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# Smart Grid Demonstration: Distributed Active and Reactive Power Control

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# SMART GRID DEMONSTRATION – DISTRIBUTED ACTIVE & REACTIVE POWER CONTROL

by

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# ABSTRACT

The present infrastructure of energy delivery was designed over 60 years ago with the goal to be centralized. However, it is aging and is under-utilized, which will potentially limit the world's ability to achieve its energy objective.  The lack of vibrant control on the grid makes it difficult to stop cascading power failure, and to achieve high penetration of renewable energy resources, such as wind and solar thus resulting in grid instability. A decentralized and distributed control mechanism implemented with a definite communication protocol solves the issues mentioned above. The electric power grid going into the future is expected to consists of distributed generators and loads. The implementation of a distributed control will benefit utility services and will create financial advantages.

One of the best solutions is to organize these distributed generators (DG) in a micro-grid structure which will then connect to the main grid through the point of common coupling (PCC). A proper organization and control of the Microgrid is always a big challenge. To overcome this, using cooperative control makes it possible to bring together different agents in the networked systems as a group and realize the desired objective. The micro grid power objective is set by a virtual leader and is transferred to the other agents in the system through a local communication channel.

A distributed cooperative control is formulated to effectively organize all the DGs in the Microgrid to produce the necessary active and reactive power to satisfy multiple objectives. It not only satisfies the active power flow from the main grid to a constant but also reduces the reactive power flow to the main grid. Moreover, the algorithm can be used to implement the demand response continuously using a combination of DGs and their local controllable loads. The approach

is to use distributed inverters with the aid of multiple local communication channels for active power compensation of the micro-grid in real-time in a distributed and cooperative manner.

*This thesis work is dedicated to my parents Rajamani Karupana Gounder and Sumathi Rajamani who constantly encouraged and believed in me throughout my life. I also dedicate this thesis to my sister Dr. Priyanka Rajamani for her continued support and motivation.*

*I cannot find words to express my gratitude to my best friends, Manoj Reddy Gopu and Manasa Kashyap Harinath without their support this thesis work would not have been possible.*

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I also take this opportunity to thank Dr. Marwan Simaan and Dr. Wei Sun for their valuable time and advice.

I would like to thank Ms. Ayesha Mayhugh, Mr. Kripa Venkat, Mr. Bart Basile, and Mr. Mekre Mesganaw for contributing their time, skills, and effort to make this work a reality. Without their support this work has not been possible.

Special thanks to Texas Instruments for funding and supplying the following items for my use:

- Hardware (4 EVM Smart Meters, 2 Grid Tie Micro Inverter, 2-SG Infrastructure EVM, 2-Data Concentrator EVM, 4-ZigBee card, 2-NFC card, 4-BeagleBK, 2- PLC Kit).
- Software (Code Composer Studio, controlSuite3.3, GUI Composer 5.5, smart meter software).

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# LIST OF ACRONYMS

| | |
|---|---|
| AC | Alternating Current |
| AMI | Advance Metering Infrastructure |
| CSI | Current Source Inverter |
| DC | Direct Current |
| DER | Distributed Energy Resources |
| DG | Distributed Generator |
| DLC | Direct Load Control |
| DOE | Department of Energy |
| DR | Demand Response |
| GUI | Graphical User Interface |
| GTI | Grid Tie Inverter |
| HAN | Home Area Network |
| MG | Microgrid |
| NEMA | National Electrical Manufactures Association |
| PLC | Power Line Communication |
| RF | Radio Frequency |
| SG | Smart Grid |
| TL | Tie Line |
| ULTC | Under Load Tap Change Transformer |

| | |
|---|---|
| UPS | Uninterruptible Power Supplies |
| VL | Virtual Leader |
| WAN | Wide Area Network |

# CHAPTER ONE: INTRODUCTION

Energy is one of the leading contributors to the economic development of any country. Energy plays a vital role for developing countries like India because it has to serve its large population [1]. Establishing a large power grid serving billions of people requires a significant investment.

The world's growing population has created a lot of problems that exist today. The most important issue of all is global warming caused by the abundance of greenhouse gases present in the atmosphere. Many of these greenhouse gases such as $CO_2$ are produced from power plants all over the world burning fossil fuel.

To reduce these emissions out into the atmosphere alternative sources of energy must be used. In the last two decades, both solar and wind energy have become an alternative to conventional energy resources [2]. These alternative energy resources are non-polluting, abundant, and renewable. In recent years, thanks to the advance in technology, better manufacturing processes have decreased their capital costs thus making them more attractive. This has led to the outburst of the distributed generators (DGs) and Smart Grid concepts [3].

The United States of America is among one of the leading countries in the world and as such, they invest lots of money and resources in the renewable energy sources [4]. Figure 1 shows US maps of the solar and wind energy; (this illustration is provided by the National Renewable Energy Laboratory (NREL)).

The other factors that motivate concepts such as Microgrid and Smart Grid are improving the reliability of the power system. With the conventional centralized power system, any disturbance can cause the complete failure of the grid (not all disturbances cause complete grid

failure but there is a possibility)[5]. For instance, the blackouts that occurred happened in the USA in 2003 [6] and in India in 2012 [7] caused billions of homes to loose electricity for several days. The world's power delivery system consists of a large number of substations, transmission lines, and distributions lines, which are not designed to withstand or quickly recover from outages. The number and duration of power outages in the U.S. continue to rise, driven primarily by weather-related incidents such as Hurricane Irene and Superstorm Sandy. The average outage duration in the U.S. is 120 minutes and is rising annually [8].

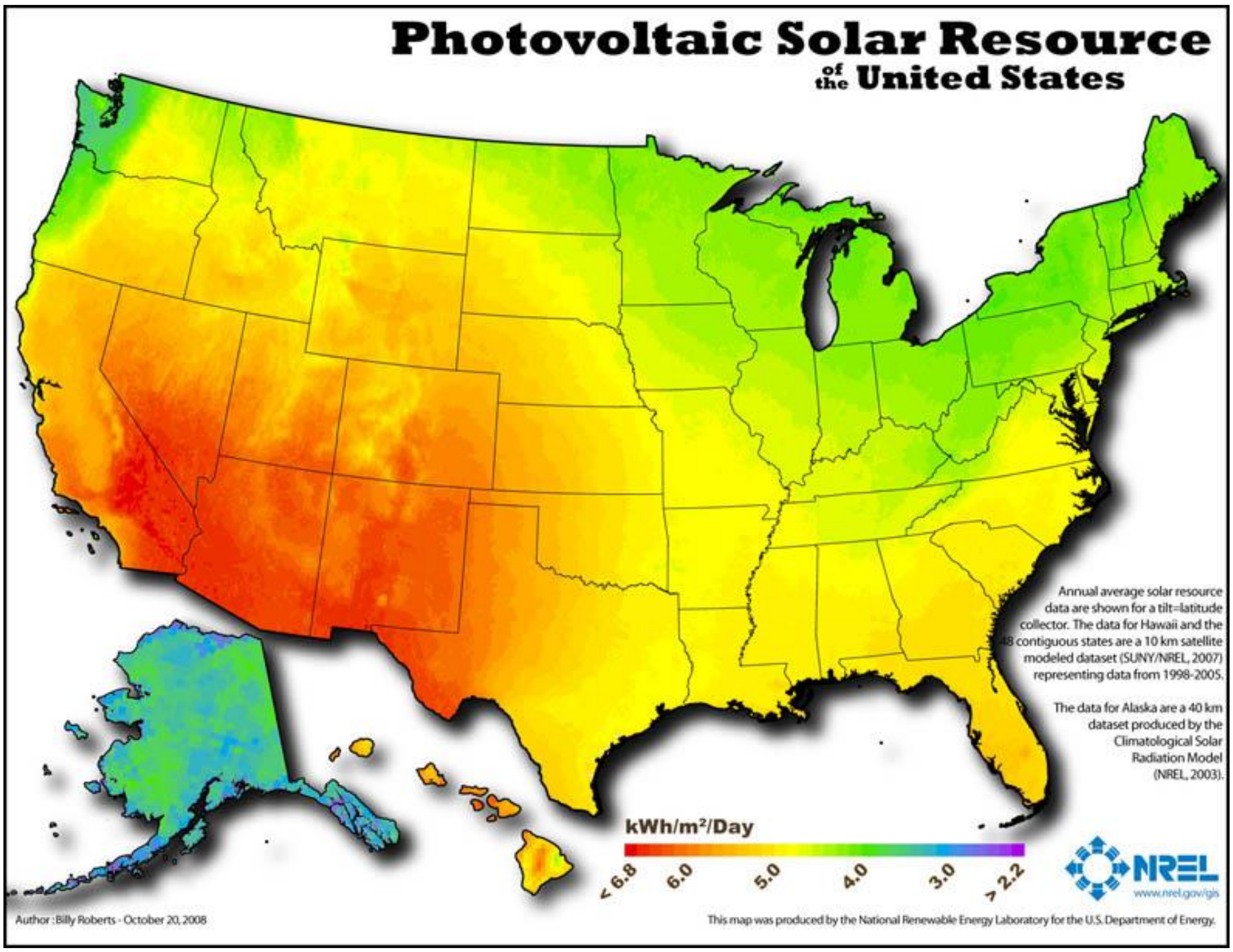


Figure 1 Photovoltaic Solar Resources of the United States, Courtesy of NREL

## The Goal of My Thesis

The goal of my thesis is to develop a hardware experimental setup on Smart Grid and communication in collaboration with Texas Instruments. The experimental setup is a Microgrid testbed setup comprised of multiple load locations. The various algorithms such as distributed cooperative control and distributive cooperative optimization have been developed and implemented in the test bed. The algorithms have been simulated using the MATLAB SimPower System toolbox and results have been obtained. The test bed gives an opportunity for various people such as industrial experts, students, and researchers to work hands on with it and practice their own algorithm. The main goal of developing this demo setup is to check how various evaluation modules can be interconnected in the system and how various algorithms gets reacted to it in real time hardware setup. The evaluation modules in the Microgrid test bed comprises of smart meter, grid tie inverters, computer controllable loads and data concentrators.

## Organization of My Thesis

The introductive chapter of my thesis defines the goal of my thesis, as well as the background information of my thesis topics which include Microgrid, Smart Grid, Advanced Metering Infrastructure, Demand Response and Distributed Energy Resources.

Chapter 2 gives an overview of the Microgrid testbed that's been built, review of the various equipment that has been used to build the experimental setup such as smart meters, grid tie inverters, and computer controllable loads, and finally a general idea about how the different equipments can communicate within themselves and with other equipments. It also covers the Graphical User Interface that has been developed as a part of the experimental setup.

Chapter 3 provides a detailed explanation of the Cooperative Distributive Algorithm that has been implemented to achieve the Demand Response (DR) in the Microgrid, and how the DR can be implemented, and an overview of the simulation and its results which is discussed in this chapter.

Chapter 4 provides a detailed explanation of the cooperative distributed optimization that has been implemented to achieve the unified voltage profile across the Microgrid and how the algorithm has been implemented using the MATLAB SimScape Power Systems and the simulation results have been shown and discussed.

Appendix A gives a detailed information about the code for communication between the smart meters and steps involved in it, and Appendix B offers programs that're being used to develop the graphical user interface.

## Microgrid

The concept of a Microgrid can be considered to be a collection of various loads and distributed generation on the distribution segment of the grid. Microgrid [9] offers a viable solution during a sudden power outage. During power outages or emergencies, the part of the grid which is unaffected can detach itself from the utilities and coordinate the generator in the area and power the grid. Rather than having backup generators turned on throughout the restoration period. The illustrative construction and operation of the Microgrid [10] is shown in Figure 2. According to National Electrical Manufactures Association (NEMA) [11], there are numerous advantages of Microgrid beyond the backup generators,

- It encourages the installation of non-conventional energy resources such as the wind, solar

and biogas.

- Electrical energy stored in the battery and the Hybrid Electric Vehicles.

The Microgrid can sense critical loads in case of power outage, it reroutes power to critical areas as possible given any situation. When there is a power outage occurs in the Microgrid and it self-heals at any given situation. Microgrid comprises four key properties [12] as follows:

- The Electricity Generation is local and distributed through the installation of rooftop solar panels at home, windmills and solar farms.
- The loads are distributed and local.
- During power outage or system failure the Microgrid has the ability to self-heal and automatically detach itself from the main grid until the system is brought back to the normal stage.
- Utilities in the Microgrid can work together for the better performance.

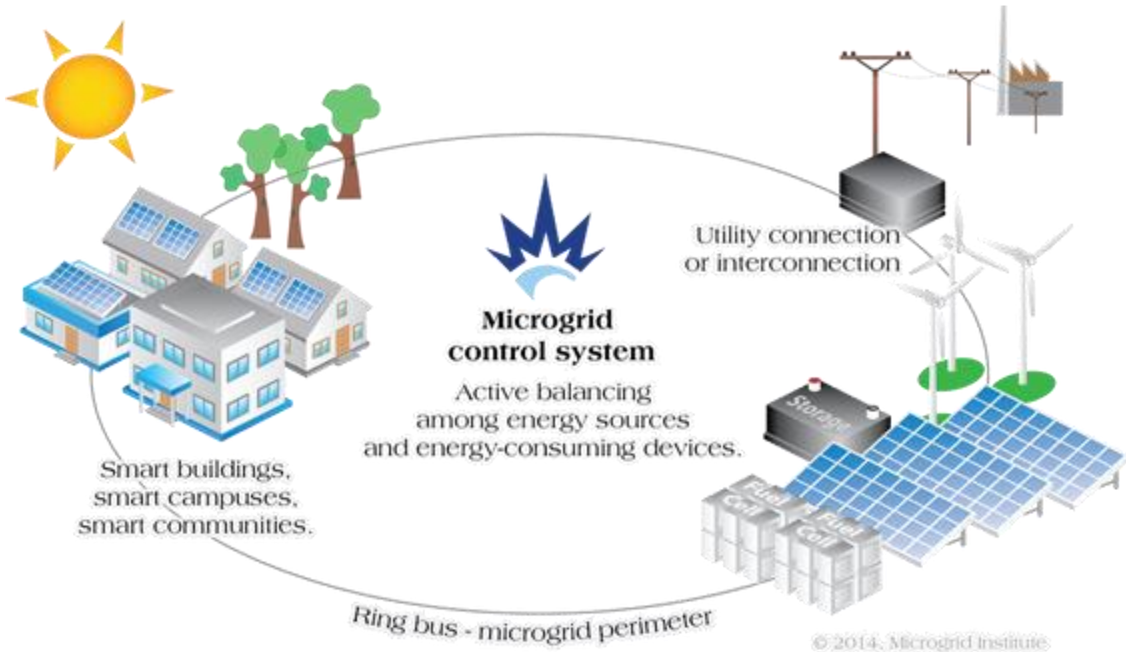


Figure 2 Microgrid, Courtesy Microgrid Institute

Smart Grid

The modern power system made up of a network of very long transmission lines, substation, transformers and more that deliver power from the power plants to the home. The DOE definition of the Smart Grid [13] is defined as a "A smarter grid applies technologies, tools, and techniques available now to bring knowledge to power–knowledge capable of making the grid work far more efficiently."

The Green American Design Group [14] notes that the main advantages of the smarter electric grid are as follows:

- Smart grid updates existing power infrastructure which increases the reliability and safety of the existing grid.
- Easy to maintain, service and decreases power outage.

- Encourage more renewable energy generation across the system.
- Reduces the pollution by promoting renewable energy.
- Introducing advancements and efficiencies yet to be envisioned. (GADG).

The electric power industry is set to bring out a revolution from a more decentralized, producer controlled network to the one that is less centralized and more consumer-interactive. The move to completely change the grid is going to create a revolution in the history of the power sector. With minimal human interaction, the amount of energy is going to be saved is tremendous.

## Advanced Metering Infrastructure

According to the Department of Energy, Advanced Metering Infrastructure [15] allows utilities to collect, measure and analyze energy consumption data for grid management, outage notification and billing purposes via two-way communication [16]. This utility network would have four tiers in the Smart Grid architecture [17]:

1. The core backbone – the primary path to the utility data center;
2. backhaul distribution – the aggregation point for neighborhood data;
3. the access point – typically the smart meter;
4. And the HAN – the home network.

### Technologies that are required for on-premises networking

Home Area Network (HANs), the bandwidth needs to accomplish this will likely fall between 10 and 100 kbps per node/device; the required level of reliability may fall into the 99 percent to 99.99 percent range; the ideal latency for in-home applications should be between 2 and 15 seconds. ZigBee[18] offers the convenience of being wireless while requiring little power, and

both technologies, notwithstanding being relatively low-bandwidth, are cost-effective and flexible. Home Plug[19], a form of powerline networking that carries data over the existing electrical wiring in the home.

**Technologies that are required to transmit the information collected from the premises**

The availability of emergency power backup at the meter will not be critical because in-home metering services are not needed during outages. Power line carrier (PLC) technology is the most common in rural and low-density areas where wireless coverage is less available due to their low bandwidth (often below 20 kbps) and requires bypasses this grid element that would normally scramble the PLC signal (like transformers).

The backhaul of information from aggregation points to the utility typically function over private networks [20].

- Backhaul can be accomplished using a variety of technologies, such as fiber, T1, or microwave networks. Star networks may also be used for backhaul of data from the hub to the utility, often utilizing commercial wireless connectivity.
- Many AMI networks only have intermittent connectivity to the utility as data concentrators are used to collect the data of various smart meters at real-time and send it to the utility companies both periodically and in real time.
- Backhauling real-time or near-real-time data from the billions of devices require not only tremendous bandwidth but also data storage capacities well beyond the current installed base.

## Demand Response

According to the Department of Energy (DOE), demand response can be defined as the "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [21].

Demand Response is implemented to reduce the electrical usage of the customers in response to increasing energy price or during the peak loads times. The communication requirement [22]  for the demand response is very similar to the Advanced Metering Infrastructure.

The DR is not implemented throughout all day of the year, it is implemented during special days when the present demand is more than the forecasted demand. During DR event utilities senses the increase in demand, instead of turning on the expensive generators, DR tries to cut down the demand by decreasing/ increasing the temperature of your air conditioning or reducing the rate of charging your hybrid electric vehicle or communicating with your inverter to supply the excessive power from the stored units. The DR can be implemented by the utilities, upon getting necessary approval from the customers and the utilities pay the customer in debates.

## Distributed Energy Resources and Storage

According to the Electric Power Research Institute (EPRI) the Distributed Energy Resources (DER) [16] can be defined as follows, "DER are smaller power sources that can be aggregated to provide power necessary to meet regular demand. As the electricity grid continues to modernize, DER such as storage and advanced renewable technologies can help facilitate the

transition to a smarter grid." In present power grid, the DER is widespread, it requires a very complex control mechanism to interface with the existing utility grid. The communication requirement for the DER is same as that of the Advanced Metering Infrastructure. During peak load times, DER can be used to supply the excessive loads. During bright sunny days and heavy windy days, DER can be used to store the excessive energy it produces and can be utilized during the peak demand time. The complex part is effectively integrating the multiple DER in the grid and controlling them. The communication network requirement for the various technologies has been tabulated in table 1, courtesy of Department of Energy.

Table 1 Wireless Capability for Different Purpose

| Application | Network Requirement | | | | |
|---|---|---|---|---|---|
| | Bandwidth | Latency | Reliability | Security | Backup Power |
| AMI | 10-100 Kbps | 2-15sec | 99-99.99% | High | Not Necessary |
| Demand Response | 14Kbps – 100 Kbps | 500ms-several min. | 99-99.99% | High | Not Necessary |
| Wide Area Situational Awareness | 600-1500 Kbps | 20ms – 200ms | 99.99 – 99.9999% | High | 24-hour supply |
| Distribution Energy Resources and Storage | 9.6 – 56Kbps | 20ms – 15sec | 99-99.99% | High | 1 hour |
| Electric Transportation | 9.6 – 100 Kbps | 2 secs – 5 min | 99-99.9999% | Relative High | Not necessary |
| Distribution Grid Management | 9.6 – 100 Kbps | 100ms – 2 secs | 99-99.9999% | High | 24 – 72 hours |

# CHAPTER TWO: MICROGRID TEST-BED SETUP

## Introduction

Reactive power is present everywhere in the modern electrical system that demands careful compensation. One of the modern approaches to the reactive power compensation is to use locally advanced inverters coupled to the grid/battery for the local reactive power compensation. A Microgrid setup with distributed energy resources is built in collaboration with Texas Instruments. This chapter deals with the Hardware section, consists of various evaluation modules used in building the test Microgrid setup and how the communication between the evaluation modules has been established. The evaluation modules discussed later in the chapter are smart meter, grid tie inverter and computer controllable loads. The other topics discussed in the chapters are communication between the smart meter and the communication between the grid tie inverter and the smart meter.

## Microgrid Description

The system shown in Figure 2 comprises of three load location i.e. load location 1, load location 2 and load location 3. The loads in the Microgrid consists of both the constant impedance loads and variable impedance loads. In the current setup, load 2 is an adjustable AC load bank, either inductive or capacitive. The loads in the Microgrid vary arbitrarily, the requirement for the active and reactive power also varies. The main objective is to minimize the amount of reactive power supplied from the main grid. The main approach is to use distributed inverters, with aid of multiple local communication channels, for reactive power compensation of the Microgrid in a

real-time, distributed, and cooperative manner. The schematic diagram of the Microgrid setup is shown in Figure 3.

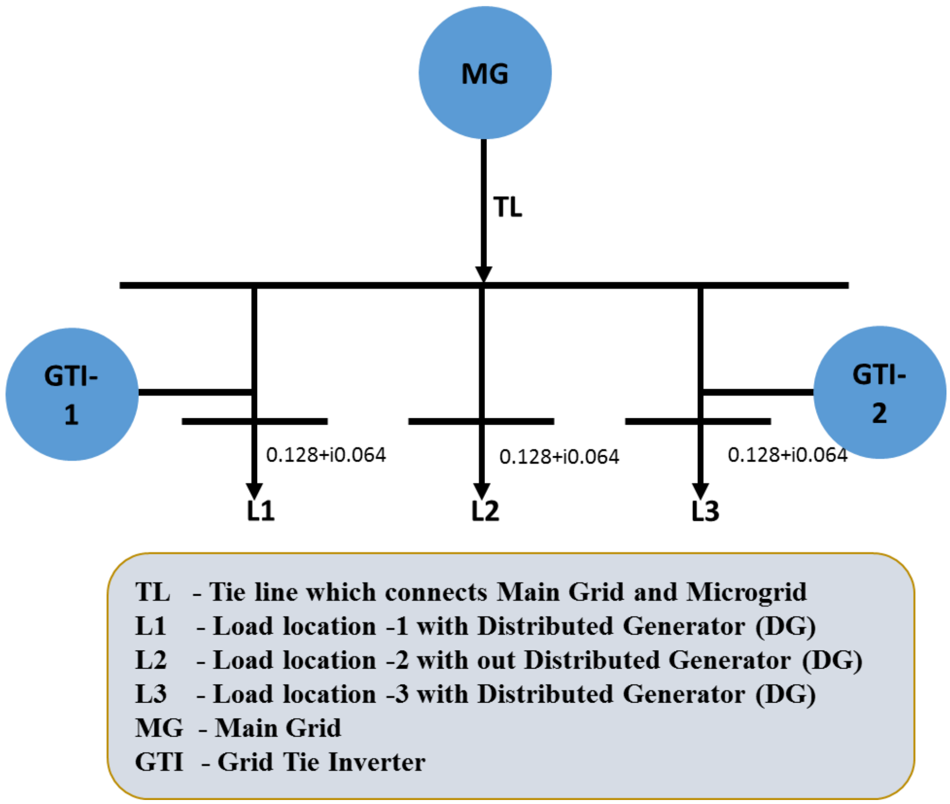


Figure 3 Schematic Diagram of the Microgrid Setup

<u>Smart Meter</u>

Energy meter is a type of equipment used to measure amount of electrical energy consumed by the device or the unit. Power is defined as the product of voltage and current[23]. Energy is the power integrated over time and is measured in kilowatt-hours (kWh). There are two types of energy meters: electromechanical meters and electronic meters. The electromechanical meter [24] operates on the principle that disc rotates at a rate directly proportional to the power consumption and by counting the number of rotations the disc made the power consumed is calculated [25]. The reading of the electromechanical meter is done manually. The electronic meter makes use of the

digital signal processors (DSP) and microcontrollers for the metering purpose and is extremely accurate for the measurement reading and display it on the LCD screen. The smart meter shown in Figure 3 has special features such as NILM (Non-Intrusive Load Monitoring)[26]. Each and every device has its own voltage and current signature [27]. NILM is a process by examining the changes in the voltage and current signature of the power system and what type of device or units is turned on. The main objective of using the smart meter in this system is to measure the real time AC power values. The smart meter is used to calculate the following parameters and it can be calculated in real time such as real power, reactive power, apparent power, RMS voltage, RMS current, frequency and power factor. These smart meters can be easily interfaced with the PCs [28]. The smart meter used to build this test bed is Texas Instrument's EVM430F6736 and the smart meter is shown in Figure 4.

Figure 4 Smart Meter

## Communication between the Smart Meters

An interesting feature about the smart meter is that they can talk to each other, with other entities in the system and to customers through the interactive Graphical User Interface (GUI). The

smart meter can communicate with other smart devices and technologies through wired or wireless communication. The wireless communication can be done in two ways [29] HAN (home area network) and WAN (wide area network).

The HAN is a secure network similar to the wireless systems in your home internet connection. It allows the smart meter to communicate with the other meters in your home such as gas meter, water meter, personal computer, and in-home displays.

The WAN is a type of mobile network that is used to send and receive data. It allows the smart meter to send and receive data [30] and also to communicate securely outside the home using the mobile network. Once the data is collected in the smart meter, it transfers the data back to the energy supplier for billing and other purposes.

The wired communication can be done through Ethernet cables or USB cables connected to the computer. In a larger system the communication between the smart meters are achieved through the data concentrators. Data concentrators are the combination of the hardware and the software module that connects a large number of the smart meters to one destination and then the data values are transferred to the utilities for various functions such as billing, real-time pricing, etc.

Both the wired and wireless communication has been implemented in the Microgrid test bed. The wired communication for the Microgrid testbed has been implemented using the RS232-USB cable, the RS232 pin is attached to the smart meter and the USB part of the pin is attached to the computer. In the computer each USB pin act as a serial COM port, and each smart meter is assigned to a particular COM port such as COM9. The smart meter sends in the data pack to the COM port and a program is written in order to fetch data pack from the COM port and convert it

to the real time values. The data pack consists of lot of information such as size of data pack, voltage, current, active, reactive, apparent power values and identification number for each smart meters. The big disadvantage of this method is the assigning of the COM port to the smart meters and its overcome by the wireless communication.

The wireless communication of the smart meter is implemented using the RF wire cars from the Anaren RF. Each smart meter is attached to the RF card which act as a transceiver, transmit the data packet from the smart meter. They have a common receiver, which receives the signal and transmits to the utilities for other functions. The receiver is a USB device with the RF receiver in it. The USB is attached to the computer which act as an USB serial COM port, then the program can be used to read the incoming data packs and then the smart meter identification number in the data pack is used to identify which particular smart meter these data corresponds to. Irrespective of the large number of the smart meter, there will be only one receiver attached to the computer which receives all the data packs.

## Grid-tie Inverter

The grid tie inverter [31] shown in Figure 5 is a power inverter that converts direct current (DC) electricity into an alternating current (AC). This allows synchronizing to interface with a utility line. The main application of the grid tie inverter is converting the power produced by the solar and windmill into an alternating power for tying it in with the grid. Today's grid tie inverter is more advanced, as they can monitor the solar output, track the maximum power and operate at that point, compensates reactive power, monitor the grid and islanding operation. These inverters are active as long as sun/wind is available, if the sun is out or the wind is not blowing the inverters

becomes idle[32]. The best way to increase the effective use of grid tie inverters is to operate them as VAR compensators to generate reactive power whenever possible [31]. The GTI inverter used in the Microgrid setup build-up is donated by the Texas Instruments and the grid tie inverter is shown in Figure 5 and the graphical user interface of the grid tie inverter is shown in Figure 6.

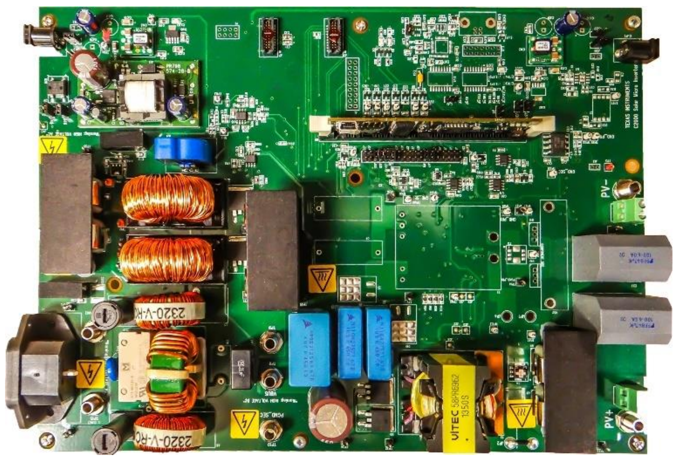

Figure 5 Grid Tie Inverter

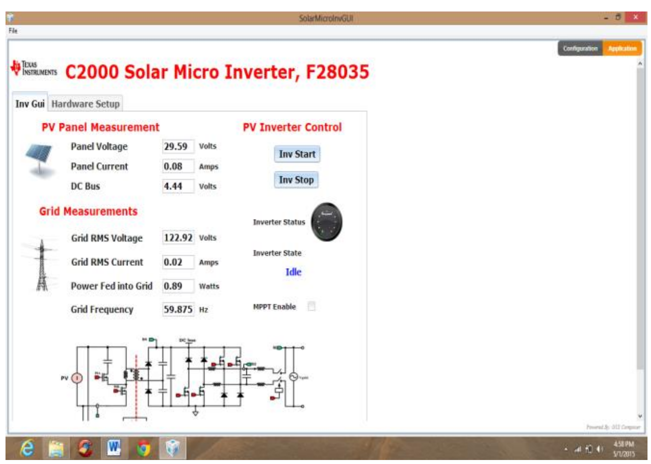


Figure 6 GTI- Graphical User Interface

**Communication between the Smart Meter and the Grid Tie Inverter**

The smart meter can communicate with the other devices, can share data, and send signals to control. In the Microgrid test bed, there is a multimode communication between the smart meters and the grid tie inverters. The smart meters send in control signals to the inverters how much of the active and reactive power must be produced out of their actual capacity.

Computer Controllable Loads

The three load locations i.e. load location 1, load location 2 and load location 3 consists of loads that can be varied from a computer. The load location-1 and load location 2 consists of constant impedance loads0. In the current setup, the load location 2 is an adjustable AC load bank both with an inductive load bank as shown in Figure 7 and capacitive load back as shown in Figure 8. The loads in the Microgrid test bed are computer controllable. The loads can be turned on and off also can be controlled from the graphical user interface using the buttons on the screens. The computer sends a signal to the microcontroller unit that controls the relay which is used to turn on and off the load loads.


Figure 7 Inductive Load


Figure 8 Capacitive Load

Development of Graphical User Interface

The screen-shot of the graphical user interface (GUI) that has been developed using the processing software has shown in Figure 8 for your reference. In Figure 8, the "SMART METERS -I, II, and III" display the voltage, current, active, reactive and apparent power values of the smart meters in real time. The "Conventional grid" picture in the middle of Figure 8 picturizes the controls implemented in the Microgrid test bed. The buttons "INVERTER ON" and "INVERTER OFF" will send command signals to turn on and off signals to the respective inverter. The buttons below the control algorithms are used to write the algorithms in the pictures.

The power produced by the respective grid tie inverters are also shown in the GUI. The buttons in the bottom of the GUI is used to control the inductive and capacitive loads from the GUI by sending signals to the GUI. The objective of the GUI is to give an easy interface for the people to work on the test bed and virtually see the results in the computer.

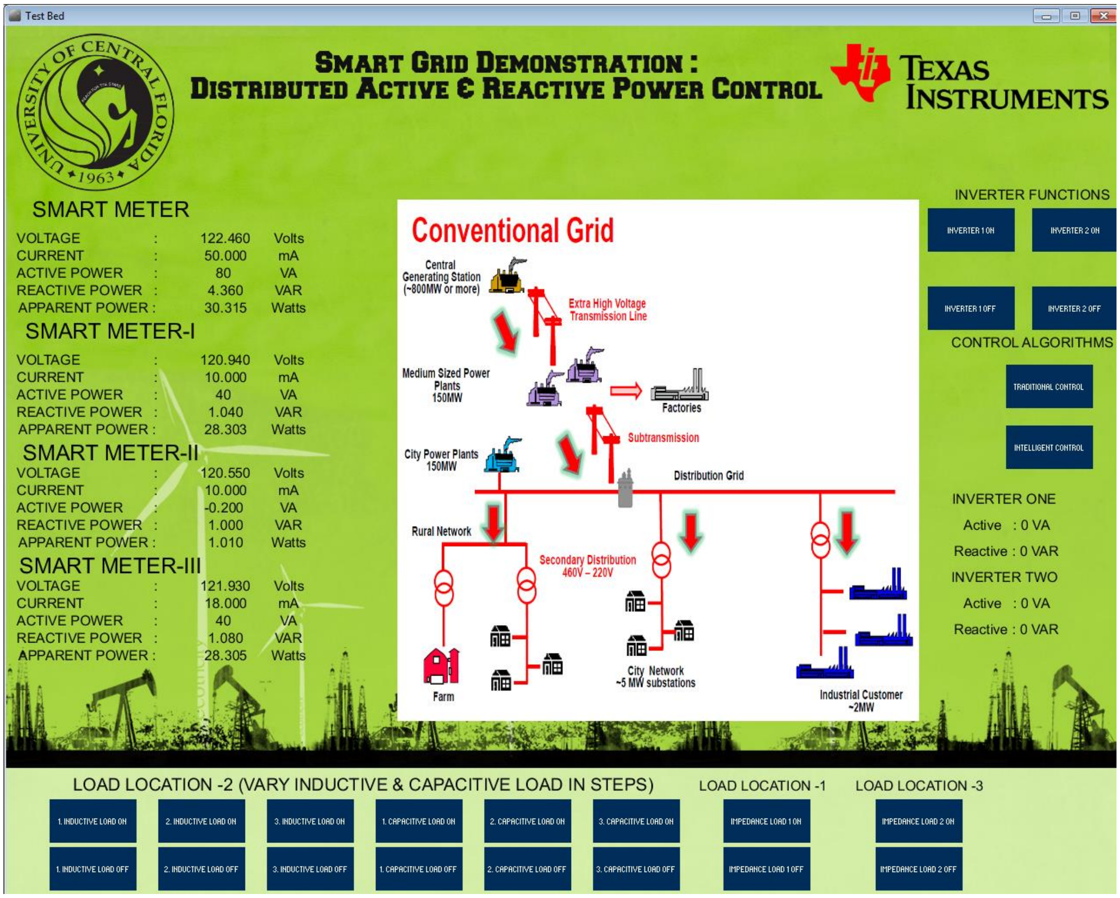


Figure 9 Graphical User Interface

## Development of Smart Microgrid testbed

This is an experimental setup for communication and control for the Smart Grid. Figure 10 shows a high-level setup of the Energy Grid with Distributed Energy Resources (DER) to form a micro-grid. The system is made up of three different loads (Load 1, Load 2 and Load 3) at locations marked Location 1, Location 2 and Location 3. These are variable inductive and capacitive load-units that can be changed intermittently. In the current setup, Load 2 is an adjustable AC load bank, either inductive or capacitive; Load 1 and Load 3 are constant impedance loads. These loads in the Microgrid vary arbitrarily and the quantity of active and reactive power fluctuates. The primary

objective is to minimize the amount of reactive power supplied from the main grid. The approach is to use distributed inverters with the aid of multiple local communication channels for reactive power compensation of the micro-grid real-time in a distributed and cooperative manner. The test bed is flexible and we can add 'n' number of load locations and the distributed measurements can be obtained with ease. When load changes, reactive power is supplied distributive by the inverters, and uniform voltage is achieved. Demand responses so inverters (together with their simulated storage devices) can maintain active power dispatch from the main grid. In the islanding operation, frequency regulation is ensured collectively by inverters.

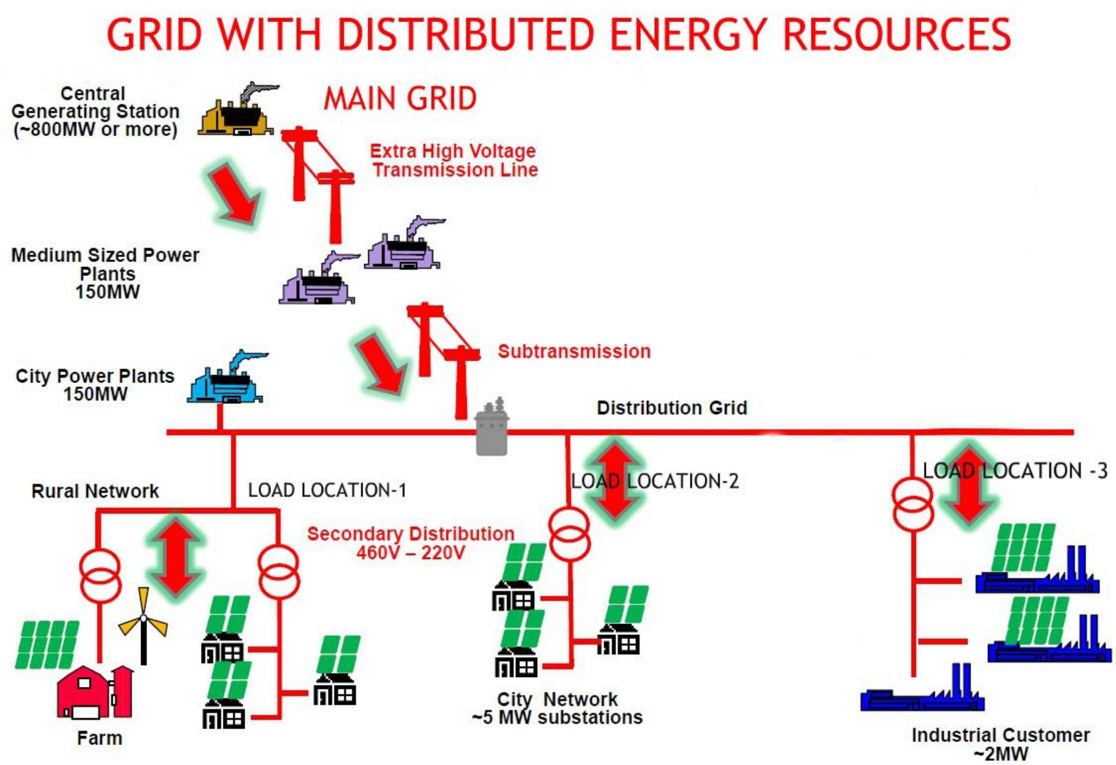


Figure 10 Main Grid Interfaced to a Microgrid with Distributed Energy Resources

When load changes, reactive power is supplied in a distributive fashion by the inverters to maintain a uniform voltage. By using the demand response mechanism along with their simulated storage devices, active power dispatch from the main grid can be maintained. In an islanding operation, frequency regulation is ensured collectively by inverters. The Microgrid testbed [33] is shown in Figure 11. The main functionality of the test bed is as follows

- Aggregate active power dispatch
- Reactive Power Compensation
- Multimode Communication
- Distributed optimization and control


Figure 11 Microgrid Test Bed

The list of equipment’s required to build the experimental setup are shown in the Table2.

Table 2 List of Equipment's used to Build the Experimental Support

| SL No | Part Number | Equipment Name | Quantity |
|---|---|---|---|
| 1. | MSP430F6779 | Single Phase E-Meter | 4 |
| 2. | TMDSSOLARUNIVKIT | Grid Tie Inverter | 2 |
| 3. | MSP430F5529 | Launch Pad | 2 |
| 4. | Relay Shield | Seed Studio | 2 |
| 5. | E3631 A | DC Power Supply | 2 |
| 6. | MODEL 8321 | Inductive Load | 1 |
| 7. | MODEL 8331 | Capacitive Load | 1 |
| 8. | 300Watt | Resistive Load | 1 |
| 9. | 300VA | AC Source | 1 |
| 10 | Connecting Wires | | As Req. |

# CHAPTER THREE: DEMAND RESPONSE BY COOPERATIVE CONTROL

## Introduction

The electric grid and its effective delivery of energy calls for the balance of generation and demand. Throughout every minute of every day these two values are in a chase to stay as close as possible to each other. As demand varies throughout any given day, generation sources need be adjusted and sometimes can lead to less efficient and costlier sources of energy being utilized to serve these increased loads. In order for utilities and grid operators to reduce the need for these costly generators at peak times, they look to the end user to curtail their demand. Remember, with a scale, you can compensate one side or the other to find a balance. Today many utilities are implementing programs that curtail loads on the residential, or demand side of the grid.

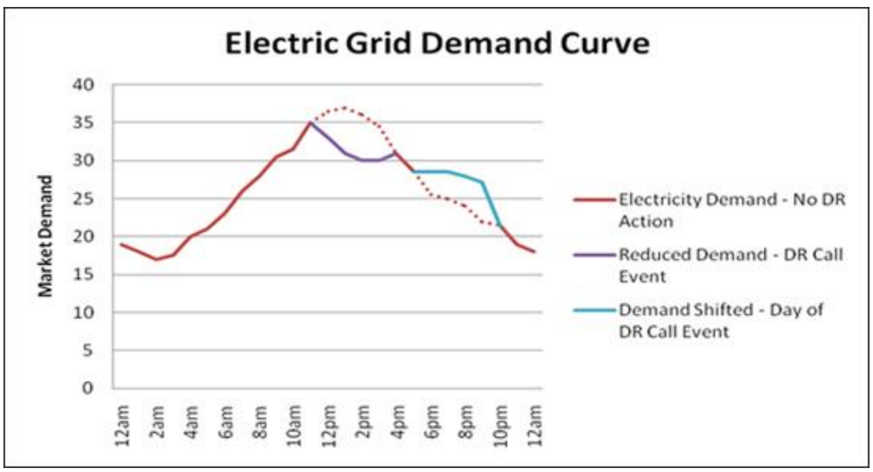


Figure 12 Electric Grid Demand Curve

## Control Methodologies for Demand Response

An example of a program that some utilities use currently is a Demand Response program [34] in which customers get a rebate or credit per billing cycle for allowing the utility to turn off

their air conditioning unit for 15 minutes a certain number of times per month or year. If this program is offered and gets accepted by millions of customers, utilities can reduce peak demand by signaling the 15-minute AC unit outages across their customer base, enabling a reduced peak demand on a given day. Verify with your local utility to see what programs they are currently offering to their customers and see if they are doing something similar.

## Demand Response Approach

Distributed generation consists of grid-wide intermittent generation that utilities are learning to grow with. This type of generation can come in the form of solar photovoltaic, wind, geothermal, biogas, natural gas, energy storage, etc. Many of these generation sources, like wind and solar, require inverters to convert the DC power to AC power. The overall grid is generally sectioned off into three major segments; generation, transmission, and distribution. Distribution being furthest from central generation facilities, contains all of the residential and commercial loads. The concept of a Microgrid can be considered to be a collection of various loads and distributed generation on the distribution segment of the grid. In this thesis, the overall concept of Demand Response was to keep the generation on the main grid as stable as possible, while adjusting local production from distributed generation as the load increases or decreases.

## Overview of the Power Objective

The actual power consumed by any device or equipment is called actual or real power, and it is always denoted by the capital letter ‘P’. The reactive loads such as inductive loads or capacitor loads does not really consume any power but it actually drops voltage by drawing more current giving a false impression that it actually consumes power, it discharges later, this type of power is

called reactive power and it is always denoted by the capital letter ‘Q’ and its unit is VAR. The combination of the active and reactive power consumed by a device is called apparent power, it is denoted by capital letter ‘S’ and its unit is VA (Voltage Ampere). Every type of generator has limits. Some operate best at certain points and cannot exceed certain thresholds. In the Microgrid testbed, we assume that the DC generators behind the AC inverters are capable of producing up to 144 VA each. This value of 144 VA is characterized as S. If the Microgrid increases its demand for both real and reactive power, the utilization ratio will determine what amount of power is produced by each inverter. A fair utilization ratio is determined so as not to overuse any particular inverter beyond its limit and equal contribution of power output from each inverter.

## Active Power Control

The real power utilization ratio $\alpha_p$ is introduced to determine what percentage of the real power is to be generated by each and every DG. The active power utilization ratio is defined as the ratio of active power generated by the DG to the maximum available active power of the DG and it is denoted by $\alpha_p$.

$$\alpha_{pinv} = \frac{P_{inv}}{\bar{P}_{inv}} \tag{3.1}$$

Where,

$P_{inv} \rightarrow Active\ power\ enerated\ by\ the\ unit\ i\ (1\ or\ 2).$

$\bar{P}_{inv} \rightarrow Maximum\ available\ active\ power\ from\ unit\ 1\ or\ 2.$

$\alpha_{qinv} \rightarrow Active\ Power\ utilization\ factor$

Reactive Power Control

The nominal power rating of each inverter is given by $S_i$ $(i\ is\ 1\ or\ 2)$. Since $S = \sqrt{P^2 + Q^2}$, it is possible to provide both real and reactive power if proportioned properly. If the active power generated by a DG is less than this nominal rating S, the unused nominal power capacity may be utilized by generating additional reactive power. The reactive power utilization ratio $\alpha_q$ is introduced to determine what percentage of the reactive power is to be generated by each and every DG.

$$\bar{Q}_{inv} = \sqrt{S_{inv}^2 - P_{inv}^2} \tag{3.2}$$

Where,

$Q_{inv}$ → Generated reactive power by the $i^{th}$ unit 1 or 2.

$\bar{Q}_{inv}$ → Maximum available reactive power by the $i^{th}$ unit.

$\alpha_{qinv}$ → Reactive power utilization factor.

Distributed Control Algorithm

In this section, the distributive cooperative algorithm is developed that will regulate the power output of the multiple generations in a distribution network[3]. The two-level control has been explained and the control strategy for the fair utilization ratio has been developed [35]. The two-level control can make the system operate well and all the DGs output converge according to the desired utilization factor profile. The communication layer that has been involved in the DGs and its contribution in the consensus. The first level control is to control the virtual leader that monitor the power flow from the main grid and the second level control is to control the followers

i.e. to control the power output of the individual DG in the system which is detail discussed in the later section.

## Communication Strategy

Within a power grid, there are two key values to pay attention to: the real and reactive power. Both play vital roles in the successful operation of the delivery of electricity. In this document, the measurement of real and reactive power values will be represented by P and Q respectively. The grid and both inverters will measure their own delivery of P and Q.

In this testbed, the grid has committed to only providing 60 W of real power to the Microgrid. If the Microgrid load increases beyond 60 W, the main grid will communicate to the two inverters to increase their production of real power. The main grid senses the increased demand of the Microgrid and measures the amount of real power above 60 W that is needed. The net real power difference that the Microgrid must produce is communicated from the main grid to the two inverters through control signals represented by α.

As for reactive power, Q, the main grid does not deliver any reactive power to the Microgrid at all. If the Microgrid demands any amount of reactive power, the main grid will communicate a control signal ($\alpha_q$) to the two inverters to compensate accordingly.

The two inverters have their own respective ($\alpha_p, \alpha_q$) pairs for real and reactive power and they must follow whatever the main grid's α values are. If communication from the main grid to the first inverter were to fail, the grid's α values can still be received from the second inverter.

The instantaneous communication matrix [36] [37] is defined by the following matrix:

$$S(t) = \begin{bmatrix} s_{11}(t) & s_{12}(t) & \dots & s_{1N}(t) \\ s_{21}(t) & s_{22}(t) & \dots & s_{2N}(t) \\ \vdots & \vdots & \vdots & \vdots \\ s_{N1}(t) & s_{N2}(t) & \dots & s_{NN}(t) \end{bmatrix} \tag{3.3}$$

If the communication link is lost between the main grid and the Grid Tie Inverter (GTI) -1. GTI -1 can communicate with the main grid through the GTI-2. This shows that despite the communication loss, there remains a globally reachable node (Main Grid). We validate that consensus is guaranteed. Refer to Figure 13.

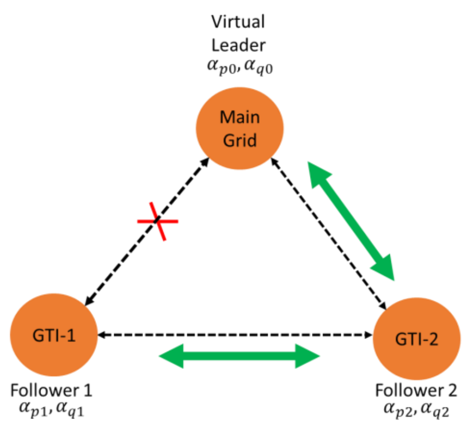


Figure 13 Communication Topology of System with One Globally Reachable Node (GTI -1 Communication Link Failed)

If the communication link is lost between the Main Grid and the GTI – 2, the GTI -2 can communicate with the Main Grid through the GTI-1. This shows that despite the communication loss, there remains a globally reachable node (Main Grid). We validate that consensus is guaranteed. Refer to Figure 14.

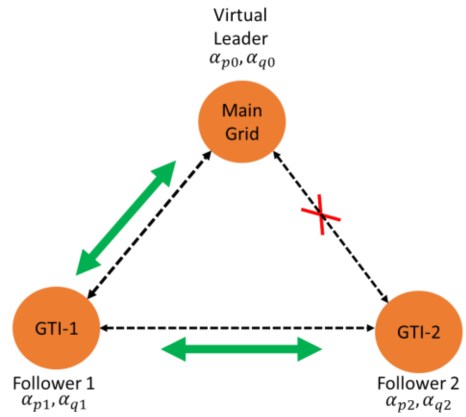


Figure 14 Communication Topology of System with One Globally Reachable Node (GTI -2 Communication Link Failed)

If the communication link is lost between the Main Grid and the GTI - 1, in addition to the connection between both the GTI-1 and GTI -2, there is no way for GTI – 1 to communicate. In this case GTI -1 is totally isolated from the group and cannot reach the global node (Main Grid) through any of its directed branches. Because the Main Grid is not globally reachable by both GTI's, the consensus is not guaranteed in this system. Refer to Figure 15.

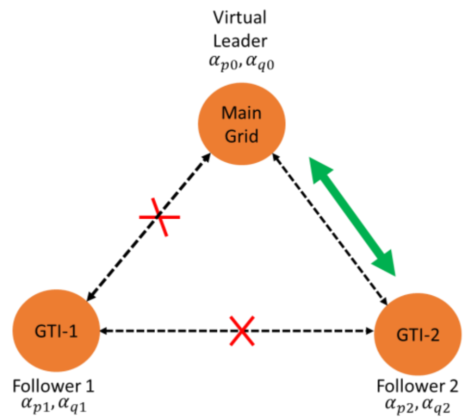


Figure 15 Communication Topology of System Without One Globally Reachable Node

Control Strategy for Fair Utilization Ratio

In this section, the control strategy for the distribution power system with n – three-phased inverter-based DG's that use the decoupled d-q control method via phased lock loop (PLL) has been developed.

The active and reactive power output of the inverter is given by the following equation

$$P_i = U_i I_{di}, Q_i = -U_i I_{qi} \tag{3.4}$$

$I_{di}$ and $I_{qi}$ → Output Currents of the d-axis and q-axis of the inverter.

$P_i$ and $Q_i$ → Denote the active and reactive power output of the inverter.

The integration control design is pursued the $I_{di}^{ref}$ $and$ $I_{qi}^{ref}$ and the differential algebraic equations can be written as

$$\dot{I}_{di}^{ref} = u_{1i} \tag{3.5}$$

$$\dot{I}_{qi}^{ref} = u_{2i} \tag{3.6}$$

The above equations denote the d-loop and q-loop dynamics through which the active and the reactive power outputs can be controlled;

Where $u_{1i}$ $and$ $u_{2i}$ → Cooperative control input to be designed.

Differentiating the equation (3.4) we can get the following,

$$\dot{P}_i = \dot{U}_i I_{di} + U_i \dot{I}_{di} \tag{3.7}$$

$$\dot{P}_i = \dot{U}_i I_{di} + U_i u_{1i} \tag{3.8}$$

Also, we have a fair utilization ratio ($\alpha_i$)which is defined as ratio of active power generated by the i$^{th}$ DG ($P_i$) to the maximum available active power at the i$^{th}$ DG ($P_{imax}$).

$$\alpha_i = \frac{P_i}{P_{imax}} \tag{3.9}$$

Differentiating the above equation (3.9), we get the following:

$$\dot{\alpha}_i = \frac{\dot{P}_i P_{imax} - \dot{P}_{imax} P_i}{(P_{imax})^2} \tag{3.10}$$

Substituting the equation (3.8) in the above equation we get the following:

$$\dot{\alpha}_i = \frac{\dot{U}_i I_{di} + U_i \dot{I}_{di}}{P_{imax}} - \frac{\dot{P}_{imax} P_i}{(P_{imax})^2} \tag{3.11}$$

$$\dot{\alpha}_i = \frac{\dot{U}_i I_{di}}{P_{imax}} + \frac{U_i u_{1i}}{P_{imax}} - \frac{\dot{P}_{imax} P_i}{(P_{imax})^2} \tag{3.12}$$

$$\dot{\alpha} = v_{1i} \tag{3.13}$$

where $v_{1i}$ → is the cooperative control law for the i$^{th}$ DG.

Using the communication matrix, the cooperative control law can be chosen as follows

$$v_{1i} = k_c \left[ \sum_{j=0}^{N_{DG}} D_{ij} (\alpha_j - \alpha_i) \right] \tag{3.14}$$

Rewriting equation (3.8) in terms of $u_{1i}$ is defined as follows,

$$u_{1i} = \frac{\dot{P}_i}{U_i} - \frac{\dot{U}_i I_{di}}{U_i} \tag{3.15}$$

Rearranging equation (3.12) we get the following:

$$v_{1i} - \frac{\dot{U}_i I_{di}}{P_{imax}} + \frac{\dot{P}_{imax} P_i}{(P_{imax})^2} = \frac{U_i u_{1i}}{P_{imax}} \tag{3.16}$$

Rearranging the above equation in terms of $u_{1i}$, and substituting the value for $v_{1i}$, the cooperative control law for the distributed DG's is given by the equations (3.17) and (3.18). The control law for the reactive power can be derived as the same way for the active power control.

The control law for the active power is given by the equation 3.17 and the reactive power control is given by the equation 3.18.

$$u_{1i} = \frac{P_{imax}}{U_i}\left[D_{i0}\alpha_p^0 - \frac{P_i}{(P_{imax})} + \sum_{j=1}^{n} D_{ij}\frac{P_j}{P_{jmax}}\right] - \frac{\dot{U}_i}{U_i^2}P_i \tag{3.17}$$

$$u_{2i} = \frac{Q_{imax}}{U_i}\left[D_{i0}\alpha_p^0 - \frac{Q}{(Q_{imax})} + \sum_{j=1}^{n} D_{ij}\frac{Q_j}{Q_{jmax}}\right] - \frac{\dot{U}_i}{U_i^2}Q_i \tag{3.18}$$

$$\frac{\dot{P}_i}{U_i} - \frac{\dot{U}_i I_{di}}{U_i} = \frac{P_{imax}}{U_i}\left[D_{i0}\alpha_p^0 - \frac{P_i}{(P_{imax})} + \sum_{j=1}^{n} D_{ij}\frac{P_j}{P_{jmax}}\right] - \frac{\dot{U}_i}{U_i^2}P_i \tag{3.19}$$

The closed loop system equation for the above control laws can be written as follows:

$$\dot{P}_i = P_{imax}\left[D_{i0}\alpha_p^0 - \frac{P_i}{(P_{imax})} + \sum_{j=1}^{n} D_{ij}\frac{P_j}{P_{jmax}}\right] \tag{3.20}$$

$$\frac{\dot{P}_i}{P_{imax}} = \left[D_{i0}\alpha_p^0 - \frac{P_i}{(P_{imax})} + \sum_{j=1}^{n} D_{ij}\frac{P_j}{P_{jmax}}\right] \tag{3.21}$$

The cooperative control law for the reactive power generation at the DG is given by the following equation (3.22)

$$\frac{\dot{Q}_i}{Q_{imax}} = \left[D_{i0}\alpha_p^0 - \frac{Q_i}{(Q_{imax})} + \sum_{j=1}^{n} D_{ij}\frac{Q_j}{Q_{jmax}}\right] \tag{3.22}$$

Suppose that the communication rule is satisfied among the grid tie inverters (GTI). Then the output ratios of their active and reactive power convergence uniformly and asymptotically to

the common value of $\alpha_{p0}$ and $\alpha_{q0}$ respectively. Equation (3.22) can be rewritten as following equation 3.23 [36]

$$\dot{\alpha_\iota} = \left[-\alpha_i + D_{i0}\alpha_p^0 + \sum_{j=1}^{n} D_{ij}\alpha_j\right] \tag{3.23}$$

Virtual Leader Control

The active power control over a specified transmission line is controlled according to Figure 16 and as follows

$$\dot{z}_0 = k_p'\left[P_{trans}^{ref} - P_{trans}\right] \tag{3.24}$$

$$\alpha_{P0} = z_0 \tag{3.25}$$

$P_{trans}$ is the desired power over the transmission line; $\alpha_{P0}$ is the resulting utilization ratio that drives equation (3.24).

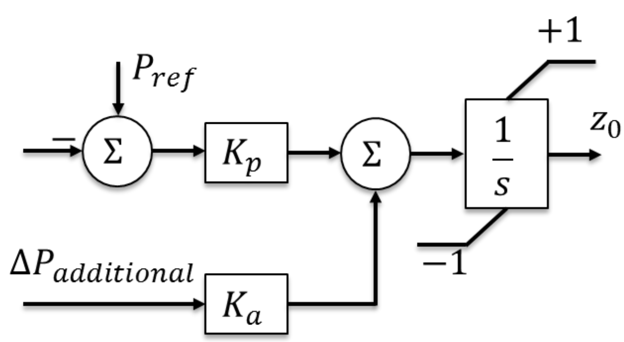


Figure 16 Control Determining Desired Ratio of P

The reactive power control over the Microgrid is controlled according to Figure 17 and as follows

$$\dot{z}_0' = k_q'\left[V_c^{ref} - V_c\right] \tag{3.26}$$

$$\alpha_{q0} = z_0 \qquad (3.27)$$

$V_c$ is the critical bus voltage of interest; $\alpha_Q^0$ is the upper utilization value which is used to drive equation (3.26).

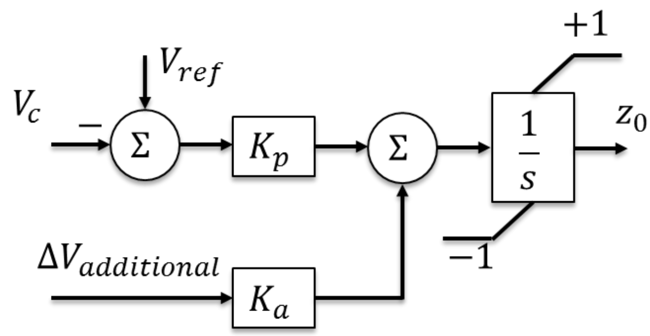


Figure 17 Control Determining the Desired Ratio of Q

The physical meaning of the control of the 3.24 and 3.25 are that, the bus voltage or the real power transmission is less than its reference value, then the proposed distributed high-level control is to command some of the distributed generators (through its local communication) to increase their reactive or real power utilization ratio and rest of the DG associated with the leader cooperatively increase their power to achieve the global objective using the distributed control laws mentioned in the previous sections and equations (3.26) and (3.27).

## Simulation Results

The schematic diagram of the Microgrid test bed system is shown in Figure 3. Simulations are performed using the SimPower Systems Toolbox of Simulink® to demonstrate the performance of the algorithm. The Microgrid test bed consists of the three load locations, the two locations are connected to the DGs. The total power requirement for the test Microgrid is P=300

WATTS, Q=150VAR. The objective is minimizing the reactive power flow from the main grid and inverters (together with their simulated storage devices) can maintain active power dispatch from the main grid to a constant value. The maximum available power at the load locations 1 and the load locations 3 are same, i.e. S=144 watts at each Grid Tie Inverter. The GTI are turned at time t=0.4 s.

The simulations result of the experiment is shown in below Figure 18-24. The data from the experiment demonstrate that utilization factors of the active and reactive power converge to a constant value.

Table 3 Expected α and $P_{trans}$ values

| Time (seconds) | Power Flow from main grid to Microgrid ($\boldsymbol{P_{trans}}$) | | $\boldsymbol{\alpha_p}$ | | $\boldsymbol{\alpha_q}$ | |
|---|---|---|---|---|---|---|
| | Active Power | Reactive Power | GTI-1 | GTI-2 | GTI-1 | GTI-2 |
| 0 | 300 | 150 | 0 | 0 | 0 | 0 |
| 5 | 75 | 22 | 0.6226 | 0.6226 | -0.5126 | -0.5126 |
| 10 | 60 | 2.5 | 0.6666 | 0.6666 | -0.6120 | -0.6120 |
| 15 | 60 | 0 | 0.6666 | 0.6666 | -0.6246 | -0.6246 |

The simulations results are shown in the following Figures 18 to 24. The active power utilization ratio for the virtual leader is shown in the Figure 18 and the followers is shown in Figure 20 and 21. The reactive power utilization ratio for the virtual leader is shown in Figure 19 and the followers is shown in Figure 22 and 23. The active and reactive power flow from the main grid to the microgrid is shown in the

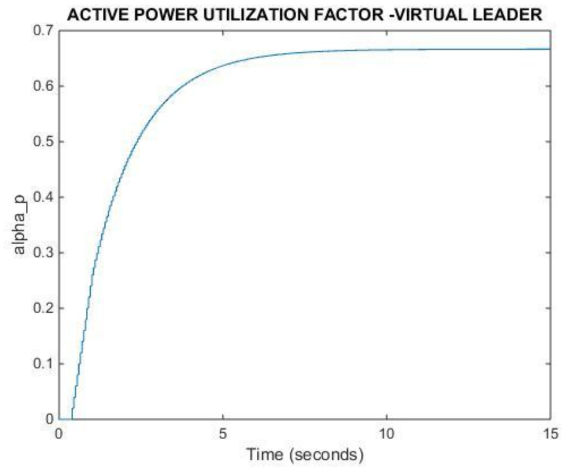


Figure 18 Active Power Utilization Factor - Virtual Leader

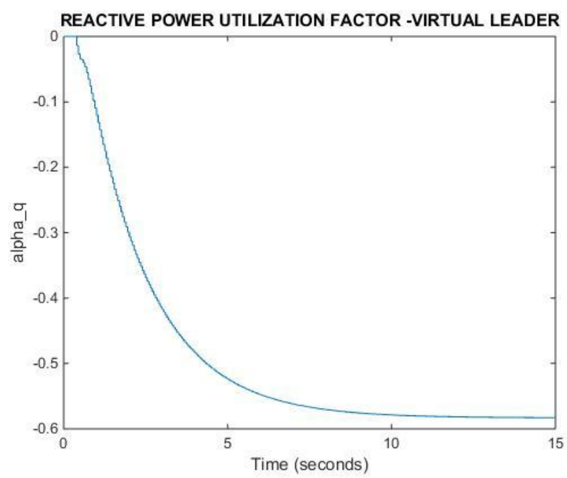


Figure 19 Reactive Power Utilization Factor - Virtual Leader

The active power utilization factor for the followers is defined by the following ratio

$$\frac{P_1}{P_{1max}} = \frac{P_2}{P_{2max}} = \alpha_p^o = 0.6666 \tag{3.28}$$

The active power utilization factor for the DGs (GTI-1 & GTI-2) are plotted and shown graphically in Figure 19 and 20. The utilization factor for the active power generation for the inverters (DG's) converges to the value of $\alpha_p = 0.6666$

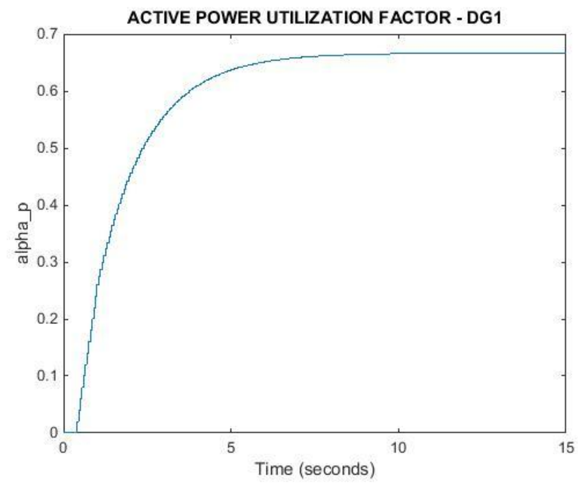


Figure 20 Active Power Fair Utilization Ratio ($\alpha_{p1inv}$)

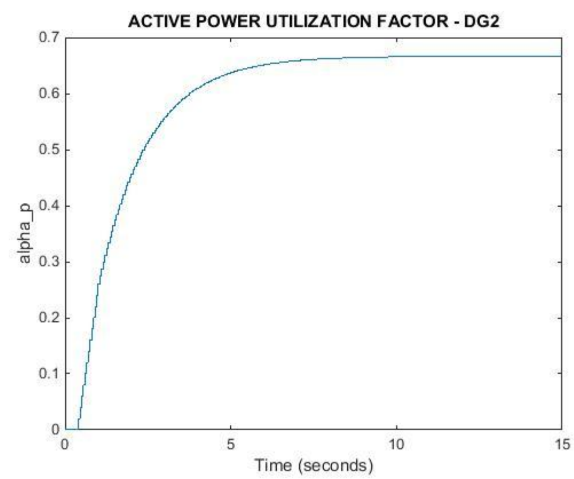


Figure 21 Active Power Fair Utilization Ratio ($\alpha_{p1inv}$)

The reactive power utilization factor for the Microgrid is defined by the following ratio

$$\frac{Q_1}{Q_{1max}} = \frac{Q_2}{Q_{2max}} = \alpha_q^o = -0.6246 \qquad (3.29)$$

The reactive power utilization factor for the DGs (GTI-1 & GTI-2) are plotted and shown graphically in Figure 22 and 23. The utilization factor for the reactive power generation of the generators for the inverters (DG's) converges to the value of $\alpha_q = -0.6246$.

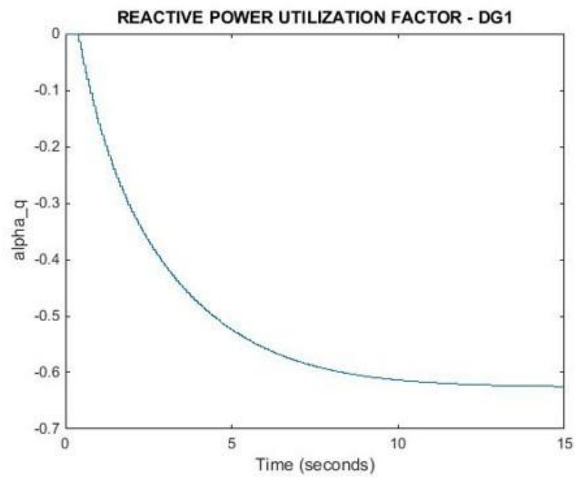


Figure 22 Reactive Power Fair Utilization Ratio ($\alpha_{q1inv}$)

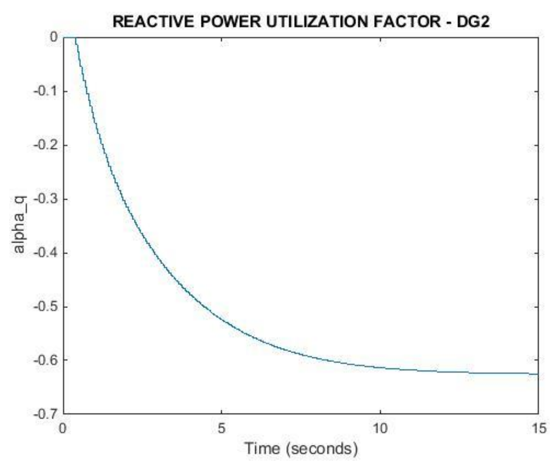


Figure 23 Reactive Power Fair Utilization Ratio ($\alpha_{q2inv}$)

The reactive power flow from the main grid to the Microgrid is reduced to zero, the fair utilization factor of the DGs get converges to the virtual leader as shown in the above Figure. The reactive power flow from the main grid to the Microgrid is shown in Figure 24.

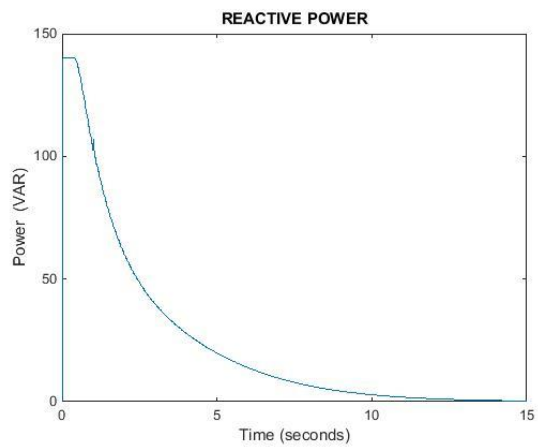


Figure 24 Reactive Power flow from the Main grid to the Microgrid

The active power flow from the main grid to the microgrid is reduced to the desirable value ($P_{ref}^{trans} = 60$), the fair utilization of the DGs get converges to the virtual leader as shown in the above Figure. The active power flow from the main grid to the microgrid is shown in the Figure 25.

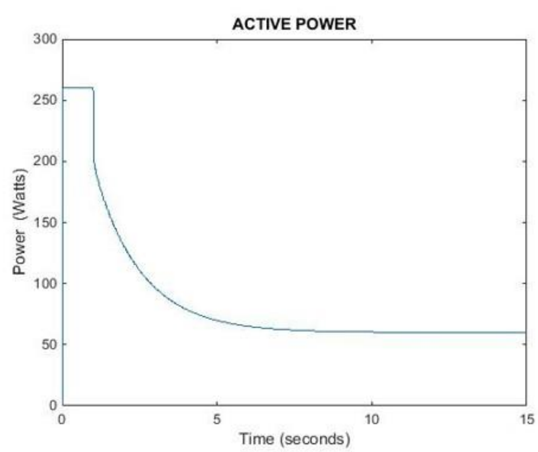


Figure 25 Active Power flow from the Main grid to the Microgrid

## Conclusion

In this chapter the application of the cooperative control to control the distributed generators in a Microgrid is investigated. The main objective of the cooperative control is as follows:

- Realize the aggregated active power flow demand from the main grid to a constant value.
- Minimize the aggregated reactive power flow from the main grid to zero.
- Fair utilization ratios in a distributed manner for the distributed generators.

The cooperative control law is also provided based on the dynamics of the grid tie inverter. The simulated results show the efficiency of the proposed control and its achieving the desired power objective.

# CHAPTER FOUR: UNIFIED VOLTAGE PROFILE BY COOPERATIVE DISTRIBUTED OPTIMIZATION

## Realizing a Unified Voltage Profile

The cooperative control was used to organize the DG in a Microgrid to satisfy multiple power objectives[3]. Power objectives included regulating some critical point voltages. It was shown that multiple critical point regulation provides improvements compared with the single critical point regulation in terms of realizing a more unified voltage profile and less voltage fluctuation.

## Current Practice of Voltage Regulation

It is always in the special interest of the utilities companies to improve the voltage profile and minimize the losses in the power system. In the traditional power system, the voltage regulation is achieved through the under load tap change transformers (ULTC) or capacitor banks. These improve the voltage level by supplying the reactive power. The voltage control in large magnitude is done by switching on/off the capacitor banks, these regulate the voltage at their respective nodes within the standard limits. It is always advantageous to take use of the DG's in improving the voltage quality. Once the voltage is brought close to the unity or reference value, the DGs can be used to fine control to further regulate these voltages.

There are various methods used for inverter control strategies like current source inverter (CSI), voltage/frequency droop control and generation emulation control. CSI feed all the available power into the grid without any reactive power compensation. CSI may cause stability problems on high penetrations [38].

## Voltage Regulation by Distributed Generators

The grid tie inverter due to their fast response and flexibility, they plan an important role in coupling the distributed generators to the utility grid. Usually, the maximum available active power produced by the inverter is always less than their nominal value Therefore, the excessive available power generation of the DGs may be utilized to produce the reactive power, whenever possible. A sophisticated control mechanism has to be designed to optimally dispatch the individual unit's reactive power to benefit the overall system performance.

These DGs reactive power generation can be utilized to further tune the voltage level to unity, which aids in the overall loss minimization.

## Cooperative Distributive Optimization Algorithm

Cooperative distributed optimization[40] is proposed to optimally dispatch the reactive power of the distributed generators (DGs). The main objective is to minimize the global cost function which will minimize the sum of the quadratic voltage errors of all the DG nodes on the system.

### Calculation of the Sub-Gradient for the Nodes with DGs

Every DG in the system knows only its own local cost function and it minimizes its cost function while exchanging information with the other units in the network.

$$F_v^* = \min_{\propto_q} \sum_{i=1}^{N} f_{v_i}, \tag{4.1}$$

$$f_{v_i} = \frac{1}{2}(1 - V_i)^2 \tag{4.2}$$

The gradient of the ith unit of the system is given as follows:

$$F_v^* = \min_{\propto_q} \sum_{i=1}^{N} f_{v_i}, \quad (4.3)$$

$$= \frac{\partial f_{v_i}}{\partial V_i} \frac{\partial V_i}{\partial Q_i} \frac{\partial Q_i}{\partial \propto_{q_i}} \quad (4.4)$$

$$= -\bar{Q}_i (1 - V_i) \frac{\partial V_i}{\partial Q_i} \quad (4.5)$$

Where $f_{v_i}$ is the i$^{th}$ unit cost function, is the utilization ratio of the i$^{th}$ unit.

The system power flow equations are expressed as follows:

$$P_{G_i} - P_{D_i} = \sum_{j=1}^{N} V_i V_j [G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}] \quad (4.6)$$

$$Q_{G_i} - Q_{D_i} = \sum_{j=1}^{N} V_i V_j [G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}] \quad (4.7)$$

Where $\delta_{ij}$ is the phase difference between the nodes i and j. Quantities $B_{ij}$ and $G_{ij}$ are the imaginary and real parts of the system Y-bus matrix. The terms $P_{G_i}, P_{D_i}, Q_{G_i}$ and $Q_{D_i}$ are the ith node active power generation, active power load, reactive power generation and the reactive power load respectively.

The reactive power flow is written as follows:

$$Q_i = Q_{G_i} - Q_{D_i} = \sum_{j} V_i V_j [G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}] \quad (4.8)$$

$$= -V_i^2 B_{ii} + V_i \sum_{j \neq i} V_j \left[G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}\right] \tag{4.9}$$

The required gradient can be derived as follows:

$$\frac{\partial Q_i}{\partial V_i} = -2V_i B_{ii} + \sum_{j \neq i} V_j \left[G_{ij} cos\delta_{ij} + B_{ij} sin\delta_{ij}\right] \tag{4.10}$$

$$= V_i B_{ii} + \frac{Q_i}{V_i} \tag{4.11}$$

The utilization factor is defined as follows:

$$\propto_i = \frac{Q_i}{\overline{Q}_i} \tag{4.12}$$

$$Q_i = \propto_i \overline{Q}_i \tag{4.13}$$

$$\frac{\partial Q_i}{\partial \propto_i} = \overline{Q}_i$$

The gradient can be found by

$$g_i = -\overline{Q_i}(1 - V_i)\frac{\partial V_i}{\partial Q_i} \tag{4.14}$$

$$g_i = -\overline{Q_i}(1 - V_i)\frac{V_i^2}{Q_i - V_i^2 B_{ii}} \tag{4.15}$$

Calculation of Units Sub-Gradient without DGs

If there is no DG installed in a node, the maximum reactive power available in that node will be zero. The subgradient/gradient method defined previously will not contribute to the

optimization. The concept of a virtual leader is applied to these nodes and it tried to regulate the voltage at its node by utilizing all other units' reactive power capacity.

For these type of nodes, the overall available reactive power capacity should be used to regulate the voltage in this type of nodes. The $\bar{Q}_i$ will be replaced by the average of all the unit's available reactive power capacity.

The modified gradient for such nodes is as follows:

$$g_i = -x_i(1 - V_i)\frac{V_i}{Q_i - V_i^2 B_{ii}}, \tag{4.16}$$

Where $x_i$ is formulated as

$$x_i(k+1) = \sum_{j=1}^{N} d'_{ij} x_j \tag{4.17}$$

Calculation of the Gradient Gains

The β gains should be chosen in such a way to give the best performance. The small gains will slow down the pace of the distributed optimization and the larger gains tend to introduce the overshoots and even sometimes causes instability on extremes.

## Simulations

The schematic diagram of the Microgrid test bed system is shown in Figure 3. Simulations are performed using the Simpower Systems Toolbox of Simulink® to demonstrate the performance of the algorithm. The Microgrid test bed consists of the three load locations, the two locations are connected to the DGs. The total power requirement for the test Microgrid is P=300 WATTS, Q=150VAR. The objective is minimizing the reactive power flow from the main grid

and inverters (together with their simulated storage devices) can maintain active power dispatch from the main grid to a constant value. The maximum available power at the load locations 1 and the load locations 3 are same, i.e. S=144 watts at each Grid Tie Inverter. The GTI are turned at time t=0.4 s.

To provide a fair result, the active power policy is chosen to be identical, to regulate the power flow from the main grid at 60Watts and the virtual leader active power utilization ratio is maintained at $\alpha_p = 0.6.$ For the reactive power control cooperative distributed optimization is employed. The Grid Tie Inverters (GTI) participate in the distributed optimization to cooperatively minimize the sum of their nodes voltage error which is expresses by the cost function i.e. equation (4.2) with n=2. The n represents the number of grid tie inverters.

The Figure 26 shows the main grid reactive power flow from the main grid is reduced to the zero, while the active power flow from the main grid is kelp constant at $\alpha_p = 0.6$ .

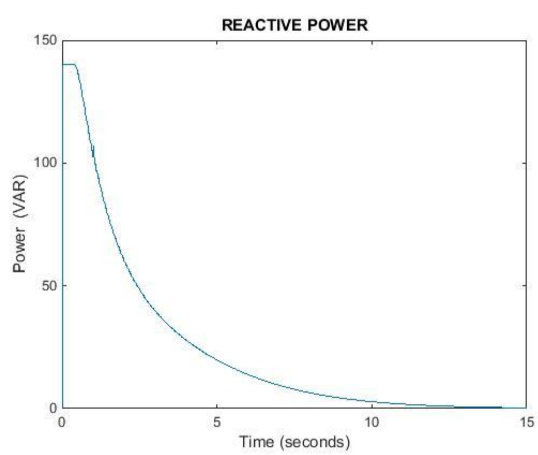


Figure 26 Reactive Power from Main Grid to the Microgrid

The plot in Figure 27 shows the Active power generation of the GTI-1 and the Figure 28 shows the Reactive power generation of the GTI -1

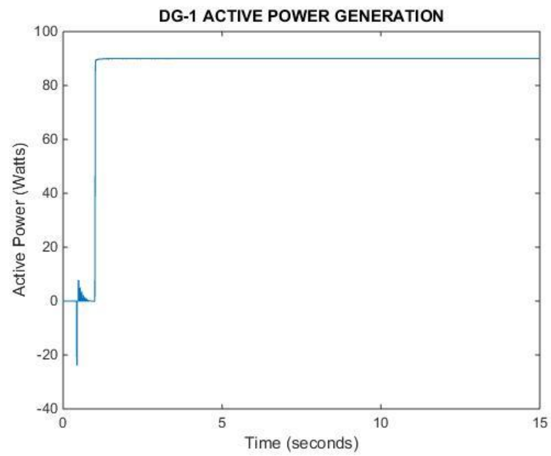


Figure 27 GTI-1 Active Power Generation

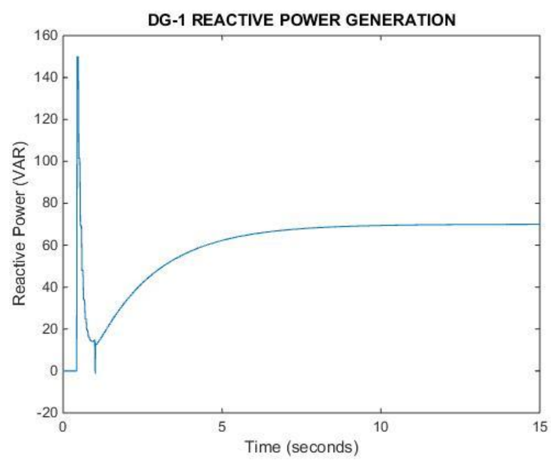


Figure 28 GTI-1 Reactive Power Generation

The plot in Figure 29 shows the Active power generation and the Figure 30 shows the Reactive power generation of the GTI -2. The power produced by the both the DGs is always same due to their similar capacities. The active power generated by the GTIs is 90W and the reactive power generated by the GTIs is 75VAR.

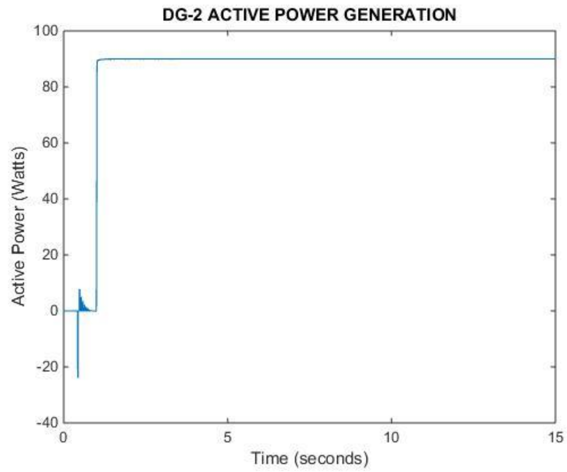


Figure 29 GTI-2 Active Power Generation

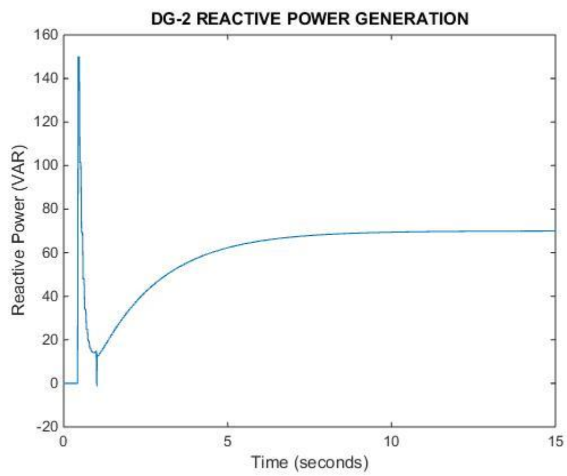


Figure 30 GTI-2 Reactive Power Generation

## Conclusion

In this chapter, the application of the cooperative distributed optimization algorithm has been explained. This algorithm is used to optimally dispatch the reactive power generation of the grid tie inverters in the Microgrid test bed is studied. In a larger power system, with some nodes without DGs also contribute to the reactive power minimization with the available communications and the measurement.

The global objective is to minimize the cost function thereby reducing the voltage errors at each node, to achieve the unified voltage profile. It is also proved that achieving unified voltage profile help in active power loss minimization. Achieving unified voltage profile results in following objectives

- Reduced losses in the system
- Energy and cost saving and economically feasible.

# CHAPTER FIVE: CONCLUSION

The review of this thesis work provides a good starting point for researchers, industrial people and academicians who are working on developing a prototype on smart grid and communication. It also provides a detailed information how the smart meters can communicate with each and other evaluation modules available with the markets. It also shows how the distributed consensus algorithms that can be used effectively in the power system to achieve the desired objective.

This document also provides information how the distributed cooperative control and distributed cooperative optimization can be effectively used to organize and control the Distributed generators in the microgrid. The experimental and simulation results employing these algorithms on a real test bed also published along with this work.

This report also gives a detailed implementation of hardware in the microgrid testbed. The present setup of the microgrid includes communication between the smart meters using wired and wireless communication and multimode communication between the smart meter and the grid tie inverter. The future work on this testbed includes demonstrating the islanding mode and physical cyber security on the microgrid.

# APPENDIX A: CODE FOR COMMUNICATION BETWEEN THE SMART METERS

The code for communication between the smart meter was writing using the java in the processing IDE. The code for the communication between the smart meter is shown. The program can be implemented in two ways, based on the smart meter connection between them.

```
import processing.serial.*;

//Setup Font
PFont f;

// The serial port for data access
Serial myPort;

//Serial buffer for incoming packerts
int[] s = new int[61];

//Packet ID Number
int ID;

//Counters
int i=0;
int j=1;
int k=0;

//Vertical Spacing between lines of text
int VertSpace = 15;

//Setup (run's once on startup)
void setup() {

  //Define window size
  size(800,900);

  //Set window title
  frame.setTitle("Test Bed");

  //List out all serial ports avaliable on the system
  println(Serial.list());

  //Define serialport as item 0 in previous list
  myPort  = new Serial(this, Serial.list()[2], 9600);

  //Pre populate serial buffer with pattern so unused entries can easily be
seen
  for (int k=0; k<=60; k++){
    s[k] = 0x5A5A5A5A;
  }

  //Define font to be used: Georgia at 14px
  f = createFont("Georgia", 14);
```

```
  //Set Text font
  textFont(f);

  //Set Text alignment
  textAlign(LEFT);

  //Set current fill color
  fill(255);

  //Set background color: Black
  background(0, 0, 0);

}

//Draw: Runs as a self contained loop
void draw() {

  //This loop condition is checked each time the draw loop runs
  while (myPort.available() > 0) {

    //Read the byte from the serial port into the read array buffer
    s[i] = myPort.read();

    //increment loop counter
    i++;
//println("the value of "+i+"is :"+s[i]);
    //Evaluate if a full packet of 50 bytes has arrived
    if (i == 50) {

      //Determine which meter this packet is from (s[5] contains the first
byte of the meter ID tag)
      ID = 153 - s[5];

      //Fill color for rectangles - black
      fill(0,0,0);

      //Blank out previous reading from current meter
      rect((ID*200),0,200,900);

      //Fill color for text - white
      fill(255,255,255);


      if (s[5]==151)
     {
      float byte_16 = s[16]<<0;
      float byte_17 = s[17]<<8;
      float voltage1 =byte_17+byte_16;

      float byte_18 = s[18] <<0;
      float byte_19 = s[19] <<8;
      float current1 = (byte_18+byte_19);

      float byte_20 = s[20] <<0;
```

```
 float byte_21 = s[21] <<8;
 float byte_22 = s[22] <<16;
 float byte_23 = s[23] <<24;
 float active1 = (byte_20+byte_21+byte_22+byte_23);

 float byte_24 = s[24] <<0;
 float byte_25 = s[25] <<8;
 float byte_26 = s[26] <<16;
 float byte_27 = s[27] <<24;
 float reactive1 = (byte_24+byte_25+byte_26+byte_27);

 float byte_28 = s[20] <<0;
 float byte_29 = s[21] <<8;
 float byte_30 = s[22] <<16;
 float byte_31 = s[23] <<24;
 float apparent1 = (byte_28+byte_29+byte_30+byte_31);
}
else if (s[5]==151)
{

 float byte_16 = s[16]<<0;
 float byte_17 = s[17]<<8;
 float voltage2 =byte_17+byte_16;

 float byte_18 = s[18] <<0;
 float byte_19 = s[19] <<8;
 float current2 = (byte_18+byte_19);

 float byte_20 = s[20] <<0;
 float byte_21 = s[21] <<8;
 float byte_22 = s[22] <<16;
 float byte_23 = s[23] <<24;
 float active2 = (byte_20+byte_21+byte_22+byte_23);

 float byte_24 = s[24] <<0;
 float byte_25 = s[25] <<8;
 float byte_26 = s[26] <<16;
 float byte_27 = s[27] <<24;
 float reactive2 = (byte_24+byte_25+byte_26+byte_27);

 float byte_28 = s[20] <<0;
 float byte_29 = s[21] <<8;
 float byte_30 = s[22] <<16;
 float byte_31 = s[23] <<24;
 float apparent2 = (byte_28+byte_29+byte_30+byte_31);

}
else if (s[5]==152)
{

 float byte_16 = s[16]<<0;
 float byte_17 = s[17]<<8;
 float voltage3 =byte_17+byte_16;
```

```
  float byte_18 = s[18] <<0;
  float byte_19 = s[19] <<8;
  float current3 = (byte_18+byte_19);

  float byte_20 = s[20] <<0;
  float byte_21 = s[21] <<8;
  float byte_22 = s[22] <<16;
  float byte_23 = s[23] <<24;
  float active3 = (byte_20+byte_21+byte_22+byte_23);

  float byte_24 = s[24] <<0;
  float byte_25 = s[25] <<8;
  float byte_26 = s[26] <<16;
  float byte_27 = s[27] <<24;
  float reactive3 = (byte_24+byte_25+byte_26+byte_27);

  float byte_28 = s[20] <<0;
  float byte_29 = s[21] <<8;
  float byte_30 = s[22] <<16;
  float byte_31 = s[23] <<24;
  float apparent3 = (byte_28+byte_29+byte_30+byte_31);

 }
 else if (s[5]==153)
 {
  float byte_16 = s[16]<<0;
  float byte_17 = s[17]<<8;
  float voltage3 =byte_17+byte_16;

  float byte_18 = s[18] <<0;
  float byte_19 = s[19] <<8;
  float current3 = (byte_18+byte_19);

  float byte_20 = s[20] <<0;
  float byte_21 = s[21] <<8;
  float byte_22 = s[22] <<16;
  float byte_23 = s[23] <<24;
  float active3 = (byte_20+byte_21+byte_22+byte_23);

  float byte_24 = s[24] <<0;
  float byte_25 = s[25] <<8;
  float byte_26 = s[26] <<16;
  float byte_27 = s[27] <<24;
  float reactive3 = (byte_24+byte_25+byte_26+byte_27);

  float byte_28 = s[20] <<0;
  float byte_29 = s[21] <<8;
  float byte_30 = s[22] <<16;
  float byte_31 = s[23] <<24;
  float apparent3 = (byte_28+byte_29+byte_30+byte_31);
}

  //Reset loop counter
  i=0;
```

```
        }
    }
}
```

# APPENDIX B: MULTIMODE COMMUNICATION BETWEEN SMART METER AND GRID TIE INVERTER

The code for the communication between the smart meter and the grid tie inverter is discussed in this section. When you connect the to the C2000ISO card via USB, you will be able to program it, as well as see a new serial port appear in the device manager. This is the interface you will be able to control it via serial COM port, with a baud rate of 9600. Please replace the function in SolarMicroInv-Main.c with this one (Starts at line 1836). The code has been written in embedded c and written below for your reference.

```
interrupt void SCIARXISR() {
    Uint16 ReceivedChar;
    static Uint16 header;
    //Pull RX character into local buffer
    ReceivedChar = SciaRegs.SCIRXBUF.all;
    //Echo character back to user
    SciaRegs.SCITXBUF = ReceivedChar;
    if (byte_count == 0)
    {
        header = ReceivedChar;
        byte_count++;
    }
    else if (byte_count == 1)
    {   //Check for a 'c'
        if (header == 0x63)
        {
            //Check for a '1'
            if (ReceivedChar == 0x31){
                Gui_InvStart = 1;
                SciaRegs.SCITXBUF = 'S';
            }
            else {
                Gui_InvStop = 1;
                SciaRegs.SCITXBUF = 'E';
            }
            byte_count = 0;
        }
            else
        {
            Gui_InvStop = 0;
            byte_count = 0;
            SciaRegs.SCITXBUF = 'E';
        }
    }
    SciaRegs.SCIFFRX.bit.RXFFOVRCLR=1;  // Clear Overflow flag
    SciaRegs.SCIFFRX.bit.RXFFINTCLR=1; // Clear Interrupt flag
    PieCtrlRegs.PIEACK.all|=0x100;       // Issue PIE ack
    return;}
```

# APPENDIX C: CODE FOR GRAPHICAL USER INTERFACE (GUI)

This section provides the detailed information about the Graphical User Interface that has been developed as a part of the hardware setup to display the values in real time and to interact with the test bed. The part of the code has been explained for better understanding. The various values of the smart meter are stored in the variables. For example, the voltage value of the smart meter is stored in the variable “voltage”. To display it in the GUI, please use the following syntax as shown in Figure 32.


Figure 31 Zoomed Screenshot Values of Smart Meter 2 GUI

```
text("VOLTAGE: ",95,250);
text(voltage,250,250);
text("Volts",325,250);
```

Figure 32 Processing Code to Display the Voltage Value

To add a button in the GUI, please use the in-build function “add button”. The syntax to add the “INVERTER -1 ON” button is shown in Figure 6.3.

```
    gui1.addButton("inverterON")
    .setCaptionLabel("INVERTER 1 ON")
//Set the position of the button : (X,Y)
.setPosition(1060,210)
//Set the size of the button : (X,Y)
.setSize(100,50)
//Set the pre-defined Value of the button : (int)
.setValue(0)
//set the way it is activated : RELEASE the mouseboutton or PRESS it
.activateBy(ControlP5.RELEASE);
;
```

Figure 33 Insert a Button in the GUI

To add a function to the button, please use the in-build function "controlP5", The syntax for the adding a function to the button is shown below in Figure 34. Please add the following function outside the traditional "void draw ()" function.

```
public void inverterON(int value){
println("Inverter 1 ON STAGE");
inv1status = "ON";
}
```

Figure 34 Writing Function for the Button

To add pictures to the GUI, please follow the syntax as mentioned in Figure 35.

```
bg = loadImage("C:/Software/NAPS/NAPS/September23/Recent2.jpg");
```

Figure 35 Syntax to load Program in the GUI

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