SELF ADAPTING SMART ELECTRICAL GRID

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MASTER OF SCIENCE

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ABSTRACT

Following the invention of electricity the electrical grid system was one of the biggest achievements of the twentieth century. It has been responsible for delivering power to millions of homes and businesses. As the demand for power increases due to the continued modernization of our society the strain on the current power grid is increasing at a steady pace. Since 1982 the demand for electricity has surpassed transmission growth by 25% each year, in essence we are using up more resource then we are generating, [15]. This has led to the system showing signs of weakness in the form of Blackouts. There have been 5 blackouts in the past 40 years out of which 3 of them have occurred in the last 9 years, [15]. At the same time requirements of more environmentally friendly power sources is supplying additional engineering challenges. Case in point, the population of US just accounts for 4% of the world's population but it is responsible for generating 25% of the greenhouse gasses that are currently emitted with the electrical grid system being one of the biggest contributors. In its present state the electrical grid system is also highly inefficient and wastes

precious natural resources used to generate this power. If only the grid efficiency is increased by 5% that would be equivalent to removing greenhouse gas emission from 53 million cars, [15]. Ultimately the thing that directly affects consumers is the dollar amount that they pay for this electricity, which has also doubled over the past couple of decades.

The present process that uses a centralized control center to balance the grid seems to be inadequate and ageing at a rapid pace. This way of power delivery is now more than 50 years old, it may have been the best that technology had to offer during that time but in today's world of rapid information exchange and distributed parallel processing its seems antiquated.

This thesis proposes a solution that is dependent on a more distributed manner in which the grid can be balanced rather than relying on a single control center. This paper puts forward a communication protocol and a communication algorithm that makes the system self-adapting to changing power demands in real-time. The algorithm is designed to prioritize distribution of power locally hence cutting down on the need to transmit power over long distances while reducing the demands on the remote power generation units.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of School of Computing and Engineering, have examined a thesis titled “Self Adapting Smart Electrical Grid” presented by Kushal K Lal, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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LIST OF ABBREVIATIONS

PP - Power Plant

KV - Kilo Volt

TS - Transmission Sub Station

DS - Distribution Sub Station

GT - Green Transformer

SM - Smart Meter

BS - Base Station

RNet - Ring Network

PLC - Power Life Cycle

NIST - National Institute of Standards and Technology

NETL - National Energy Technology Laboratory

EPRI - Edison Electric Institute

ACK - Acknowledge (ack)

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CHAPTER 1

INTRODUCTION

1.1 Thesis Foundation

One of the main goals of this research is to make the solution implementable and practical in the real world. Due to this constraint the research could not recommend drastic solutions that would require a complete top down change in the way power is being delivered making the implementation too costly. So while trying to use the existing structure the research is aimed at suggesting ways in which we could manage power efficiently while maintaining a relative low cost of upgrading old equipment to provide additional functionality in the existing electrical grid structure. So let's first look at a Source to Destination model of how and where power is generated to how it ends up in our home and businesses.

1.2 Source to Destination Model

- PP (Power Plant) - Power gets generated at a power plant which come in different types and sizes.
    - There are power plants that use fuel to generate electricity
        - Coal Fired Power Plants (coal)
        - Combined/Simple Cycle Power Plants (Natural Gas)
        - Nuclear Power Plants (Uranium a highly radioactive material).

- Other than fuels there are other natural resources that are employed such as
    - ♦ Hydroelectric Power Plants which rely on immense pressure generated by a large water reservoir constrained with the use of a Dam.
    - ♦ Wind Farms which harness wind energy.
    - ♦ Solar Power Plants that utilize photovoltaic cells in large number to harness the energy imparted by the photons created by our Sun to generate electricity.
    - ♦ Geo Thermal Plants generate power from the thermal energy that is generated by the core of the earth.
    - ♦ Tidal Wave Power Plant harnesses the tidal motions of the sea to generate power.

These power plants have the capacity to generate power anywhere from 1 MW to 1500MW and between 8KV (Kilo Volt) to 25KV. Connected to the power plant is a transformer that steps up the voltage to between 150KV to 800KV in preparation for transmission of the power.

- ▪ TS (Transmission Sub Station) generally transmit power between 150KV to 800KV. Transmission Sub Stations deliver power to the Distribution substations.

- DS (Distribution Sub Stations) are generally located in areas of power consumption. The purpose of this Distribution Substation is to step down the voltage of the power that it receives from the Transmission Sub Station so that it can be sent out for local industrial and commercial consumption. There are generally a handful of Distribution Sub Stations in a City or Town depending on the size of the city or town. The Distribution Sub Station steps down the power to about 4KV to 15KV.
- DT (Distribution Transformer) The local transformer (single phase distribution transformer in case of residential area is generally responsible for providing power to 4 to 6 houses) then receives this power and steps down the power to 120V/240V which is then used by the consumer in their home.
- SM (Smart Meter when we speak in the Smart Grid context but in general term we can refer to this as Meter). The meter is responsible for tracking electricity usage within a home/commercial organization or at the consumer. The average consumption of the US house hold is 903 kWh (Kilo Watt Hour) per month during the 2012 year as reported by the US Energy Information Administration, [13].

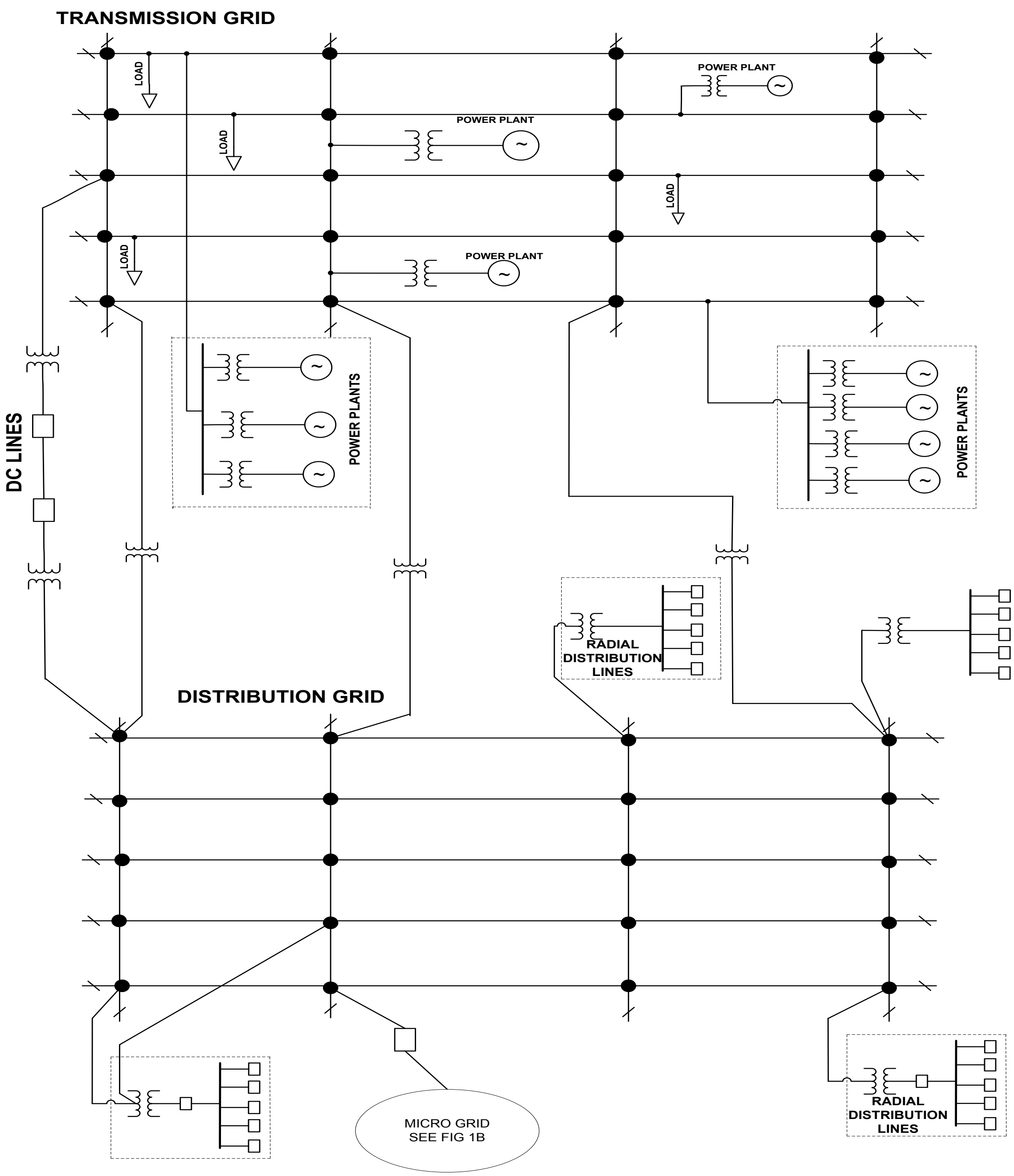

Figure 1 - Electric Grid Overview

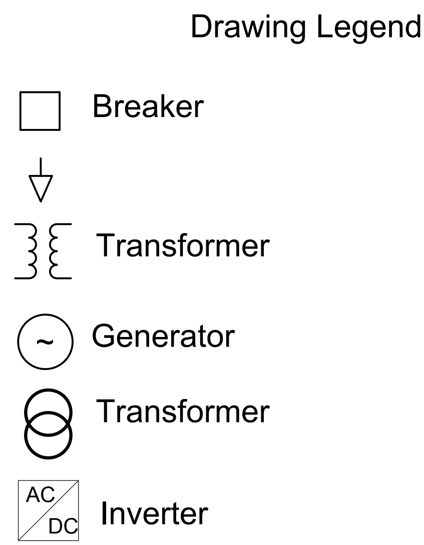

Figure 2 - Figure 1 Legend

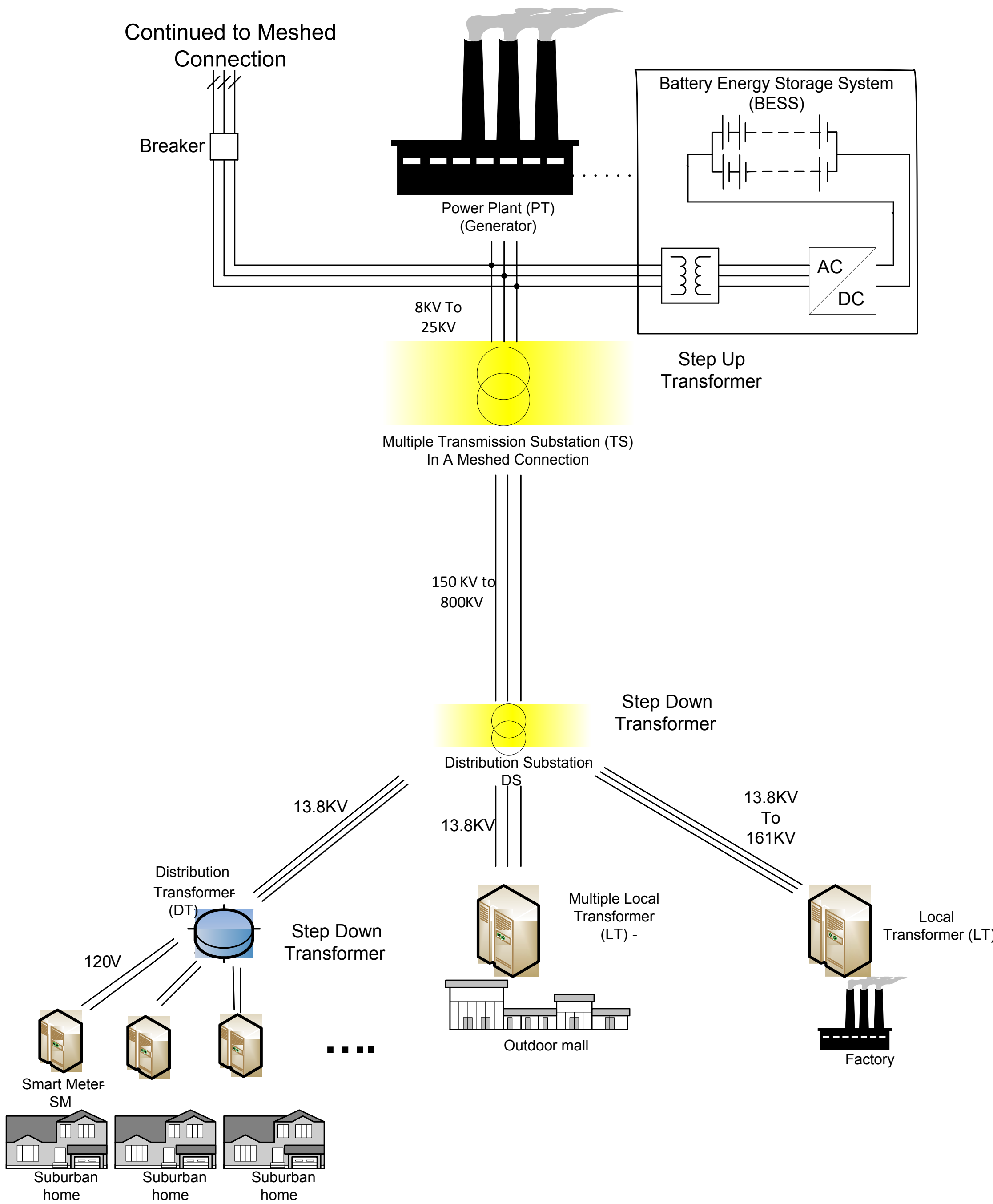

Figure 3 - Micro-Grid

1.3 Overview of the Electrical Grid

To form the basis of the research let's look at the current grid system. The high voltage meshed grid consists of longer connections which have the highest voltage since this is where the power will travel the longest and then feed into smaller radial grids shown in figure 1 as the commercial grid. This in turn feeds into even smaller radial grids labeled as a residential grid. Although the figure 1 is ideal and symmetrical in the real world the actual structure of the grid might be more mixed and unusual while keeping the basic design structure and concepts the same. The transmission components of the grid are responsible for collecting power from the source and distributing this power to the distribution component, which then are charged with distributing it to the different type of consumers. The type of consumer is defined based on the size and the power utilized by the consumers. The type of consumer will play an important role in determining how the proposed algorithm will manage and maintain satisfactory level of power supply to a particular grid based on what type it is.

As evident from the figure 3 in a typical system the flow of power is top to bottom, flowing from the source to the consumer, because so far we have not had the scenario where the consumer generates power by themselves. Ideally the HV meshed Grid is designed so that in the case of power shortage and emergencies essential institutions will retain power for a longer duration as compared to non-essential areas due to its star or meshed configuration. We look at some of the factors that give the grid its signature structure.

1.3.1 Top Down Power Flow

As evident from figure 1 and figure 3 power is delivered is always delivered from top to bottom. Power plants are the sole producers of power and it flows to the consumers commercial/residential for consumption.

1.3.2 Redundancy

Another factor to consider in the figure 1 is redundancy due to the mesh structure of the grid. Any end consumer connected to this mesh grid takes advantage of the built in redundancy in the meshed structure to be able to consume power even if a predesigned number of transmission/distribution lines are out of service. This provides them with the advantage of drawing power from multiple locations and provides a level of redundancy in case of failure. Non critical systems are usually designed to be serviced through a single substation and hence there is limited redundancy.

The description above is of an ideal system, so in reality there could be scenarios where residential part of the grid has extra redundancy built into it because it is connected to the source through multiple substations. All these are exceptions to the rule but in general practice follow the same source to load delivery of power.

1.3.3 Redundancy Based on Critical Function at End Consumer

All commercial institutions such as hospitals, prisons, police stations and fire stations are critical and require power to be functional and might choose to tap (connect) into the HV meshed grid at multiple points to remain functional in the worst of crisis. On the other hand residential locations are non-critical and can afford to function as a primary shelter for its residents for a limited time.

1.4 Changes Needed for Smart Grid

Considering that we have to enhance the present grid system to function as a smart grid we have to make some very fundamental shifts in the way we think about generating and delivering power. There are some aspects of the current Grid Structure that we would want to keep such as redundancies due to meshed structure, and redundancy based on multiple connections to the meshed grid for critical consumers. On the other hand we need to make the Smart Grid be able to handle power flow top to bottom as well as bottom-up. Let's look at some of these upgraded requirements that we will need.

1.4.1 Easily Pluggable Power Source & Top Down and Bottom-Up Power Flow

One of the basic shift in thinking involved in a smart grid from the power generation and distribution perspective are that any node in the grid can have a power generating and consuming aspect to it, contrasting this to the legacy grid system in which, the main node is the only node that generates power, whereas the commercial and the residential nodes consumed power.

Example scenarios of a smart grid where nodes can be producers and consumers are:

- Solar panels on residential locations, qualify them as a producer of electricity, which if not completely consumed by the resident can be fed back into the grid.
- Large commercial farms which have the acreage and environmental circumstances to support wind farms serve a dual purpose as a power producer and a consumer.

Since the nodes can generate power and often times produce excessive power that is beyond the present requirement of that node they are capable of providing the excess power to any of the nodes they are connected to. We look at a couple of examples where a node would generate enough power to have excess capacity which it can then share with adjacent nodes, leading us to make a fundamental change and requiring our grid system to be capable of providing power top down as well as bottom-up.

- Use Case 1: Assuming we have a residential location or residential node where large percentages of residences are solar panel equipped. The hours in a day when a residence consume the least power is also the time they may also generate the most amount of power. This is because in many households residents are either away at work or at school during the day time, which is also the peak production time for solar systems. Now if this is a common trend where the power produced by each house hold is more than the power consumed. We can easily come to the conclusion that summation of all power produced in the residential node subtracted by summation of all power consumed in the residential node will be a positive figure. Hence the residential node in general could have surplus power. Now in case of a residential node this surplus power can either be shared with a neighboring residential node or can be shared with a commercial node. Since we are considering day time it is highly likely that any commercial node will have a higher demand for electricity during this period. This scenario also leads to a high amount of cost savings by utility companies which are responsible for providing electricity to residential and commercial locations. In the above case where the residential nodes are producing excess power the utility company can purchase the power for a lower cost and supply to its commercial customers, hence reducing its overall cost (by avoiding remote power source and saving on transmission) and passing on the savings to its customers.

- Use Case 2: Wind farms located on commercial agricultural land have the ability to produce larger amounts of power while allowing farming activities to continue simultaneously. Power produced in this method can again be used to support equipments at the commercial location during peak hours and can contribute towards surplus power in the commercial node during non peak hours. Surplus power generated at commercial locations will be more than the surplus power generated at residential locations due to size of scale ratio. Logically then this power can be shared with adjacent commercial nodes following which it can then be shared with residential nodes depending on demand for additional power from any neighboring nodes.

So far we have formed a basis that the smart grid is going to be top down and bottom up from a node (commercial node, main node, residential node) perspective, we have also come to the conclusion that since nodes are producers and consumers during different operating hours of the day an algorithm needs to be designed that will decide appropriately how to respond to request for power from adjacent nodes and how to decide redundancy of service based on various criteria. As of right now this structure and hierarchy of nodes that we are trying to identify resembles a network of connected nodes where the connection between different nodes is defined by a base station (BS), this switch will have the capability to analyze utilization information from all the nodes that it manages and respond appropriately to additional power requests from other connected substations or send a request for additional power to other connected substations based on a polling and current surplus supply.

1.4.2 Efficiencies (Local Power First)

The most amount of power is lost once generated is during the transportation phase of the Power Life Cycle (PLC) thus contributing to a portion of the loss of the systems overall efficiencies. Efficiency is the ratio of energy spent to produce power and the energy that actually makes it to the consumer. The difference in these two factors is caused due to the loss of energy during transmission and other wastes that occur during the power generation process. So naturally it makes sense to reduce the need to transport power over longer distances. This will be one of the main driving factors in the communication algorithms that are built this thesis to decide how to distribute power.

1.4.3 Communication Infrastructure (Real-Time Load Balancing)

Since we are giving each base station the authority to decide as a collective how to distribute power it will need the communication infrastructure that links all the BS units together.

CHAPTER 2

RESEARCH PROBLEM

2.1 Problem Description

The aim of this thesis is to provide a solution that will mitigate some of the issues that are inherent in the present electrical grid system. These are as follows:

- The Top down of Power Flow of the present electrical grid system does not have the capability to accept a new source of power without disturbing the balance of power distribution.
- Power grid maintenance and operations are made in a control center that is responsible for a section of the grid. This poses two problems, first of them being a single point of failure and the second is the difficulty that it poses for horizontal expansion. A single control center can only manage a finite section of the grid so if the number of distribution networks increases then either the processing capability of the control center needs to be increased or division of work will need to be shared between multiple control centers, each control center would have responsibility of a section of the meshed grid.
- In today's electrical grid the control centers rely on sensors and meters placed strategically all over the grid to detect power flow and utilization. The data from

these devices are used to make operation decisions at the control center. This kind of model has worked so far since the number of devices from which information is derived is manageable. What happens if the number of devices that are able to provide feedback to the Grid System increases exponentially? Will the singular control system model be able to handle such a load?

2.2 Review of Past Work

Historically any research in this field has been financed and published by private organization like ABB which have big stake in the energy industry or governmental organization that have the responsibility of providing infrastructure to its citizens. Some of the major areas of research in the Smart Grid field have been in

- Load Forecasting, Chao et al. [1]
- Power flow calculations and analysis, Chao et al. [1]
- Distributed systems and Integration technologies, NETL [7], NETL [5], Rahimi et al. [4]
- Self Healing Systems, NETL [5], NETL [8], EPRI [12]
- Energy Storage and Usage, Rahimi et al. [4], Johnson [2], Wolf and Islam [3]
- Non-Renewable resource management, Johnson [2], Lewis [11]
- Alternative source of energies, Rahimi et al. [4]

- Sensors and Measurements, NETL [6]
- Control Systems, EPRI [12]
- Automation, Fribush et al. [9]
- Grid Security, NETL [5], Fribush et al. [9], ABB [10]
- Cost Analysis, EEI [14], ABB [10]

One of the common themes that emerges from the research that has been done in Smart Grid all around the world is that every country chooses to implement its Power infrastructure in slightly different manner with its own set of redundancies requirements, standards, choice of fuel or power plants and power distribution goals. In the United States NIST (National Institutes of Standards and Technology) has been charged with setting standards in this field. This is the reason why NIST produces many guideline papers that outline the communication standards and technology standards. Such standards ensure that the future solution however distributed they might be still function and integrate with each other. Having government recommended standards has not deterred the private energy companies from thinking outside the box and providing cutting edge technologies. Only time will tell which technology or approach to solving these common problems will win out over others and become the standard.

Most of the other researches focus mainly on the last mile problem of power usage analysis and affect of usage pattern as it correlates to external circumstances such as weather and type of power. Not a whole lot of analysis has been done on reducing waste due to the inherent inefficiencies built in to the present electrical grid system. Also most of the solutions don't take into account the future of Power generation which will be more local, renewable and distributed.

2.3 Justification for Research

The objective of this research is to improve the efficiency and utilization of power delivery through integrated communication infrastructure in a Smart Grid system. Smart Grids will be the backbone of tomorrow's power infrastructure. As the demand for power increases due to the growing population of the world and due to the continued modernization of our society the strain on the present power grid would rise. At some point the inefficiencies and waste involved in the present power delivery system has to be managed to meet the growing demand. Congestion which is due to lack of adequate transmission investment and increase bulk power transaction has increased from $750 Million in 2004 to $1.6 Billion in 2006. This is 7% to 10% of annual billing cost. These stats although dated prove that the cost of inefficiencies is expensive and a strain on resources [10, pp. 4]. Some more fact that comes from the US Department of Energy [15, pp. 6] states that the demand for electricity has surpassed transmission growth by 25% each year putting more strain on the transmission equipments leading to occasional blackout due to single points of failure. According to a study done by US Department of Energy

[15, pp. 7] if the grid efficiency was increased by 5% it would be equivalent to removing greenhouse gas emission produced by 53 million cars.

Although smart grid technologies are being researched all over the world the National Institute of Standard and Technology is responsible for publishing new standards in the US for adoption by the companies that will eventually provide components of this smart grid. There have been numerous guidelines that have been published by NIST in various topics relating to the Smart Grid systems.

2.4 Solution Approach

In our approach we identify that the SM detects either a drop in power usage or increases in power usage and then proposes the steps and decision that are required to be made to address change in the Smart Grid all in the context of data and communication algorithms. Our schema executes the following steps.

- SM detects drop/increase in power
    - Construct drop/increase request
    - Define communication protocol that comes into play when SM sends this request to its peers (other SM's) and its parent DT
    - Define drop/increase response (ack)
    - Define reliability protocol that assures the delivery of the request/response

    - Define recovery protocol that assures the system recovers from message delivery failure
- SB receives the drop/increase request
    - In case of multiple DT's receiving the request form this SM define the communication protocol that will be used to decide which one of the DT's will be the coordinator.
        - Construct the coordinator request
        - Define communication protocol that comes into play when the contending DT's send the coordinator request to one another
        - Define the Coordination selection algorithm
    - Queuing process of requests for Fulfillment (Down on power provide power)/Utilization (Excess power take some power)
    - Fulfillment/Utilization process and the communication protocol involved in this process
        - Priority of which request gets Fulfilled/Utilized first
        - Define Pre-Fulfillment/Pre-Utilization request
        - Send Pre-Fulfillment/Pre-Utilization request to ensure that there is still need for service
        - Define Fulfillment/Utilization request

- In case there isn't a Fulfillment request to process a Utilization request then generate a increase in power request to be sent to the peer DT's and the parent DS.
- In case there isn't a Utilization request to process a Fulfillment request then generate a drop in power request to be sent to the peer DT's and the parent DS.

So far we have outlined communication between SM – DT – DS. These steps are recursive and will follow the same outline in DT – DS – PP. Except at the PP if the net of Fulfillment and Utilization is greater than zero then the Power Plant increase output (Peak Load Power Plants) by that much and in case it is less than zero then it will decrease output by that much.

CHAPTER 3

SOLUTION AND SCHEME

3.1 Smart Meter Function

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In this section we describe in detail the working of our schema. The main component in the detection algorithm is the Smart Meter. Smart Meter is a device that interfaces at the consumer's location. It is not only necessary for us to construct a system where it can react to decreasing or increasing power but also to make the system capable or remembering the trends of these increases or decreases so that it can take steps to reduce the number or triggers that require the system to perform power management. To make the process of detecting increase or decrease in power more efficient and predictable the device would need to collect a lot of usage data from its endpoint. Data such as:

- Daily and Hourly watt usage
- Inside temperature, outside temperature and its correlation with the amount of power being used.
- If the consumer also produced power then all the information regarding how much is being produces and at what times of the day as it correlates to the weather outside.

- Other factors such as number of appliances that are in active use, the type of construction, roof type and other build specification that would have an impact on the power consumption of the consumer.

The detection stage needs an indicator that signals either a decrease in power or increase in power. Considering every interface point (smart meter, distribution transformer, distribution substation, and transmission substation) let's give them a general term of node. A node detects the decrease or increase of power and informs its parent and peer nodes about this with a request. If the parent node is requested for more power then it provides it as long as it has access (from the other resources that it monitors, like the other home in this case the parent is a distribution transformer) to excess power. If the node pings about increase in power then the node will push excess power out to the parent. This structure will continue to function in this manner between a node of any type and its parent. Figure 4 below illustrates the node and its parent depending on the context of the node.

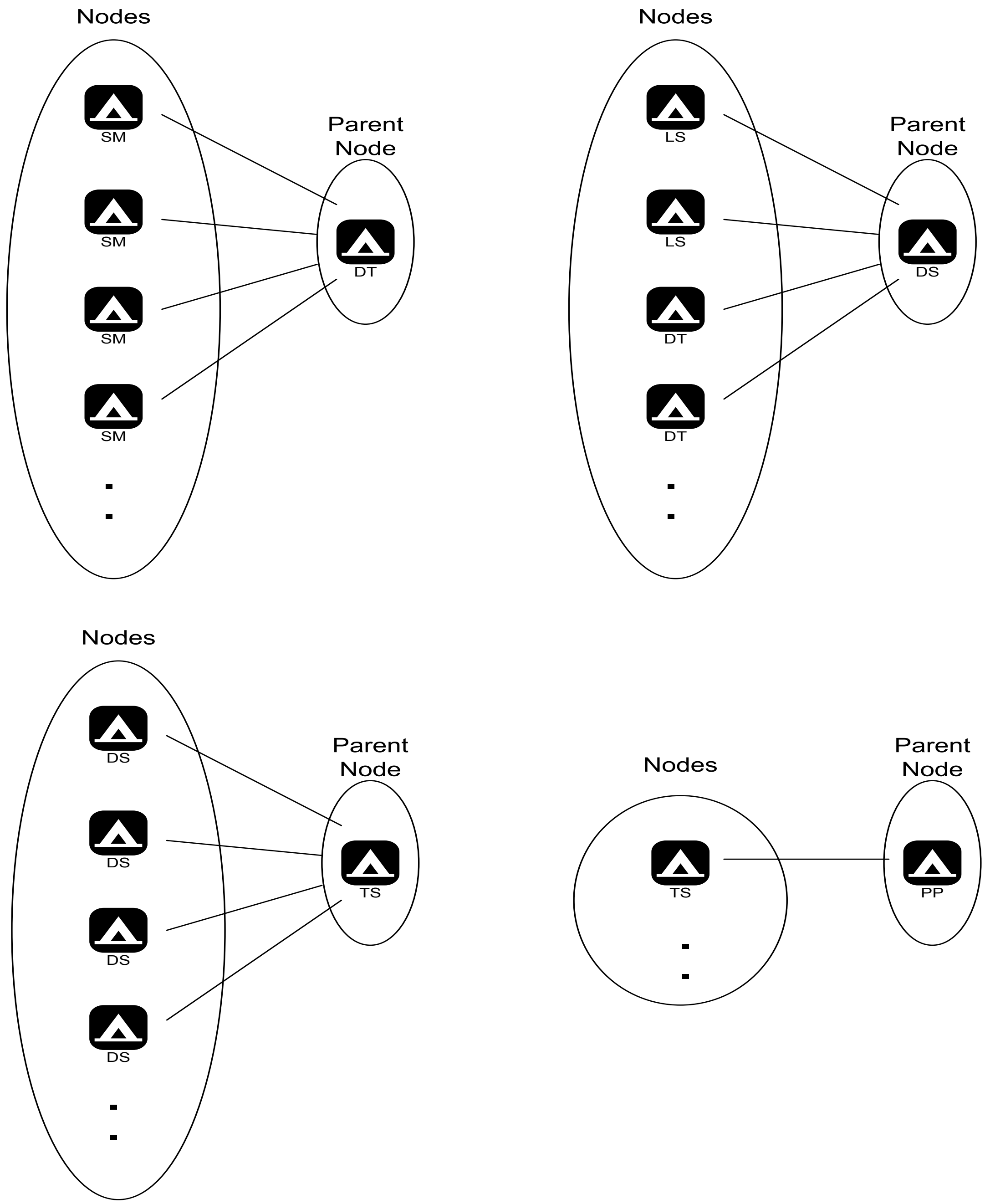


Figure 4 - Communication Hierarchy

3.2 Network Topology

In this section it has been established that a communication network is required so we discuss some of the options available to us and their advantages and disadvantages.

- **Fully Connected Network (Figure 5)** is a fully connected network where in all the substations are connected to all other substations. The drawback to this structure is the excessive amount of traffic that is being generated in the network because every substation is communicating with every other substation. Also the amount of network information being processed by one substation is always n-1 where n is the number of substations in a grid. Fully connected networks are inefficient but they do allow all the substations to be aware of the current status of the complete network since they are receiving all the information.

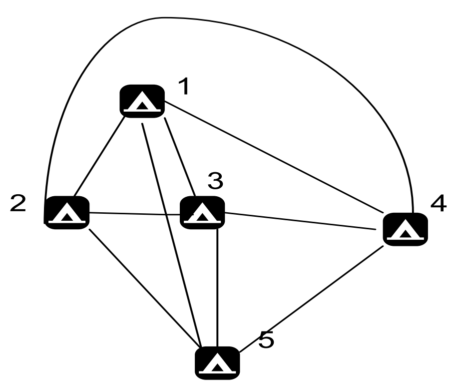


Figure 5 - Fully Connected Network

- **Centrally Connected Network (Figure 6)** is a centralized network where substation 1 works as a controller for all the substations and makes decisions based on data transmitted to it from all the substations. Major disadvantage of this system is the single point of failure which is substation 1; also substation 1 needs to have massive amounts of resources dedicated to it if it is charged with controlling all the other substations singlehandedly. Advantage of this system is the single point of decision making which will have zero collision between request and response since there is only one entity making the decisions.

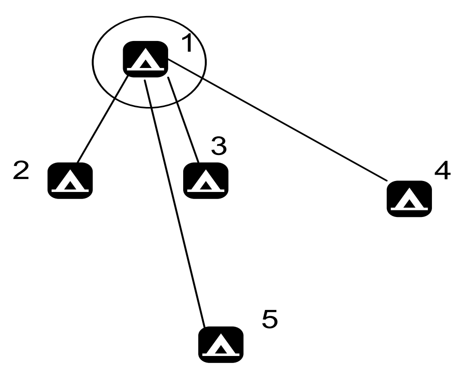


Figure 6 - Centrally Connected Network

- **Clustered Network (Figure 7)** shows cluster networking with a single controller within each group. Substation 1 is the controller for substation 1, 2 and 3. Substation 4 is the controller for substation 4 and 5. In this scenario the controller will try and resolve the power request within the group first if that is not successful then the controllers will communicate among themselves to resolve the power distribution issue.

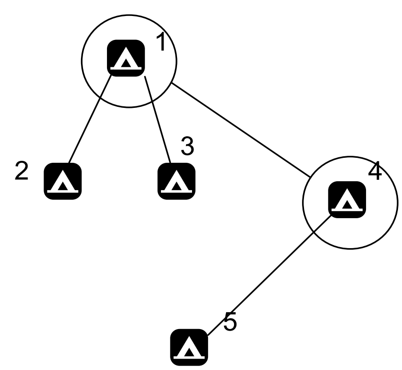


Figure 7 - Clustered Network

- **Geographically Connected (Figure 8)** shows a network that shows one connection between any two substations and this connection is based on closest geographical location. So for example 1 is closer to 3 hence they are connected, 2 is closest to 3 hence they are connected and so on. In this structure 2 send 3 its understanding or table ranking of the system and 3 sends 2 its understanding of the system ranking. Both the ranking table information are merged at each substation and used as reference to find sources of additional power.

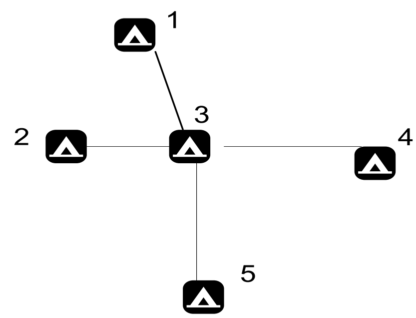


Figure 8 - Geographically Connected Network

Looking at all the options available to us the best solution would be one that would not require a whole new setup of the network infrastructure so then why not just use the circuit model as the network. The Geographically connected network will be the preferred option since it connects closely located nodes via just one connection as show in figure 9 below forming a circuit that closely resembles the grid structure with minimal connection.

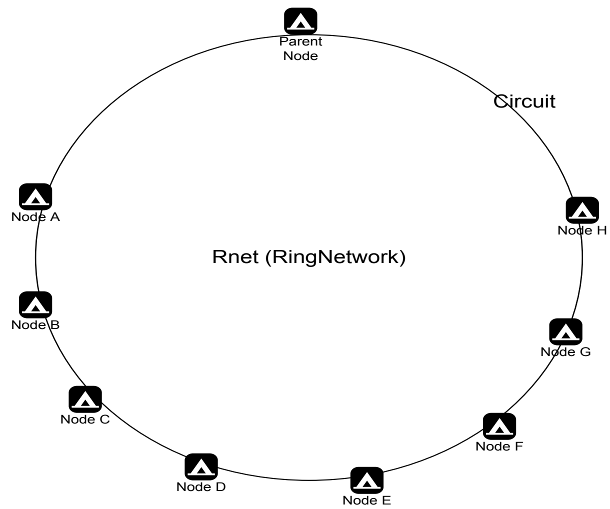


Figure 9 - Ring Network

- **Ring Network (Rnet)** so in Figure 9 if Node F wanted to send a request it would send it in a anti-clock wise direction. In essence informing its peer nodes of the request and one or more parent nodes of the same request. An advantage of this ring network is that if there is a failure or system breakdown the request would not reach back to node f and hence informing it of the breakdown in converse if it gets its own request back then it can be assured that all the nodes received the message.

Figure 10 and figure 11 show the communication circuit infrastructure that will make up the Grid and a complete Grid Communication infrastructure.

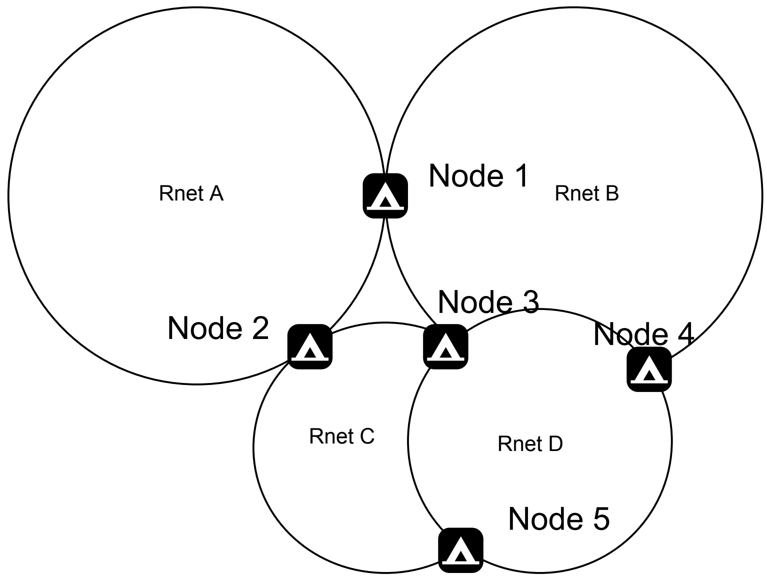


Figure 10 - Multiple Ring Networks

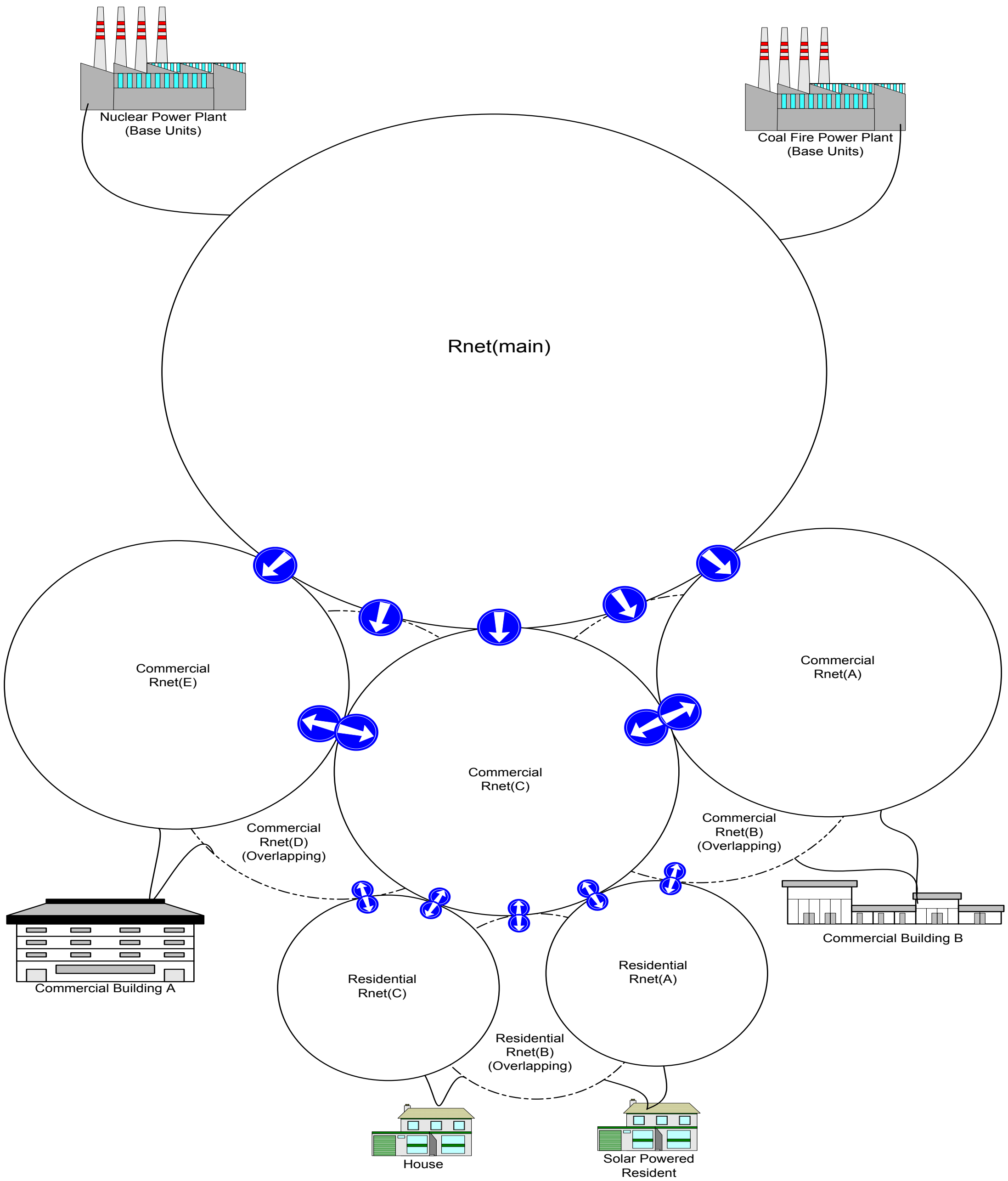


Figure 11 - Micro grid Network and Ring Network Implementation

3.3 Proposed Algorithm and Schema

Let's look at the different component and the messages that they use to communicate with each other. As shown in the network topology in figure 9, 10 and 11 a component (SM, DT, DS, PP) will communicate with its peer (components of the same type) on one ring network and will communicate with its children on another ring network (except SM since they don't have any children). For ease of reference let's refer to Peer Network as Peer-Net and let's refer to the Children network as Child-Net.

3.3.1 Construct Drop/Increase and Ping Request

All three requests we are defining here use the same schema to carry their message on the network.

Message Components

- Version (1 Bytes) [= 1]
- Message Type - MT (1 Bytes) [Drop Request = 1 , Increase Request = 2, Ping = 7]
- Node Type - NT (1 Bytes) [SM = 1, DT= 2, DS = 3, PP = 4]
- Check Sum (2 Bytes)
- Request Identifier GUID (16 Bytes) [Unique ID identifying the original Increase/Drop or Ping request]
- Source ID (4 Bytes) [Unique numeric ID given to a node]

- Ring ID (4 Bytes) [Unique numeric ID given to a ring network. Some nodes can be part of multiple ring network, in these scenarios they have to be aware of where they are sending what message]
- TTL (4 Bytes – Timestamp based) [Time after which message will be discarded from message to act as garbage collection]
- Message (8 Bytes) [Utilization/Fulfillment units]

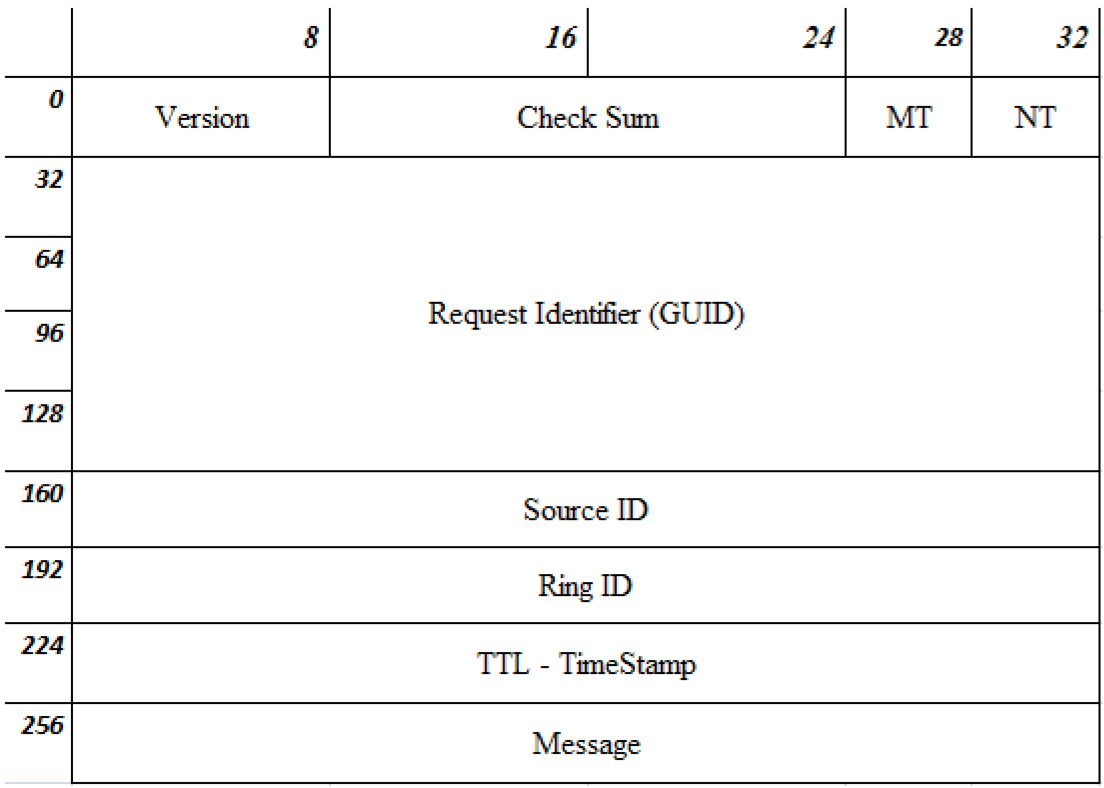


Figure 12 - Drop, Increase, Ping Request Schema

3.3.2 Define Communication Protocol for Ping

Every component that is a parent uses this Ping message to update its self with regards to the power usages at the child components. For example DT is the parent for the SM's under it. DS is the parent for the DT's under it and PP is the parent for the DS's under it.

- The parent node sends the Ping request in the clock wise direction on its Child-Net with appropriate Version #1, RT, NT, New GUID, Source ID, Ring ID, TTL Time Stamp and 0 units (Watts) dropped or increase. If the node is part of multiple Ring Networks then it will send a copy of this message on the other network with the appropriate Ring ID.
- When the children receives this message it will update the Message by summing their current utilization with the existing value in the message
- If a node that receives this message is of the same node type it ignores it and lets it pass as is.
- The message arrives back at the parent which it identifies with the Requester Identifier GUID. This ensures the requester that all its children in the ring network (Child-Net) have received and updated the value of the message. Hence the value that is currently in the message that it received is the current utilization of the network as a whole.

- If the parent node receives the same message from different ring network then it knows that it has to sum this value with the result from the other ring network to give the effective utilization of all the child components under it.

3.3.3 Define Communication Protocol for Drop/Increase Request

- The node sends the Increase request in the clock wise direction with appropriate Version #1, RT, NT, New GUID, Source ID, Ring ID, TTL Time Stamp and the units (Watts) dropped or increase. If the node is part of multiple Ring Networks then it will send a copy of this message on the other network with the appropriate Ring ID. If it is a drop request that the node has to send then instead of sending it on the network it constructs the drop request similarly and keeps it in it fulfillment queue.
- Every node in the ring network will receive the message and take a copy of the message to process in its Utilization queue (since its only going to receive increase requests) while letting the message pass-through to the next node in the ring.
- The message arrives back at the requester which the requester identifies with the Requester Identifier GUID. This ensures the requester that all its peers (other SMs) in the ring network and at least one parent node has received its request.

3.3.4 Define Response & Accept Schema

Message Components

- Version (1 Bytes) [= 1]
- Message Type - MT (1 Bytes) [Response = 3, Accept = 6]
- Node Type - NT (1 Bytes) [SM = 1, GT= 2, DS = 3, PP = 4]
- Check Sum (2 Bytes)
- Request Identifier GUID (16 Bytes) [= GUID of the Request]
- Source ID (4 Bytes) [Unique numeric ID given to a node]
- Ring ID (4 Bytes) [Unique numeric ID given to a ring network. Some nodes can be part of multiple ring network, in these scenarios they have to be aware of where they are sending what message]
- TTL (4 Bytes – Timestamp based) [Time after which message will be discarded from message to act as garbage collection]
- Destination ID (4 Bytes) [Unique numeric ID of the requester node]
- Responder Identifier GUID (16 Bytes) [= GUID of the Fulfillment Request]
- Message (8 Bytes) [Utilization/Fulfillment units]
- Ack Flag [Responder sets it to 0, if the original requester accepts the response then the request set it to 1]

	8	16	24	28	32
0	Version	Check Sum		MT	NT
32	Request Identifier (GUID)				
64					
96					
128					
160	Source ID				
192	Ring ID				
224	TTL				
256	Destination ID				
288	Responder Identifier (GUID)				
320					
352					
384					
416	Message				
448	Ack / UnUsed				

Figure 13 - Response & Accept Request Schema

3.3.5 Define Communication Protocol for Response

- If a peer node can utilize what's in its Utilization Queue to fulfill what's in its fulfillment queue it will respond immediately to the requester node by sending the response in the clock wise direction on its Peer-Net with appropriate Version

#1, RT, NT, Request GUID, Source ID, Destination ID, Ring ID, TTL Time Stamp and the units to be utilized or fulfilled, Ack =0.

- Every node in the ring network will receive the message but only the node that has its name in the destination ID will use the message.
- If the receiving requester is still interested in the response it will set the Ack = 1, it will reserve this unit of utilization to make sure nobody else can claim it and send it in the clockwise direction with the Source ID and Destination ID as is.
- The message arrives back at the responder which the responder identifies with the Source ID which should match its ID. This ensures the requester that the intended recipient (other SMs) received the message. If the Ack flag is set it knows that the increase power requester has accepted its offer and the agreed upon power unit for utilization. If it is not set then it knows this it needs to ask some other node for power and will drop this particular utilization request from its utilization queue.

3.3.6 Define Communication Protocol for Accept at SM

- If the SM node receives a Ack= 1 for the response that it sent then this is an indication that the original requester of the increase in power request is ready to transfer over the power to this node. This is when the node will send a Accept Request in the clock wise direction on its Peer-Net with appropriate Version #1, RT, NT, Request GUID (of the original increase request), Source ID, Destination ID, Ring ID, TTL Time Stamp and the units to be utilized or fulfilled, Ack =0.

- Every node in the ring network will receive the message but only the node that has its name in the destination ID will use the message.
- If the receiving increase in power requester is still interested in the Accept Request it will set the Ack = 1, adds this value to its utilization because it is now providing it for the source node and send it in the clockwise direction with the Source ID and Destination ID as is.
- The message arrives back at the node that send the accept request which the requester identifies with the Source ID which should match its ID. This ensures the requester that the intended recipient (one of its peers) received the message. If the Ack flag is set it knows that the increase power requester has accepted and is being provided. The node subtracts the amount from its utilization since it is now using the excess power that is being provided to it. If it is not set then it knows this it needs to ask some other node for power and will drop this particular utilization request from its utilization queue.

3.3.7 Define Communication Protocol for Accept at DT, DS, PP

- If the node receives a Ack= 1 for the response that it sent then this is an indication that the original requester of the increase in power request is ready to transfer over the power to this node. This is when the node will send a Accept Request in the clock wise direction on its Peer-Net with appropriate Version #1, RT, NT, Request GUID (of the original increase request), Source ID, Destination ID, Ring ID, TTL Time Stamp and the units to be utilized or fulfilled, Ack =0.

- Every node in the ring network will receive the message but only the node that has its name in the destination ID will use the message.
- If the receiving increase in power requester is still interested in the Accept Request it will generate a response for an existing increase in power utilization to be sent on its child-net. The node does so because these nodes don't generate power only SM and PP does. This response is based on the virtual utilization of opposite polarity to the message received from its peer. This node will go through the Response-Accept cycle and if it gets an ack =1 for its accept on the child-net it will send the peer-net accept after setting the Ack = 1, in the clockwise direction with the Source ID and Destination ID as is.
- The message arrives back at the node that send the accept request which the requester identifies with the Source ID which should match its ID. This ensures the requester that the intended recipient (one of its peers) received the message. If the Ack flag is set it knows that the increase power requester has accepted and is being provided. Again since only SM or PP can utilize power this node will create an increase in power request to be sent on its child-net based on the

virtual utilization of opposite polarity to the message received from its peer. It is a given that there will be some child nodes that will respond to this increase request because the whole reason for this node to make the original response on its peer-net was the utilization increasing which in essence reflects the summation of the child nodes utilization that it is responsible for.

3.3.8 Define Reliability Protocol that Assures the Delivery of the Request/Response

- The check sum assures that the message is not lost or distorted during transportation
- Since this is a ring network every message sent by the sender is also received by it and terminates at it.

3.3.9 Define recovery protocol that assures the system recovers from message delivery failure

- The TTL time stamp ensures that if the message is past its TTL then the last node that receives it is responsible for removing it from circulation.
- This TTL also is the timer for the node that sent the message that if it does not received this message back in TTL then it needs to retry the message. After 3 tries with varying interval the requester/responder discards the message completely

3.3.10 Parent Node Responding with a Queued Response

There could be scenario where a node has multiple parents that it reports to via the ping messaging. In this scenario the queued response is used to make sure that only one parent at a time are tracking a child that has multiple parents and the utilization of this common child is not shared multiple times.

Message Components

- Version (1 Bytes) [= 1]
- Message Type - MT (1 Bytes) [Queued = 4]
- Node Type - NT (1 Bytes) [SM = 1, GT= 2, DS = 3, PP = 4]
- Check Sum (2 Bytes)
- Request Identifier GUID (16 Bytes) [= GUID of the Request]
- Source ID (4 Bytes) [Unique numeric ID given to this node]
- Destination ID (4 Bytes) [Unique numeric ID of the requester node]
- Ring ID (4 Bytes) [Unique numeric ID given to a ring network. Some nodes can be part of multiple ring network, in these scenarios they have to be aware of where they are sending what message]
- TTL (4 Bytes – Timestamp based) [Time after which message will be discarded from message to act as garbage collection]
- Message (8 Bytes) [Empty]

- Ack Flag [Responder sets it to 0]
- Sign Flag [Negative = 0, Positive = 1]
- Coordinator selection data [size not defined because for the purpose of this thesis we are going to use Message field and select coordinator based on who has more resources to provide. But in the future this data could be use to make the coordinator selection process more efficient]

	8	16	24	28	32
0	Version	Check Sum		MT	NT
32	Request Identifier (GUID)				
64					
96					
128					
160	Source ID				
192	Destination ID				
224	Ring ID				
256	TTL - TimeStamp				
288	Message				
320	ack | sign | Un-Used				
352	Coordinatior Selection Data (Future Expansion)				

Figure 14 - Queued Request Schema

3.3.11 Define Communication Protocol for Queued

- The parent node sends a response to the requester node by sending the response in the clock wise direction with appropriate Version #1, RT, NT, Request

GUID, Source ID, Destination ID, Ring ID, TTL Time Stamp, Message has the net of Utilization and Fulfillment with the sign flag set appropriately and Ack =0. Every node in the ring network will receive the message but only the node that has its name in the destination ID will use the message apart from other parent node that might be part of the ring network.

- If the requester that receives this message is part of another ring network then it copies this message and circulates it there too.
- This action makes the requester aware that the request is being taken care of and if there are multiple parent nodes that are connected to the requester then they become aware of each other. The requester makes of note of the parent that wins the coordinator selection test and only responds to that parents ping message.
- The parent nodes in the multiple parent node scenarios are now aware of each other and decide who the coordinator is based on the net of Utilization and Fulfillment figures. The parent nodes that fail the test discard the request and the parent node that wins is now responsible for the servicing the requester.

3.3.12 Other Coordinator Selection Criteria's

There are two possible scenarios where multiple parent nodes can receive the request from one child. The first scenario is where the ring network is home to multiple parent nodes. The second case is when a child node is part of two ring networks with its own designated parent node.

Coordinator selection is applicable if a node has multiple parents. Generally a node would have multiple parents for redundancy. Example smart meters would have access to only one distribution transformer, as an improvement to the current system we could cluster a set of geographically adjacent distribution transformers to build some redundancy at this level. In case there are multiple parents for a node there need to be some kind of voting mechanism to decide which parent would be most capable of resolving the request of increasing/decreasing power.

The parent nodes collect aggregated information from its nodes for example distribution transformers would know how many homes under it have power generation capability and their history of requesting increase/decrease in power. So every node that has the perspective of being a parent node and hence a coordinator would track certain set of information that will play a part in determining the coordinator at that level. Some of the matrix that would collect is:

Capability & Priority to service decreasing/increasing power

- Total number of current request for increasing/decreasing power request from its child nodes. The net of fulfillment and utilization request in its queue. This is the technique used in this thesis
- Total number of producer/consumer child nodes and their total production capability and history
- Total number of primary connections at the same node type with Increasing/Decreasing power request (other adjacent nodes of the same type).
- Total number of secondary connection at the same node type with increasing/decreasing power request (nodes adjacent to primary connection
- Total number of N Level connection at the same node type with increasing/decreasing power request (nodes adjacent to N-1 level connection)
- Previous history of being selected as a coordinator and its performance in successfully resolving the decreasing/increasing power request.
- Current list of decreasing/increasing power request that it is being the coordinator for

CHAPTER 4

SIMULATION AND RESULTS

4.1 Description

The simulation program is written using .NET framework libraries. The UI as show in figure 15 is built using the Windows Forms infrastructure in .NET. The program utilized the background tasks available in Windows form to simulate running each of the components in the model on its own thread. SQL server database is used as the common communication infrastructure to send data to and from each of these independent components running on separate threads based on the ring network that was defined.

4.2 Simulation Model

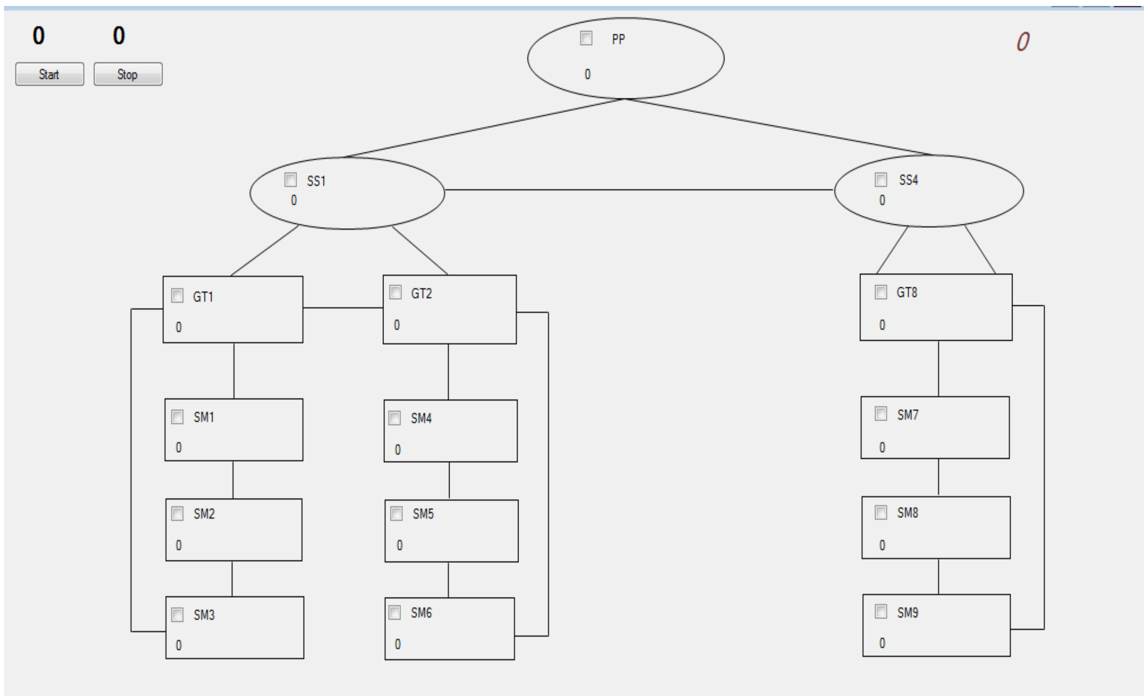
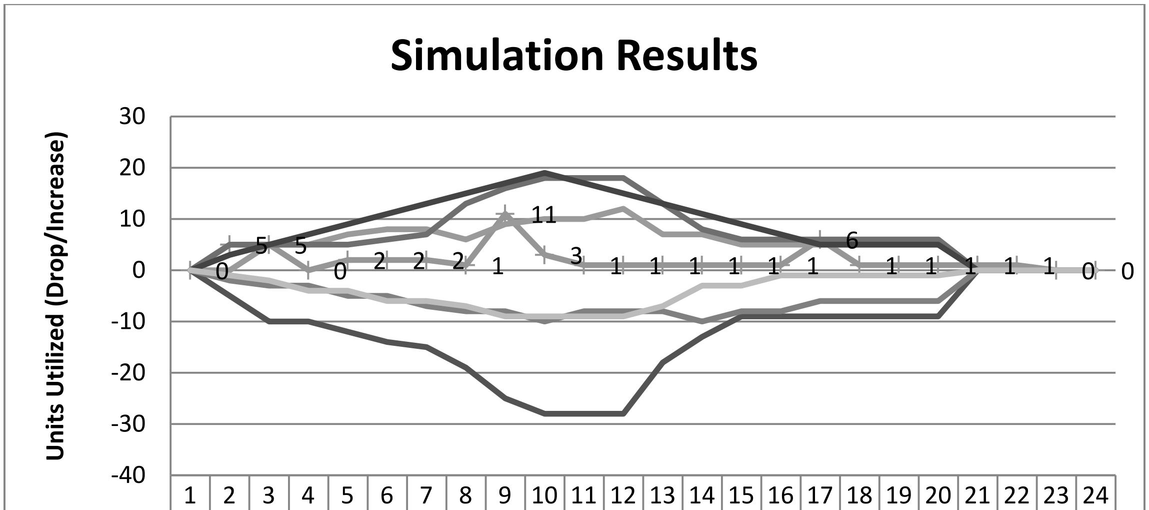


Figure 15 - Simulation Model

The simulation model represents a simple structure showing 9 SM's where SM numbered 1 to 3 are under DT1 (DT aka GT – Green Transformer), 4 to 6 are under DT2 and 7 to 9 are under DT8. DT1 and DT2 are under SS1 and DT8 under SS4. SS1 and SS4 are ultimately under PP. There are a total of 6 ring networks in the above model, RNet6 {DT1, SM3, SM2, SM1}, RNet7 {DT2, SM4, SM5, SM6}, RNet8 {DT8, SM7, SM8, SM9}, RNet2 {SS1, DT1, DT2}, RNet5 {SS4, DT8} and RNet1 {PP, SS1, SS4}. The simulation model is flexible and can accommodate additional component by just adding additional object to the diagram with appropriate component type tag (SM, DT, DS and PP) and ring network connections. At run time the simulation recognizes dynamically the number of components in the model and assigns separate threads to each of the components to run on. The total thread count is indicated by the label above the start button. The start button begins the simulation where as the stop button ends the simulation. The number of threads that are terminated when the simulation is stopped is indicated above the stop button. The label on the top right corner of the screen counts the time elapsed. The integer label seen in each of the component is where the current utilization of the component is shown. At run time the simulation also shows the Utilization Queue count, the Peer Message Sent count and the Child Message Sent count at each of the components.

4.3 Input – Output and Graph



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
PP	0	5	5	0	2	2	2	1	11	3	1	1	1	1	1	1	6	1	1	1	1	1	0	0
SM1	0	-5	-10	-10	-12	-14	-15	-19	-25	-28	-28	-28	-18	-13	-9	-9	-9	-9	-9	-9	0	0	0	0
SM2	0	0	5	5	7	8	8	6	9	10	10	12	7	7	5	5	5	5	5	5	0	0	0	0
SM3	0	5	5	5	5	6	7	13	16	18	18	18	13	8	6	6	6	6	6	6	0	0	0	0
SM4	0	3	5	7	9	11	13	15	17	19	17	15	13	11	9	7	5	5	5	5	0	0	0	0
SM5	0	-2	-3	-3	-5	-5	-7	-8	-8	-10	-8	-8	-8	-10	-8	-8	-6	-6	-6	-6	0	0	0	0
SM6	0	-1	-2	-4	-4	-6	-6	-7	-9	-9	-9	-9	-7	-3	-3	-1	-1	-1	-1	-1	0	0	0	0

Figure 16 - Simulation Results

In the simulation results shown in figure 16 the inputs provided was to the Smart Meters (SM) numbered 1 to 6. This time scale that starts with 1 going up to 24 where each time unit was of 1 minute duration. The input at a particular time on a SM can be seen in the table included in figure 16. The input was selected specifically to represent a model which should result in a balanced state (PP = 0 throughout) as an expected outcome. We can see that the simulation output represented by PP shows the reaction of PP (line graph with data) based on the fluctuation on SM's. If the algorithm worked perfectly it should have been all zeros but we can see from the graph in figure 16 that it is close to zero most of the time indicating some effect of messaging lag that resulted in this non zero values but overall it is a good result that proves that most of the time the SM's were able to resolve the differences locally amongst themselves using the algorithm.

4.4 Verification

We can look at some message exchanges that took place between the components and how they got resolved. Let's pick the message at time interval 2 in ring network id 6. As we can see from the log in figure 17 and figure 18 SM1 generated a increase in power request which was responded to by SM3. SM1 acknowledged (ack = 1) this response from SM3 following which SM3 sent an accept message which SM1 acknowledged (ack =1) too hence resolving the excess power. As discussed earlier the message GUID remains consistent throughout the message lifecycle as seen in the example below allowing tracking of this information.

ID	FromDevice	LinkID	MessageGUID	MessageType
307	SM1	6	D4499771-0E22-49FB-8DC7-FD49BDEDBE9C	2
314	SM3	6	D4499771-0E22-49FB-8DC7-FD49BDEDBE9C	3
323	SM3	6	D4499771-0E22-49FB-8DC7-FD49BDEDBE9C	6

Figure 17 - Message Type Verification (Table)

<table>
<tr><th>ID</th><th>Message</th></tr>
<tr><td>307</td><td>1||2|1|d4499771-0e22-49fb-8dc7-fd49bdedbe9c|11|6|4/27/2014 11:09:48 PM|5</td></tr>
<tr><td>314</td><td>1||3|1|d4499771-0e22-49fb-8dc7-fd49bdedbe9c|13|6|4/27/2014 11:09:49 PM|11|00c50080-52ef-4abe-87fc-92a6bb27a714|5|1</td></tr>
<tr><td>323</td><td>1||6|1|d4499771-0e22-49fb-8dc7-fd49bdedbe9c|13|6|4/27/2014 11:09:50 PM|11|00c50080-52ef-4abe-87fc-92a6bb27a714|5|1</td></tr>
</table>

Figure 18 - Message Verification (Table)

In figure z we can see the communication route taken by each of the messages and these correspond to and match the ring network defined in the simulation model.

ID	MessageID	ForDevice
1006	307	GT1
1028	307	SM3
1030	307	SM2
1032	307	SM1
1031	314	SM2
1034	314	SM1
1035	314	GT1
1064	314	SM3
1068	323	SM2
1069	323	SM1
1071	323	GT1
1090	323	SM3

Figure 19 - Ring Network Verification (Table)

CHAPTER 5

FUTURE ENHANCEMENTS

Historical data of drop/increase request from a particular node can be stored and utilized to make the network prepare for future request and to make the request and response processing efficient. Some of the data could also be used to improve the physical grid structure so that number of adaptive request (request for increase or decrease in power) from a certain location could be reduced. Additional research can be done on the communication protocols to reduce message counts and messaging cost. Incorporation of the queue message algorithm to solve coordinator conflict in simulation can be studied in depth to identify the best way in which parent nodes can manage child nodes.

CHAPTER 6

CONCLUSION

The basis of the research has been built upon the idea that any part of the grid could be power producer or power consumer, also power is consumed locally first before being offered to other distant connections hence saving on transportation cost reducing loss of energy and increasing efficiency of the grid overall. The grid can add as many nodes as desired since the distribution request is handled locally the controls that keep the power balanced is also localized.

BIBLIOGRAPHY

[1] Yen-Ting Chao, Sheng-Ta Lee, Hong-Chan Chang, Tsai-Hsiang Chen, “An improvement project for distribution transformer load management in Taiwan” IEEE Transactions on Power Systems, vol. 18, pp. 875-881, May 2003

[2] Johnson, A.P. “The history of the Smart Grid evolution at Southern California Edison” IEEE Innovative Smart Grid Technologies (ISGT), pp. 1-3, Jan 2010

[3] Wolfs, P. ; Isalm, S. “Potential barriers to smart grid technology in Australia” IEEE Power Engineering Conference, 2009. AUPEC 2009, pp. 1-6, Sept 2009

[4] Rahimi, F. ; Ipakchi, A. “Demand Response as a Market Resource under the Smart Grid Paradigm” IEEE Transactions on Smart Grid, vol. 1, pp. 82-88, June 2010

[5] National Energy Technology Laboratory, Office of Electricity Delivery and Energy Reliability. (2007, Feb). A Systems view of the Modern Grid, [Online]. Available: https://www.smartgrid.gov/sites/default/files/pdfs/a_systems_view_of_the_modern_grid.pdf

[6] National Energy Technology Laboratory, Office of Electricity Delivery and Energy Reliability. (2007, Mar). A Systems view of the Modern Grid: Sensing and Measurement, [Online]. Available: https://smartgrid.gov/sites/default/files/doc/files/Systems_View_Modern_Grid_Appendix_B2_Sensing_Measurement_v_200712.pdf

[7] National Energy Technology Laboratory, Office of Electricity Delivery and Energy Reliability. (2007, Feb). A Systems view of the Modern Grid: Integrated Communication, [Online]. Available: https://smartgrid.gov/sites/default/files/doc/files/Systems_View_Modern_Grid_Appendix_B1_Integrated_Communicat_200707.pdf

[8] National Energy Technology Laboratory, Office of Electricity Delivery and Energy Reliability. (2007, Mar). A Systems view of the Modern Grid: Self-Heals, [Online]. Available: https://smartgrid.gov/sites/default/files/doc/files/Systems_View_Modern_Grid_Appendix_A1_SelfHeals_v20_200704.pdf

[9] Fribush, David; Parker, Scudder; Enterline, Shawn. (2010, Jan). Electric Evolution: Issues Posed and Opportunities Presented by the emergence of the Smart Grid, [Online]. Available: http://www.veic.org/documents/default-source/resources/reports/smart-grid.pdf.

[10] ABB. (2007). Energy Efficiency in the Power Grid - ABB Corporate Communications, [Online]. Available: http://www.nema.org/Products/Documents/TDEnergyEff.pdf

[11] Dr Lewis, Philip "Smart Grid 2013 Global Impact Report," VaasaETT, San Francisco, CA, Impact Report 2013, 2013

[12] Electric Power Research Institute. (2010, Dec). Wide Area Control Systems for the Self-healing Grid, [Online]. Available: https://smartgrid.gov/sites/default/files/doc/files/Wide_Area_Control_System_for_Selfhealing_Grid_SHG.pdf

[13] U.S Energy Information Administration. (2014, Jan). How much electricity does an American home use, [Online]. Available: http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3

[14] Edison Electric Institute. (2006, May). Rising Electricity Cost: A Challenge For Consumers, Regulators and Utilities, [Online]. Available: http://www.eei.org/whatwedo/PublicPolicyAdvocacy/StateRegulation/Documents/rising_electricity_costs.pdf

[15] US Department of Energy. The Smart Grid: An Introduction, [Online]. Available : http://energy.gov/oe/downloads/smart-grid-introduction

VITA

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