient at self-organizing the electric grid. However, until the electrical connection constraints are resolved, theoretically self-organizing the grid is a moot point.

6.6. Performance of the self-organizing algorithm

The self-organizing algorithm designed for microgrids was simulated under various conditions such as changing the number of microgrids, varying the number of microgrids in status "1", as well as changing the amount of surplus electricity available.

It was observed that output of the algorithm depends on following factors:

1. Type of generators present in the microgrid network
2. Predicted total loads

3. Time of the day
4. Feasibility of connection between microgrid carrying surplus electricity and microgrid requiring that electricity.

Thus there are almost infinite combinations that are possible. For example, a microgrid with solar generator may be able to produce same amount of power as a microturbine during the day but it cannot produce the same power during night, so even though self-organization network is same in both cases during the day it will be different during night.

However, by running many combinations, we were able to make some definite conclusions on the maximum number of microgrids one can self-organize with electrical constraints. Until 4 microgrid network, the self-organization algorithm works at a high efficiency, which means if electricity is available then it will reach the electricity deficient microgrid. However from 5 microgrids onwards the percentage drops significantly for certain combinations, especially when using renewable sources. Figure 19 depicts the performance of self-organizing algorithm when subjected to various microgrids under different combination of load, generator and time.

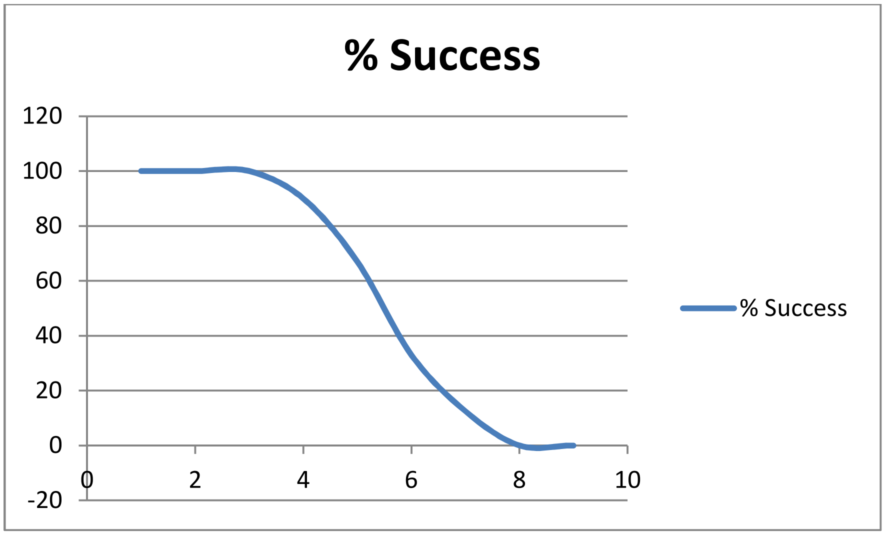


Figure 19. Performance of self-organizing algorithm

This graph is the plot of number of microgrids in a network vs. the success of the self-organizing algorithm. The success of the algorithm is defined by the number of times the grid as successfully reorganized so that the microgrid with excess electricity was able to reach microgrid with less electricity than required. As seen in the plot, self-organizing algorithm's performance degrades after 5 microgrids. This is due to the fact that there are electrical connection constraints attached to self-organizing and actual electricity cannot be transferred for more than 2 hops.

6.7. Role of renewable sources in microgrids

Although this observation does not directly pertain to the research done in the thesis, some observations were made regarding the contribution of renewable sources in satisfying the demands from microgrids. We considered three renewable sources; solar generation, biomass and wind.

It was observed that the biomass is probably the most effective method of utilizing renewable sources at scale of microgrid even though the initial investment is higher, one cannot setup biomass at a small scale. Solar energy is second and wind energy was the least efficient way for microgrids. Following table depicts the average amount of energy generated by three methods on an initial investment of $100K [29]. We have averaged out sunny as well as cloudy days as well as windy and quiet days to get a better idea of average electricity produced.

Table 5. Comparison of renewable sources

Source	Electricity Generated (KWH)
Wind Energy	10 KWH
Solar Energy	11.2 KWH
Biomass	14 KWH

The only downside of solar powered electricity is the fact that it is limited to the time sun is out whereas wind and biomass can give steadier supply of electricity.

Figure 20 depicts the electricity generated by the three sources over period of 24 hours. We assume that biomass can give constant electricity throughout the day.

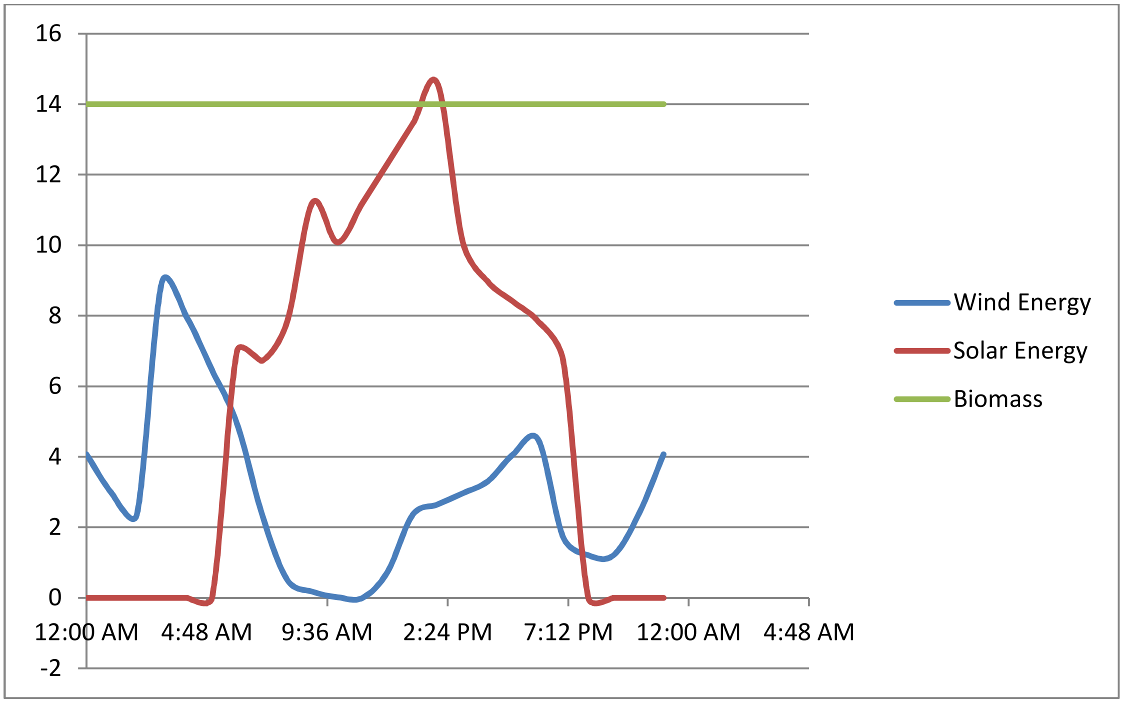


Figure 20. Electricity generated by different renewable sources over 24hrs.

As one can see, biomass produces constant electricity, whereas wind and solar power generation fluctuates with changes in weather conditions.

CHAPTER VII

CONCLUSION AND FUTURE WORK

In conclusion, this thesis was aimed at simulating the communication network for microgrids and possibility of self-organizing a microgrid network. In the initial part of this thesis, it was observed that Wi-Fi, ZIGBEE and Bluetooth protocols are well suited for intra-microgrid communication. These protocols have the required range, latency and security to be deployed in a microgrid. It was also observed that the topology best suited for intra-microgrid communication is a tree-topology, which was simulated in MATLAB. The work also looked into the communication network for inter-microgrid communication and tried to decide a suitable protocol for it. It was found that inter-microgrid communication network is ad-hoc and either GPRS or PLC will be suitable for such communication.

The limitations of electrical grid became evident while self-organizing a microgrid network. It was clear that microgrids cannot be self-organized if they were separated by a great distance or if they were not part of same substation. However limited success was achieved in self-organizing a cluster of 6 microgrids using a modified OSPF algorithm which helped alleviating the load on utility.

For future work in this area, one can research on inter microgrid communication network in greater detail and look into the messages that has to be exchanged between the microgrids. One can also look into the methods to self-organize a larger grid effectively. Also, a possible business model to generate revenue in microgrids is a fascinating idea as each microgrid can bid against one another as well as against utility to provide electricity at cheapest rate.

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