SMALL WIND TURBINE BASED PACKET ENERGY SYSTEM WITH BATTERY STORAGE

by

© Md Shakhawat Hossain

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ABSTRACT

In this thesis, an application of a grid connected small wind turbine with a battery based storage system is presented. Small wind turbine has been used to charge the battery, and the system connection to the grid is determined by the load dispatch center. Once the system is connected, it delivers power at full inverter rating. Therefore, it can be considered as a packet energy system. Such a system can profit from net metering and variable rate electricity which are available in some Canadian provinces. Energy storage system has been designed in HOMER. A control algorithm has been proposed and simulated in Matlab/Simulink with 3 case studies to investigate the impacts of different charging and discharging scenarios. Sizing and cost calculations indicate that such a system can be used by residents who are interested to generate profit from variable rate electricity. This research shows that a small wind turbine based packet energy system can make renewable energy sources more practical and supply energy on demand. The proposed energy system can take energy flow instructions from Smart Energy Dispatching Centers (SEDCs) and deliver power. The system has been modeled using low order transfer functions and energy packets have been generated by switching randomly. A prototype of the battery based energy storage system has been designed and implemented. Lab tests and simulation results indicate that the designed packet energy network system is able to provide energy packets as required by the grid. Additionally the simulation results show that the output power from a very large energy packet network will be stable with the existence of large load fluctuation.

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d_L - Lower energy demands from customer

d_U - Upper energy demands from customer

g_L- Lower energy generations

g_U - Upper energy generations

I_b - Battery charging current

W_s - Wind speed

P_{out} - Output power of the inverter

V_b - Battery voltage

C_{load} - Change of load

C_{PWM} - Change in PWM

List of Abbreviations

AMI - Automatic Metering Infrastructure

AMR - Automatic Meter Reading

CanWEA - Canadian Wind Energy Association

DFIG- Doubly Fed Induction generator

DG - Distributed Generation

DNO - Distribution Network Operator

EPN – Energy Packet Network

GPRS - General Packet Radio Service

GSM - Global System for Mobile Communications

IPS - Intelligent Power Switches

NIST - National Institute of Standards and Technology

NREL – National Renewable Energy Laboratory

PEV - Plug-In Electric Vehicle

PI – Proportional Integral

PMSG - Permanent Magnet Synchronous Generator

PWM – Pulse Width Modulation

SEDCs - Smart Energy Dispatching Centers

SG - Smart Grid

SOC – State of Charge

SOH – State of Health

WECS – Wind Energy Conversion System

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Chapter 1

Introduction

1.1 Background

Wind energy is one of the fastest growing major sources of electricity around the world. Canada’s geography makes it ideally suited to capitalize on large amounts of wind energy. Every Canadian province is now taking advantage of clean wind energy. Currently, Canada’s installed capacity is 7,803 MW with 184 wind farms and 4,376 wind turbines. About 3% of Canada’s domestic electricity demand is met by wind energy and it is equivalent to over 2 million Canadian household load [1].

The Canadian Wind Energy Association (CanWEA) believes that 20% of Canada’s electricity demand can be satisfied from wind energy by 2025. It is also expected that Canada’s wind energy sector will be a real player in a $1.8 trillion global wind industry by generating $79 billion of investment, creating at least 52,000 full-time jobs which will also include the rural communities, and producing $165 million in annual revenues for municipalities. This sector will help to add 55,000 MW of clean generating capacity that will strengthen the existing electrical grids. Wind energy can also cut Canada’s annual greenhouse gas emissions by 17 Megatons [2].

The quality of Canada’s wind resource is better than any of the world’s current leading wind energy nations such as Germany, Spain and the United States. Canada has higher quality wind power sites because of its landmass and long coastlines. Canada's total electricity demand can be met by tapping the wind potential of just one quarter of one percent of landmass.

Wind energy resources in the form of distributed generation (DG) are being integrated in power systems to increase power generation. Distributed generations not only provide grid support but also reduce carbon dioxide emission. Addition of renewable energy may create energy fluctuations within the power grid due to its unpredictable nature and intermittent output characteristics. Power electronic converters and energy storage systems are used as the interface between distributed generation and the grid to compensate for the unpredictable nature of renewable energy. Voltage and frequency regulation, load shifting and outage protection can be provided with the use of energy storage system.

Capital cost is the most important consideration in determining the economic feasibility of small-scale renewables with battery storage. Net metering allows customers to offset their electricity consumption with small-scale renewable generation over an entire billing period. Net metering uses a single bi-directional meter that registers the flow of electricity in both directions. With net metering, customers can also store energy during off-peak demand periods (overnight) and inject it back into the grid during periods of high electricity demand. This can also help to smooth the typical mountain and valley shape of the typical load curve.

The Smart Grid is considered as the next generation energy grid. Two-way flows of electricity and information make it a widely distributed and automated energy delivery network. Smart grid can also be defined as Energy Packet Network (EPN) by using the internet concepts in the existing grid. EPN offers smart management of energy flow. In the existing grid, there is instantaneous current flow towards the point of consumption. But in an energy packet network, energy will flow like a packet in the internet. An energy packet can be described as a pulse of power which lasts for a certain time. So, the unit of the energy packet is kWh. The flow of energy in an energy packet network is controlled by a Smart Energy Dispatching Center (SEDC), which is basically a computer control center.

Canada has good quality of wind resources and the uses of small wind turbines are increasing day by day. More focus on grid connected small wind turbine with battery based energy storage is needed. There should be more research to profit from net metering and variable rate electricity using the battery based energy storage system. It is also essential to improve the existing grid to cope with the new energy packet form of energy transfer using advanced metering infrastructure.

1.2 Literature Review

1.2.1 Wind turbine and energy storage systems

The application of wind energy has a very long history. New strategies are being adopted to increase the number of renewable energy sources and distributed generators in order to improve the stability and quality of the grid [3]. Normally, wind turbines use doubly fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG). Permanent magnet synchronous machines have higher efficiency, high power density, and robust rotor structure as compared to induction machines. Permanent magnet synchronous machines are more popular for small wind turbines. It has no rotor current. PMSG also reduces the weight of the nacelle and costs less as the system can be used without a gearbox [4]. A number of alternative concepts have been proposed for direct drive electrical generators which can be used in grid-connected or standalone wind turbines. In [5], the problem to adapt a small and standard permanent magnet (PM) synchronous machine for direct coupling to a small wind turbine is discussed. The analytical model of small permanent magnet synchronous machines is used with the terminal voltage characteristics and operating power capability of a small PM based wind turbine is examined to study the effect of the design parameter changes of the machine.

In [6], modeling of variable speed wind turbines in power system and its dynamics simulations is presented. The purpose of this model is to investigate the impact of large amounts of wind energy on the behavior of an electric power system with the help of power systems simulation software. In [7], a mathematical model of the standalone wind energy conversion system with battery storage was developed. The developed model was used to calculate the response of the system to a prerecorded wind gust. Data acquisition system was used to determine the actual response of the system. Then the measured response was compared with the actual response. Several methodologies for optimal design or unit sizing of stand-alone or grid-connected hybrid systems have been proposed in [8]–[11].

In [12], the authors have analyzed a residential wind and solar power system with storage during two years of operation. It also includes discussion on system reliability, power quality, loss of supply, and effects of the randomness of the wind and the solar radiation on the system design. A simulation package was developed for a wind–diesel–PV power system in [13].

In [14], dynamic modeling and control of a grid-connected wind–PV–battery hybrid system with versatile power transfer has been discussed. Stability and dispatchability of its power injection into the grid has been considered in this research. Three different modes have been discussed there. The modes are: normal operation without use of battery, dispatch operation, and averaging operation. The concept and principle of the hybrid system and its supervisory control are described as well.

The renewable energy based distributed generation systems are normally interfaced to the grid through inverter and energy storage systems. Rather than using fossil fuel, battery based energy storage can be used to provide fast frequency regulation, load following, and ramping services. Lithium-ion battery technology shows many advantages compared to lead-acid batteries and nickel-metal-hydride batteries. These batteries provide high power and energy density, high working cell voltage, low self-discharge rate, and high charge–discharge efficiency [15]–[19].

In [20], a grid connected lithium-ion battery energy storage system (BESS) has been implemented and its performance for load leveling and peak shaving has been investigated. Active and reactive power has been regulated with the help of implemented controller. This controller satisfies the system limits using the state of charge (SOC) of the battery. During the simulation in Matlab, BESS is connected to the grid through a long transmission line.

Table 1.1: Comparison of different SOC estimation schemes [21]

Technique	Summarized Features	Pros	Cons
Discharge	Discharge and measure time to a threshold	Most accurate	Offline & time consuming
Coulomb counting	Counting charges been injected/pumped	Easy	Loss model & need accuracy
Open circuit voltage	VOC-SOC look-up table	Accurate	Time consuming
Artificial network	Adaptive artificial neural network system	Online	Training data needed
Impedance	Impedance of the battery (RC combination)	SOC and SOH	Cost & temp-sensitive
DC resistance	R_{dc}	Easy	Only for low SOC
Kalman filter	Get accurate information out of data using filter	Dynamic	Large computing

Table 1.1 shows the comparison of different SOC estimation schemes. In [21], a high-efficiency grid-tie lithium-ion battery energy storage system has been discussed.

Coulomb counting and open-circuit voltage models have been used to estimate the state of charge of the battery. Charge equalization circuits have been controlled using the SOC information to mitigate the mismatch among the series connected battery cells. The proposed system has been validated by implementing a 1-kW prototype. From the experimental results, it is found that the system with SOC balancing has gained 33% more capacity than the system without SOC balancing when the SOC is maintained between 30% and 70%.

In [22], the authors created two models of typical remote Canadian communities using HOMER. This model has been developed to determine how a generic energy storage system could help to improve the economics of a high penetration wind diesel system.

From the literature review, it is found that various works have been done in wind energy based energy storage system. On the other hand, no works were found that incorporate the wind energy system to develop the energy packet network. More studies should be done to integrate the advanced metering infrastructure with the wind turbine and battery storage system to provide smart energy flow. The wind energy system can operate in real time with the use of advanced metering infrastructure.

1.2.2 Literature on the advanced metering infrastructure in smart grid

The smart grid is considered as the next generation energy grid. Two-way flows of both electricity and information make it a widely distributed and automated energy delivery network. Table 1.2 gives some ideas about the difference between the existing grid and the smart grid. The smart infrastructure system, the smart management system, and the smart protection system are the three major parts of smart grid [23].

Table 1.2: The comparison between the existing grid and the smart grid [24].

Existing Grid	**Intelligent Grid**
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

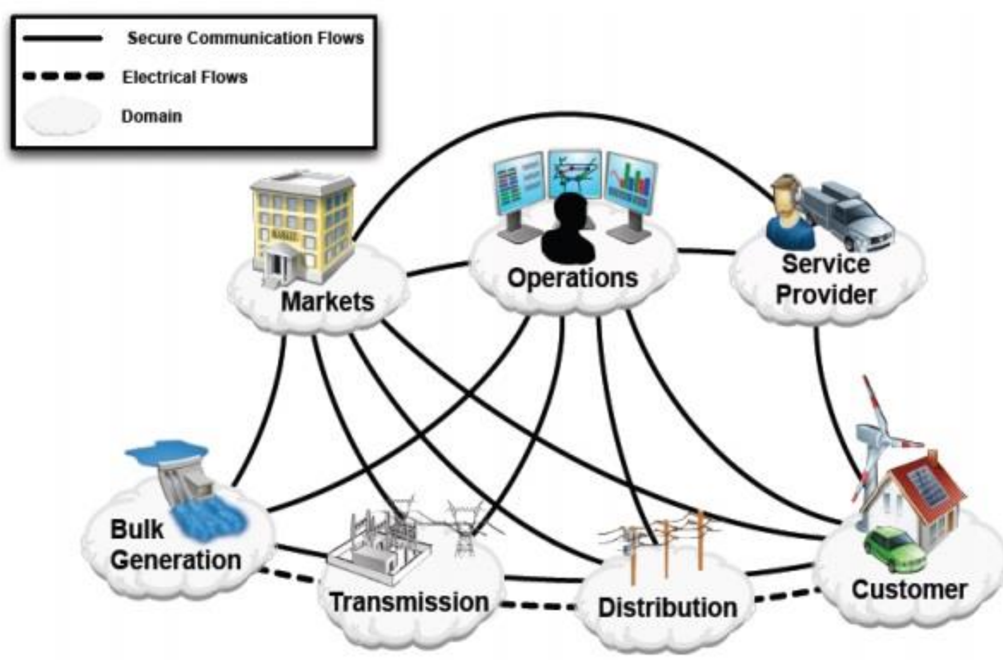

Figure 1.1: Interaction of actors in different smart grid domains [25]

National Institute of Standards and Technology (NIST) provided a conceptual model of smart grid as shown in the Figure 1.1. Smart grid has been divided into seven domains. The brief description of the domains and actors is given in Table 1.3. In general, all actors with similar objectives are in the same domain. However, communications between and within the same domain may require different communication protocols and mediums. Actors in one domain may require communicating with actors in another domain to enable the smart grid functionality and make it more reliable as shown in Figure 1.1.

The deployment of smart grid is not solely dependent upon the improvement of power equipment. It also depends on the improvement of computer monitoring, analysis, optimization, and control from smart energy dispatch center to the distribution and transmission grids. Therefore, a smart communication system is used to send and receive data in both directions.

Table 1.3 : Domains and Actors in the Smart Grid Conceptual Model [25]

Domain	**Actors in the Domain**
Customer	The end users of electricity. May also generate, store, and manage the use of energy.
Markets	The operators and participants in electricity markets
Service Provider	The organizations providing services to electrical customers and to utilities.
Operations	The managers of the movement of electricity
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity

Smart meter is one of the most important components used in the smart grid. Automatic metering infrastructure (AMI) systems [26] are widely regarded as a logical strategy to realize smart grid. Automatic meter reading (AMR) is the technology of automatically collecting diagnostic, consumption, and status data from energy metering devices. This technology also transfers the collected data to a central database for billing, troubleshooting, and analyzing. The difference between AMI and AMR is the two way communication between the meter and the grid. Because of this, all information is available in real time and on demand. This allows the smart grid to improve system operations and demand management.

Electricity meters are used to measure the quantity of electricity supplied to customers. Accumulation meter is the most common type of meter used. It records energy consumption over time. Meter readings are manually collected to assess how much energy has been used within a billing period. But recently, industrial and commercial consumers with large loads have increasingly been using more advanced meters, such as interval meters. It records energy usage over a short interval which is typically every 15 or 30 minutes. Energy suppliers can use this short interval data to design tariffs and charging structures. It will also help the customers to understand and manage their usage of electricity. As smart meters have two-way communications, they can provide a real-time display of energy use and pricing information, dynamic tariffs and facilitate the automatic control of electrical appliances.

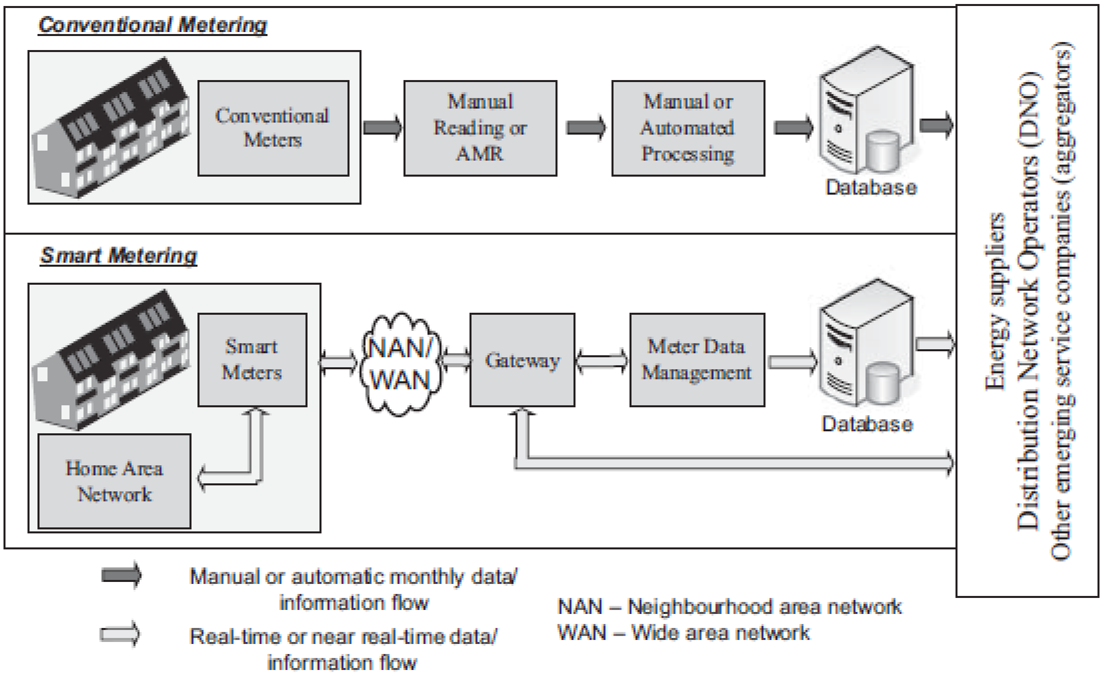

Figure 1.2: Comparison of conventional and smart metering [27]

The comparison between conventional metering and smart metering is shown in Figure 1.2. Smart meters have two-way communications to a Gateway and/or a Home Area Network (HAN) controller. Smart meter data is transferred to the energy suppliers, Distribution Network Operators (DNOs) and other emerging energy service companies through the gateway. They may receive meter data through a data management company or from smart meters directly. An existing smart meter can communicate with the following communication channels:

- Optical port – IR communication interface
- DLC modem
- GSM/GPRS communication interface with antenna
- RS 485 communication interface

- M-Bus communication interface

A smart meter can perform the following functions using these communication channels [28]:

- Collection of energy consumption information
- Reading of energy consumption information on request.
- Collection of supply quality information (e.g. sags, voltage measurements) of individual customers.
- Collection of information saved in profiles of individual customers and/or a (larger) number of customers.
- Collection of power failure duration information of individual customers and/or a (larger) number of customers.
- Setting and retrieving different tariff structures
- Retrieving device status.
- Remote connection and disconnection of the energy supply of individual customers.

Different companies are using different configurations in smart meter. But the basic working principle is more or less the same for all smart meters. A simplified block diagram of the smart meter is shown in Figure 1.3.

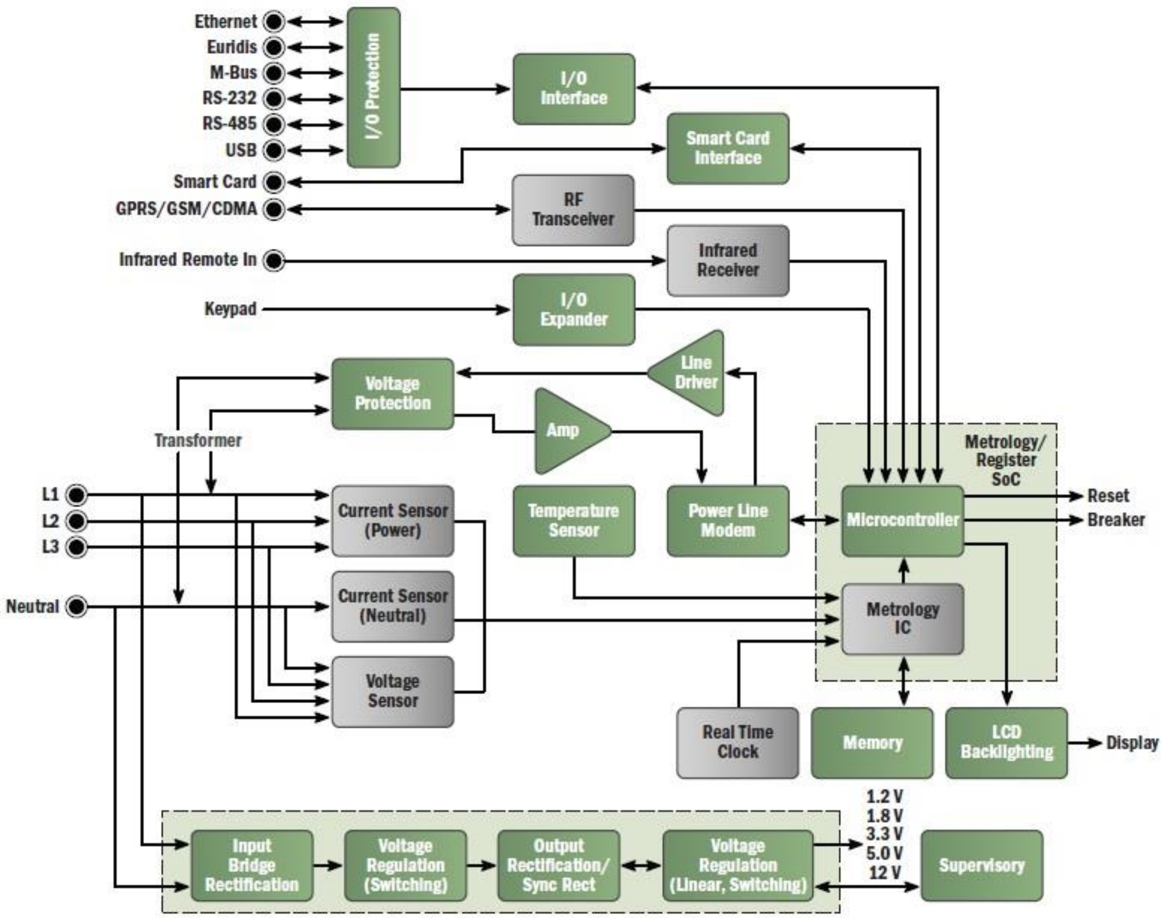

Figure 1.3: A simplified smart meter block diagram [29]

Smart meter data has been analyzed to focus on forecasting and load profiling in [30]–[34]. Some significant contributions in segmentation are made in [35]-[40]. In [38], self-organizing maps (SOM) and K-means are used to find load patterns from the smart meter data. Different clustering algorithms, such as hierarchical clustering, K-means, fuzzy K-means, and SOM are used to segment customers with similar consumption behavior in [37].

Smart meter data used in [41] is provided by Pacific Gas and Electric Company (PG&E). It contains the electricity consumption of residential PG&E customers at 1 hour intervals. There are 218,090 smart meters and the total number of 24 hour load profiles is 66434179. This paper proposes a different approach that decomposes the daily usage patterns into daily total usage and a normalized daily load shape. There is a lot of research being done to get information from smart meter data, which helps the control center to take decision about the energy production and demand side management.

From the literature review, it is found that most of the works have been done in analyzing smart meter data to make load profile and to forecast the load. No work has been done incorporating the battery storage status with the smart meter. Smart energy dispatch center can take updated status of the battery storage system using the smart meter. More studies should be done to use the smart meter with the storage system.

1.2.3 Literature on energy packet network (EPN)

In [42], a new model named "Energy packet networks (EPNs)" has been suggested. This EPN can store and forward energy units in quantized form to and from various devices. Some analogies have been shown here between energy request and distribution system and data networks. Energy packet network offers smart management of energy flow. Here, energy flows like a packet in the internet rather than the continuous instantaneous flow of current towards points of energy consumption. Energy packet can be described as a pulse of power which lasts for a certain time. So, the unit of the energy packet is kWh.

The duration of the energy packet is determined by the grid according to the requirement. The flow of energy in energy packet network is controlled by a Smart Energy Dispatching Center which is basically a computer control center. It tries to optimize the energy flows by making the best use of available renewable energy sources and existing pricing policies. In [43], the authors tried to identify the fundamental similarities and differences between the internet and the electrical grid. They also tried to identify areas where the grid can be made smarter and greener using internet concepts and technologies.

In [44], a new type of power system is proposed. Here, a wide-area synchronized power system is subdivided into smaller or medium sized cells. These cells are connected through asynchronous coordination control. By separating the power grid into cells, the fluctuations of renewable power can be managed within the cell. The fluctuations of one cell cannot affect other cells because each cell is separated by ac/dc/ac conversion. In this way, a digital grid can accept high penetrations of renewable energy. It can also help to prevent wide area blackout. If fault occurs in a line, power can flow through other paths because a number of such paths are available among cells.

In [45], plug-in vehicle charging has been proposed using charge packets which are analogous to discrete data packets used in communication system. Here, packetized charging breaks the required charge time into many small intervals or packets. A charge management coordinator device at the distribution substation determines whether additional load on the system can be served. If charging is not possible with existing resources, the PEV resubmits a request after a certain time. If charging is possible, the PEV will charge for the duration of the packet. PEV will submit new requests for subsequent packets until the battery is fully charged. Here it is also recommended that 5 seconds request interval and 5 seconds packet in length is superior in terms of both total cost and equal access.

An energy packet network can serve different purposes [42]:

- Provide real-time information about the requests on the one hand, and the sources of energy on the other.
- Schedule the flow of current to and from electricity storage units depending on the availability and demand.
- Real-time scheduling of energy demand so as to meet certain desirable objectives, e.g. scheduling electric heating in a large building.

In [46], the authors propose an electric power system with intelligent power switches (IPS) based on the Internet and micro-grid. Packetized energy is transferred from power sources to loads through IPS. In [47], the authors proposed two in-home power distribution systems. Information is added to the electric power distribution and electricity is distributed according to the supplied information. A switching circuit system based on alternating current (AC) power distribution and a switching circuit based on direct current (DC) power dispatching system via power packets are proposed. The drawback of this system is that it requires high power switching devices.

An internet-based energy provisioning concept has been proposed in [48]. Customers can order and request future power demands through a system called Online Purchase Electricity Now (OPEN). It will encourage customers to exactly order the electricity they need for consumption or storing locally. The paper indicates that reliability of the electric grid can be improved with this kind of virtual energy provisioning system. System concepts and implementation strategies are also discussed in the paper. Several methods have been proposed to represent the demand orders for the customers here as well.

From the literature review, it can be understood that energy packet network will play a vital role in future grid. Internet concepts are being used in smart grid to make it more reliable, secured and cost effective. As integration of renewable energy is increasing day by day, it is necessary to divide the whole system in some small blocks where every block can provide some fixed energy depending on the inverter specification. Thus, the energy dispatch center will know the updated status of each block to send the energy request for fixed duration rather than continuous energy flow. More research should be performed in a small wind turbine based energy packet network with battery storage to improve the existing system. This energy packet network will use the advance metering infrastructure to send updated information of the battery storage system to the smart energy dispatch center to provide smart energy flow.

1.3 Research Motivation and Objectives

The quality of Canada's wind resource is better than other leading wind energy nations of the world. In case of hydro, new dams and generators will be far away from consumers. It will also be more costly to develop. The same situation will be true for nuclear power. Higher construction costs for hydro and nuclear stations can only mean more expensive electricity. So, wind energy can be the best choice to produce electricity.

The blackout that occurred in central Canada and the north east United States in August 2003 made 50 million people to live without electricity for a certain time. This event also made the Ontario economy neutral for days as major industries waited for the grid to stabilize. That blackout demonstrated the fragility of the electricity system. During that blackout, a large generating plant in Ohio had shut down unexpectedly. Because of that unexpected shut down, 265 plants were also shut down. There have been several smaller blackouts since 2003. Three decades of under-investment in the transmission and distribution system and over reliance on centralized power generation can be considered as two main factors behind this problem. New and advanced transmission and distribution infrastructure can fix this kind of unwanted situation. Energy generation with storage should be spread broadly instead of relying on a few large power plants. Wind energy with battery storage fits perfectly into this scenario.

Net-metering is a program whereby eligible customers with renewable generation facilities can reduce their net energy costs by exporting surplus generated energy to the grid for credit against the energy the customer consumes from the grid. With the smart meter and variable electricity rates, some customers are able to take advantage of lower rates by switching some of energy use to mid- and off-peak periods. Canada was the world's 4th largest exporter of electricity in 2007 [49]. It has a long history of energy and electricity trade with the Americans. So exporting the electricity generated by the wind energy will create more opportunities for Canada. Research should be done in grid connected battery based energy storage system to make some profit using net metering concept and variable energy rate.

Smart grid is considered as the next generation energy grid. Two-way flows of both electricity and information make it a widely distributed and automated energy delivery network. From the literature review, it is found that smart grid can also be operated and controlled as an Energy Packet Network (EPN) by using the internet concepts in the existing grid. Presently, grid connected small wind turbine is used to generate electricity as a distributed generating source. Power flow of distributed generation can be controlled with the use of energy packet network. Small wind turbine based energy storage can be integrated into energy packet network with the use of smart meter. No work is found in the literature review related to this. The smart energy dispatch center can use the advanced metering infrastructure to get updated status of the energy storage with the use of communication channels of the smart meter. More studies should be done to examine the performance of the wind energy based storage system in energy packet network.

The objectives of this research are given below:

- To design a battery based energy storage system with a simple supervisory control algorithm to profit from net metering and variable rate electricity. Owners can make profit from this energy storage system depending on the peak and off-peak prices. Energy will be exported to the grid from the designed storage system to make profit from the distribution company.
- To design and implement a small prototype of this battery based energy storage system to visualize how such a system can work.
- To design and model a small wind turbine based packet energy system with battery storage. Wind turbines will charge the batteries depending upon wind availability. Smart energy dispatch center (SEDC) will send request to energy storage system through advanced metering infrastructure to provide energy packet for a fixed duration. The duration of the energy packet will be decided by the dispatch center depending on the energy demand from customers, load forecast and energy production. Each packet's magnitude will be the name plate rating of the grid-tie inverter. A SEDC will always have an updated status of the battery-inverter system that could supply energy packets. The proposed system will be modeled and simulated in Matlab/Simulink.
- To use the prototype of the battery based energy storage system to demonstrate the system and its ability to provide energy packets without any issue.

1.4 Thesis Organization

This thesis is written in the manuscript format according to the School of Graduate Studies of Memorial University of Newfoundland guidelines [50]. As the papers are dealing with closely related subjects, there exists a certain amount of overlap of the introductory material among the chapters.

In chapter two, energy storage system has been designed to profit from net metering and variable rate electricity rate available in some Canadian provinces. The variable rates in different time of a day are discussed here. The energy storage system has been designed in HOMER and a control algorithm has been proposed to investigate the impacts of different charging and discharging scenarios. The proposed control algorithm has also been simulated in Matlab/Simulink. This analysis includes 3 case studies with different electricity prices and battery state of charges. This chapter was accepted and published in the conference proceedings and presented in IEEE Newfoundland Electrical and Computer Engineering Conference (NECEC) 2013, St. John's, Newfoundland and Labrador, Canada.

The work of Chapter 2 is extended in Chapter 3, where a prototype of battery based energy storage system has been implemented. Here, MATLAB's Data Acquisition Toolbox (DAT) has been used. It allows MATLAB to acquire data from sensors and to send out electrical signals that can be used to control or drive external devices. DI-148U has been used to acquire the data from sensors. Legacy interface is used for DATAQ data acquisition hardware. Four analog input signals have been defined to measure the battery voltage, charging current, discharging current and the grid current from the experimental setup. The battery voltage, charging current, discharging current and the grid current are displayed during charging from the grid and discharging to the grid. It is shown that profit could be generated if we have an efficient energy storage system. This chapter has been accepted and presented in the IEEE Canadian Conference on Electrical and Computer Engineering (CCECE) 2014, Downtown Toronto, Ontario, Canada.

In chapter 4, a small wind energy system with battery storage has been simulated in Matlab/Simulink. The system has been modeled using low order transfer functions. Random switching has been done to get energy packets from the model. Large variable load with the presence of random fluctuations is applied in simulation to check the stability of the designed packet energy system. A prototype of the battery based energy storage system has been designed and implemented to demonstrate control to produce an energy packet. ActiveX control has been used to produce digital output from DI-148U which is used to control inverter’s on/off state. It is also shown that how energy packet network can be implemented using already available commercial technology. This chapter has been accepted for publication in the International Journal of Energy Science (IJES) 2014.

Summary of the research work, research contributions and future work have been included in chapter 5.

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Chapter 2

Design of an Energy Storage System to Profit from Net-Metering and Variable Rate Electricity

Preface

A version of this manuscript has been published in the conference proceedings of IEEE Newfoundland Electrical and Computer Engineering Conference 2013, St. John's, Newfoundland and Labrador, Canada. This paper has been presented in that conference. The co-author Dr. Tariq Iqbal supervised the first author Md. Shakhawat Hossain to develop the research and helped him to use the best possible way to implement the idea using existing techniques. Md. Shakhawat developed the model, conducted simulation, analyzed the results and wrote the paper while Dr. Iqbal reviewed the manuscript and provided necessary suggestions.

Abstract

This article analyses the application of battery-based storage system to profit from net-metering and variable rate electricity available in some Canadian provinces. By integrating some energy storage in a home, it is possible for customers to manage their energy consumption in response to energy prices variation over a day. In the present analysis the energy storage system has been designed in HOMER and a control algorithm has been proposed to investigate the impacts of different charging and discharging

scenarios. The proposed control algorithm has also been simulated in Matlab/Simulink. The analysis includes 3 case studies with different electricity prices and battery state of charges. From the simulation results it is found that the proposed control algorithm is able to control the battery energy system as required in a typical home. The outcome of this case study can be extended and used by residents who are interested to make profit from variable rate electricity.

Index Terms: Energy Storage System, Net-Metering, Variable Rate Electricity.

2.1 Introduction

Storage technologies have added some flexibility to energy systems. This technology is essential prerequisite for high penetration of stochastically variable renewable energy sources (RESs) [1]. Proper storage topologies, such as centralized or semi-centralized facilities, become a challenge to implement.

Battery-based energy-storage system for household-demand smoothening is considered to be the most promising one. Other storage technologies at distribution-grid level, such as flywheels, super-capacitors and superconducting magnetic energy storage are designed mainly for peak-power supply/storage [2]. An alternative to batteries could also be hydrogen-based energy-storage systems. But it is not used extensively due to their relatively high cost and low energy-storage efficiency compared to batteries [2]. For this reason batteries are conventional technologies widely used in commercial applications.

Their modularity [3] is one of the main factors to install them either at household or at distribution-feeder level. 30-45% decrease in the variability of the daily demand profile can be achieved when there is 1 kW of peak demand, with a battery system of 0.1 kW rated power and up to 0.6 kWh battery capacity [4].

Demand Side Response (DSR) under time-of-use tariffs [5] can be improved by using appliances after midnight, heating water at night and using technology that would automatically switch off appliances. This will compel consumers to be concerned about the unit price variations over the whole day. It would be more efficient for consumers to manage their energy consumption according to the energy prices by integrating energy storage with demand response.

Future intelligent grid technologies such as smart grids, smart metering, smart pricing, peak load curtailment, demand-side management may create uncertainty for consumers with regards to the price of power. With that technology, consumers will have control over their power consumption, decide when to purchase power and how much they consume. Utilities may decide peak and off-peak prices and increase them during power shortages [6]. Battery-based energy storage systems with effective energy management allow consumers to shift electricity purchases to reduce peak electric demand. It will also lower electricity cost and add value to intelligent grid technologies by minimizing cost-related uncertainty.

The purpose of this research is to design an energy storage system to profit from net metering and variable rate electricity. Net energy metering is common these days. Customers can generate power using renewable energy sources such as wind and solar to offset the cost of their electric usage with energy they export to the grid. A specially programmed smart meter is installed to measure the difference between electricity the customer purchases and exports to the grid. The energy will be exported to the grid from the designed storage system to make profit from the distribution company depending on the prices of the electricity.

2.2 Net-Metering and Variable Rate Electricity

2.2.1 Net-Metering

Net-metering is the electricity policy proposed to promote the generation of power from small renewable sources. Under net-metering, a system owner receives retail credit for all the electricity they generate unless they produce more electricity than they consume during any given billing period.

Under the net metering program, a smart meter is installed. It electronically tracks how much electricity is used and when it is used. This information is used with time-of-use pricing. Smart meters track the energy use in a home on an hourly basis. It also sends this information automatically to the local distribution company (LDC).

Smart meter has some advantages. It supports the implementation of time-of-use prices. By time-stamping the consumption data, local distribution companies can determine how much electricity was used during off-peak times and how much was consumed during on-peak periods. This capability allows consumers to find electricity savings by shifting their electricity use. Like internet connection, the smart meter is also connected into a wide computer network.

Many companies support the net metering program. Some companies are PG & E, SCE and SDG & E. The criteria below must be met to qualify for net energy metering program at PG & E [7].

- Generator size must be less than or equal to 1 MW.
- Generating system must be powered by an eligible renewable power source.
- No interconnection to a secondary network distribution line.
- Generating system components must be reviewed and approved by PG & E.
- Establishment of an electrical account with PG & E at the interconnection site.
- If another company supplies electricity, then the owner must contact that company about net energy metering.
- Owner needs to complete and supply all required documentation to PG & E.
- Owner needs to allow PG & E to inspect the system and install the required “net meter” accessible to a PG & E meter reader.
- Received written authorization from PG & E to operate in parallel.

The net energy metering (NEM) programs are given below [7]:

- **Standard NEM:** This is a solar and wind energy program for Residential and Small Commercial rate customers whose generator size is 30 kilowatts or less.

Table 2.1: Time-of-use price of Ontario Energy Board

Summer Rates			Winter Rates		
Period	Time	$/kWh	Price	Time	$/kWh
Off-peak	12am-7am	0.067	Off-peak	12am-7am	0.067
Mid-Peak	7am-11am	0.104	On-peak	7am-11am	0.124
On-peak	11am-5pm	0.124	Mid-Peak	11am-5pm	0.104
Semi-Peak	5pm-7pm	0.104	On-peak	5pm-7pm	0.124
Off-peak	7pm-12am	0.067	Off-peak	7pm-12.am	0.067

Table 2.2: Time-of-use price of SDG&E

<table>
<tr><th colspan="3">Summer Rates</th><th colspan="3">Winter Rates</th></tr>
<tr><td>Period</td><td>Time</td><td>$/kWh</td><td>Price</td><td>Time</td><td>$/kWh</td></tr>
<tr><td>Off-peak</td><td>10pm-6am</td><td>0.195</td><td rowspan="2">Semi-peak</td><td rowspan="2">6am-6pm</td><td rowspan="2">0.206</td></tr>
<tr><td>Semi-Peak</td><td>6am-11am</td><td>0.212</td></tr>
<tr><td>On-peak</td><td>11am-6pm</td><td>0.301</td><td rowspan="2">Off-peak</td><td rowspan="2">6pm-6am</td><td rowspan="2">0.197</td></tr>
<tr><td>Semi-Peak</td><td>6pm-10pm</td><td>0.212</td></tr>
</table>

- **Expanded NEM:** This is a solar and wind energy program for Agricultural and Demand Rate customers whose generator is of any size and for Residential and Small Commercial rate customers whose generator capacity is over 30 kilowatts
- **NEMVNMA:** This is a solar energy program only for customers living in low income multi-family affordable housing.

- **NEMBIO:** This program is only for customers with generators fuelled from an eligible biogas digester.
- **NEMFC:** This program is only for customers with eligible fuel cell generators.

2.2.2 TIME-OF-USE PRICES

With time-of-use prices, the price of electricity will depend on time of use. There are many different time-of-use prices. It varies according to the company and location.

Table 2.1 shows the rates from the Ontario Energy Board (OEB) website [8]. And Table 2.2 shows the rates from the SDG & E website [9].

With a smart meter and time-of-use rates, we are able to take advantage of lower rates by switching some of our energy use to mid- and off-peak periods. In [10], the authors try to devise a methodology for managing domestic electric energy consumption with storage devices in distribution networks. They investigate the impacts of different charging and discharging scenarios under three types of prices.

2.3 System Design in HOMER

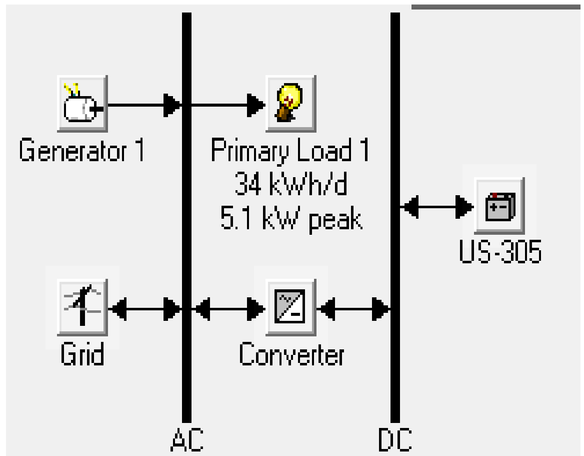

Figure 2.1: Energy storage system in HOMER

The proposed energy storage system has been designed in HOMER as shown in Fig. 2.1. In this section, HOMER, a computer model developed by National Renewable Energy Lab (NREL) and distributed by HOMER energy, is used to design the energy storage system. As the grid always charges the battery to 100% state of charge (SOC) in HOMER, here a diesel generator has been used to charge the battery. And the system is connected to the grid so that excess energy can be sold to the grid to make profit. On-peak and off-peak electricity rates used in this project is \$0.124/kWh and \$0.067/kWh respectively.

2.3.1 Generator Specification

As HOMER does not allow bidirectional energy storage, a 10 KW diesel generator shown as “Generator 1” in Fig 2.1 was added in HOMER to represent energy purchase from the grid. The capital cost and replacement cost is set to \$5495. The fuel price has been adjusted such that the price of electricity per kWh will be equal to the grid purchase price that means \$0.067/kWh. The fuel consumption is assumed to be 0.4 L/kWh, so the fuel price is 0.067(\$/kWh) / 0.4(L/kWh) = \$0.1675 /L.

2.3.2 Household load

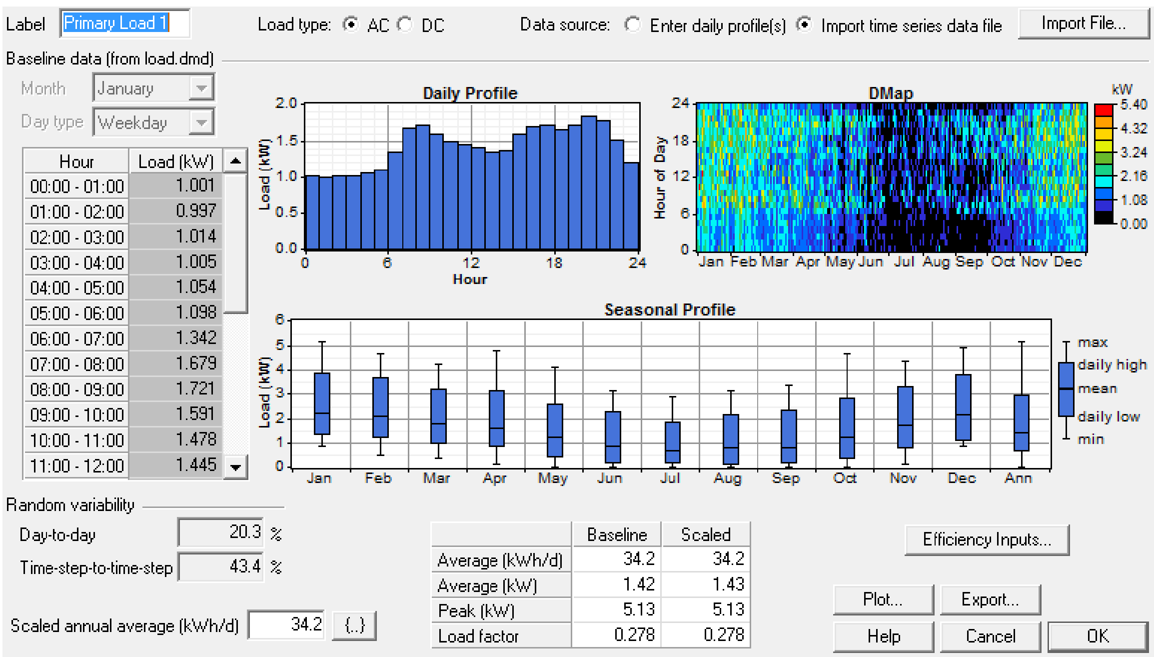

Figure 2.2: Household load used in HOMER

Fig. 2.2 shows the household load used in HOMER. The average load is assumed to be 34.2 kWh/d. The peak load and load factor is 5.13 kW and 0.278 respectively. This is shown as “Primary Load 1” in Fig 2.1.

2.3.3 Converter Specification

An 11.4 kW bidirectional converter has been used in HOMER, shown as “Converter” in Fig 2.1. The capital cost and replacement cost is set to $4,022. The lifetime and efficiency of the inverter output is set to 15 years and 85% respectively.

2.3.4 Battery Specification

6V 305Ah USB US-305 battery shown as “US-305” in Fig 2.1 has been used in the model. The capital cost and replacement cost is set to $234. And the O&M cost is $50 per year. Eight batteries are used per string to produce 48V DC bus.

2.3.5 Grid Specification

The grid purchase is set to 0 as the generator will charge the battery and serve the load when there is no enough energy in battery. Grid has been used only for selling excess energy.

2.3.6 System Control

Here cyclic charging has been used to charge the battery and serve the load. Set point state of charge is also set to 90%.

2.3.7 Optimization Result

From the optimization results it is found that approximately 17,435 kWh/yr. energy is needed to buy from grid to serve the household load of 12,483 kWh/yr. using 4 strings of batteries (8 batteries per string) due to the efficiency of battery and inverter. The efficiency of battery and inverter is 80% and 85% respectively. So it can be said that if the battery is charged at low price period to serve the load when electricity price is high, then 12,483×0.124 – 17,435×0.067 = $380/yr. (approx.) can be earned only from the household load. We can also earn by selling electricity to the grid during the high price period by increasing the number of batteries depending on the owner's decision.

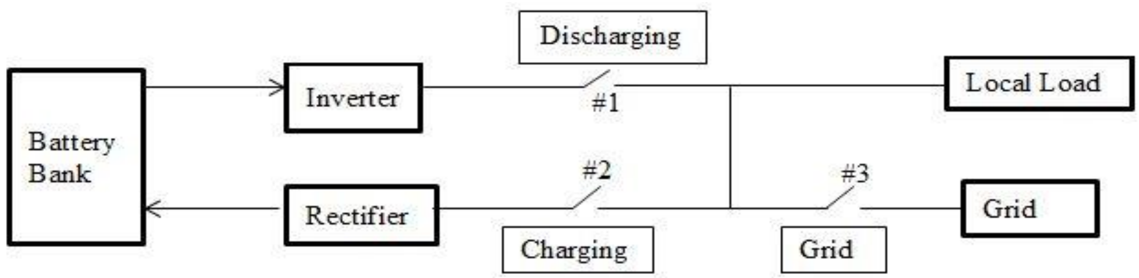

Figure 2.3: Block diagram of the designed energy storage

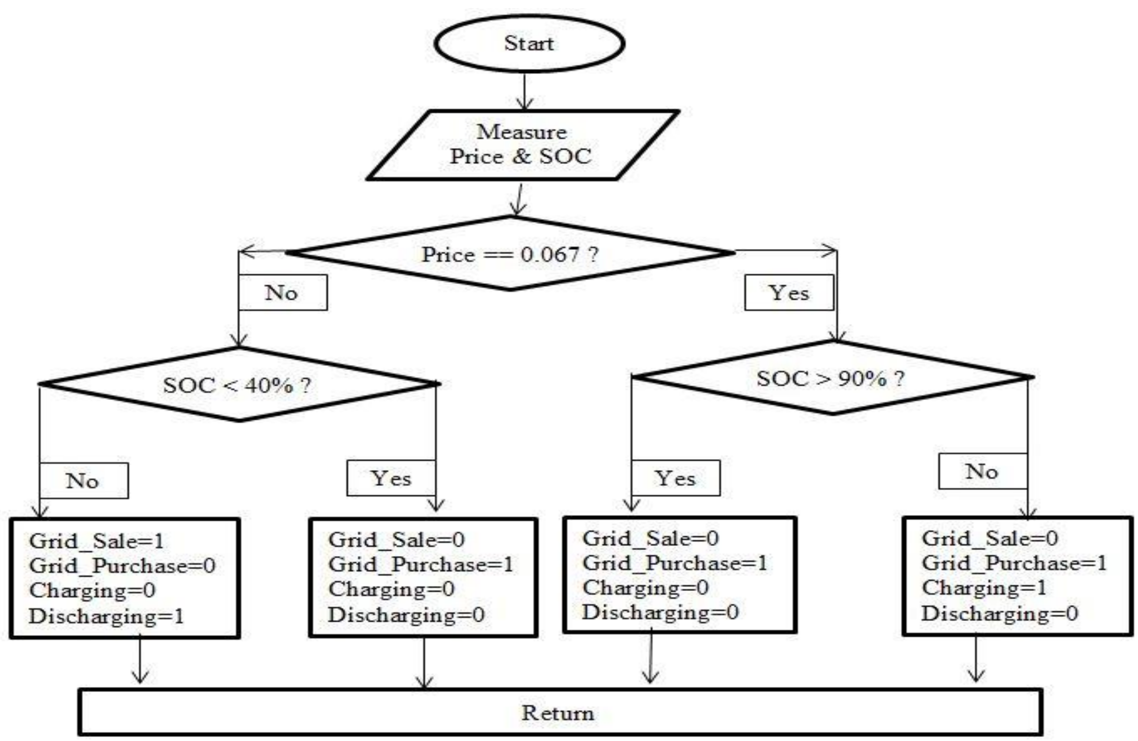

Figure 2.4: Control algorithm of energy storage system

2.4 System Design and Control in Matlab/Simulink

Block diagram of the designed energy storage system is shown in Fig. 2.3. The control algorithm according to the designed energy system is shown in Fig. 2.4.

In the control algorithm electricity price and state of charge (SOC) of the battery will be measured. Then different actions will be taken by checking various conditions. Depending on the values of electricity price and SOC of the batteries, control value of four circuit breakers will be generated. Battery will be charged when charging is 1 and discharged when discharging is 1 and vice versa. The algorithm has been implemented through the m code in Matlab.

The battery storage system has been implemented in Matlab/Simulink with the proposed control algorithm to control the charging and discharging of the battery from and to the grid. It also controls the load connection with battery and grid. Fig. 2.5 shows the designed energy storage system modeled in Matlab/Simulink. Fig. 2.6 shows the grid model used in energy storage system model.

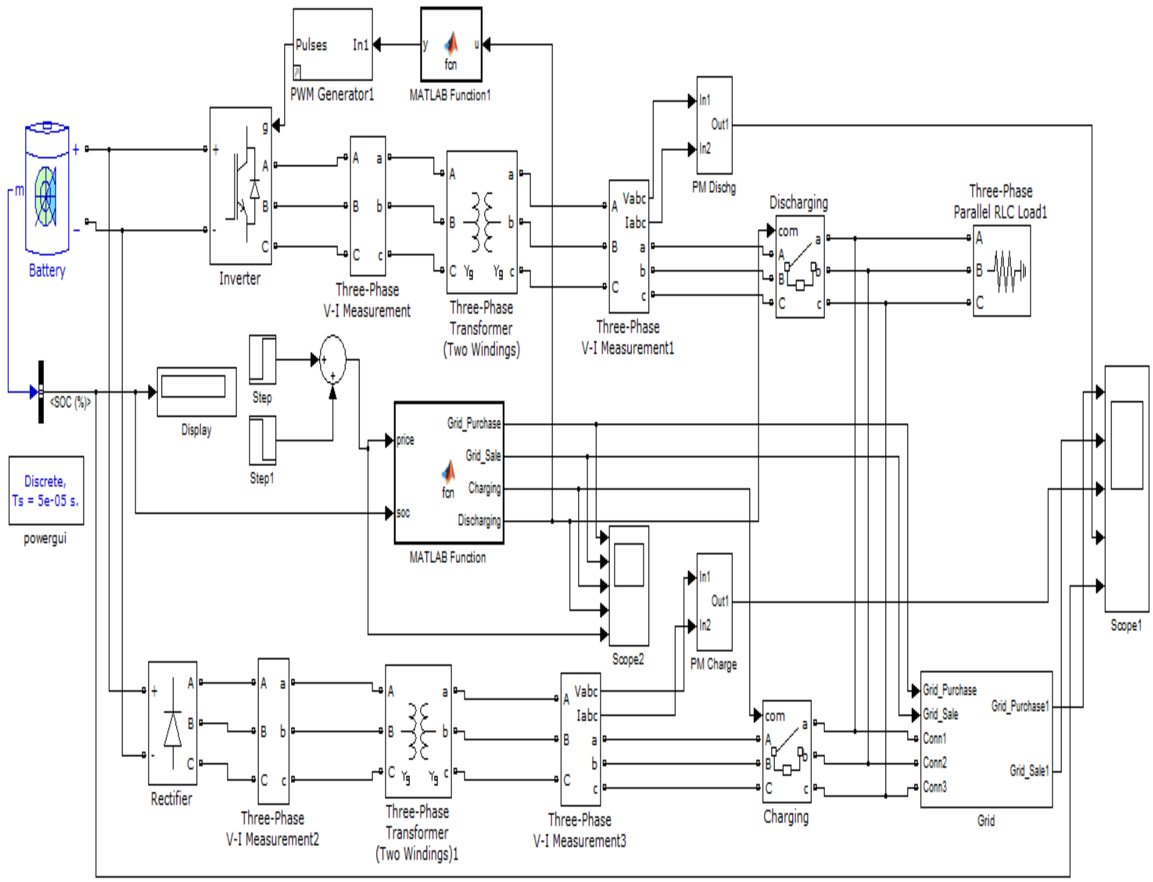

Figure 2.5: Energy Storage System Model in Simulink

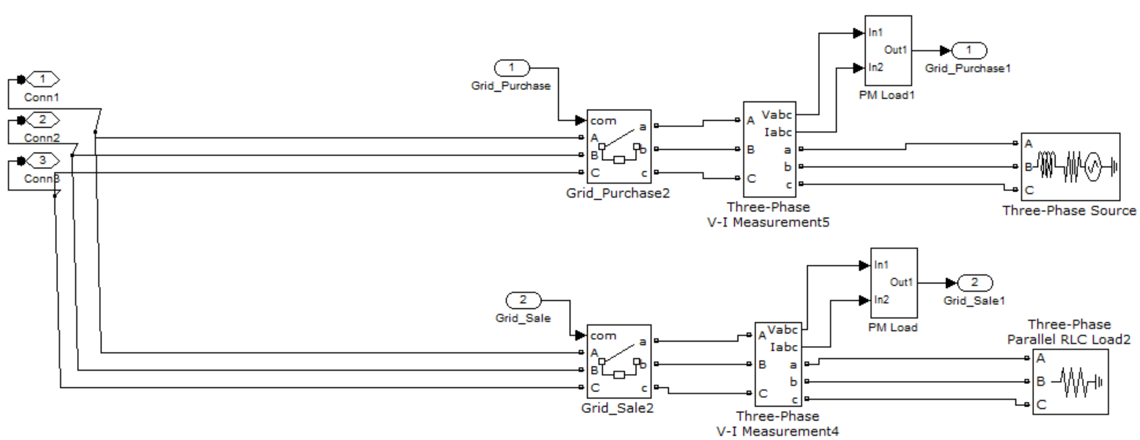

Figure 2.6: Grid Model in Simulink

2.5 Simulation Results & Discussion

The proposed control algorithm has been investigated with the designed energy storage system in Matlab for three cases.

2.5.1 Case 1: when SOC = 30%

Fig. 2.7 shows values of the control variable with different electricity prices when battery state of charge is 30%. Battery will be charged from the grid and household load will be connected to the grid when the electricity price is low. Battery is not allowed to be discharged during that time. But during higher price battery is disconnected from the grid and only household load will be connected to the grid as battery has no sufficient energy. Fig. 2.8 shows the power flow from/to battery and grid depending on the control values when battery state of charge is 30%

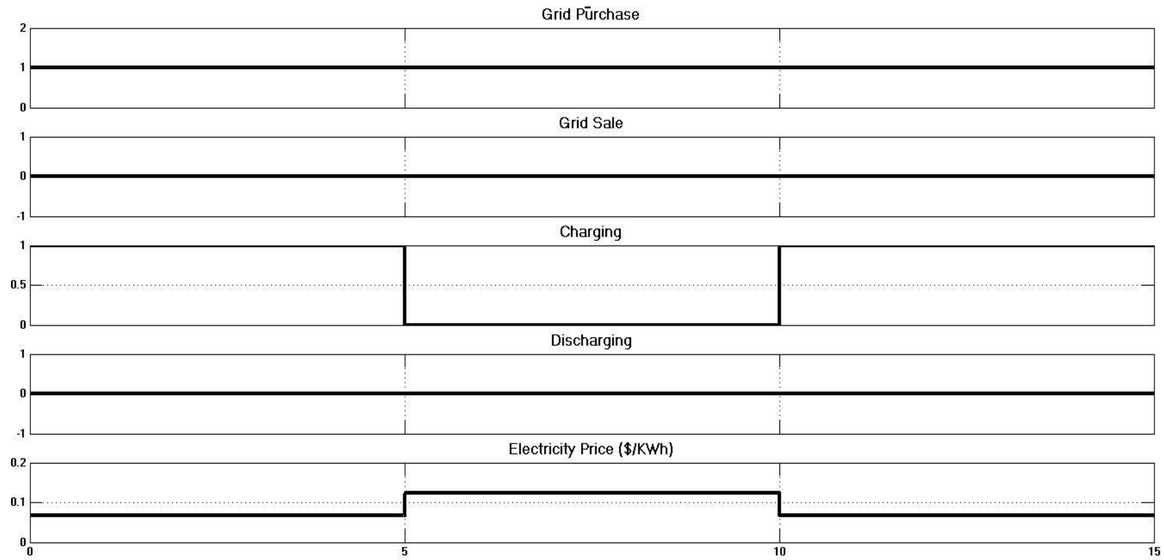

Figure 2.7: Control Values with respect to time for SOC=30%

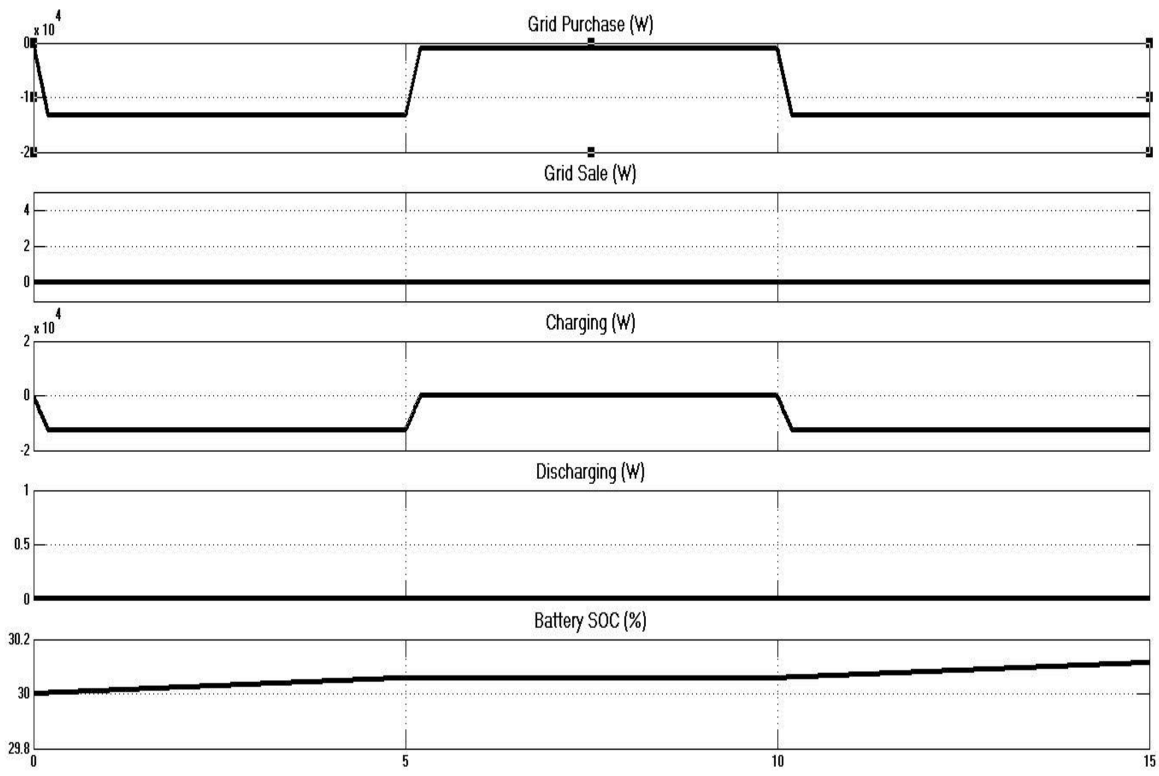

Figure 2.8: Power flow with different electricity rates with respect to time when

SOC=30%

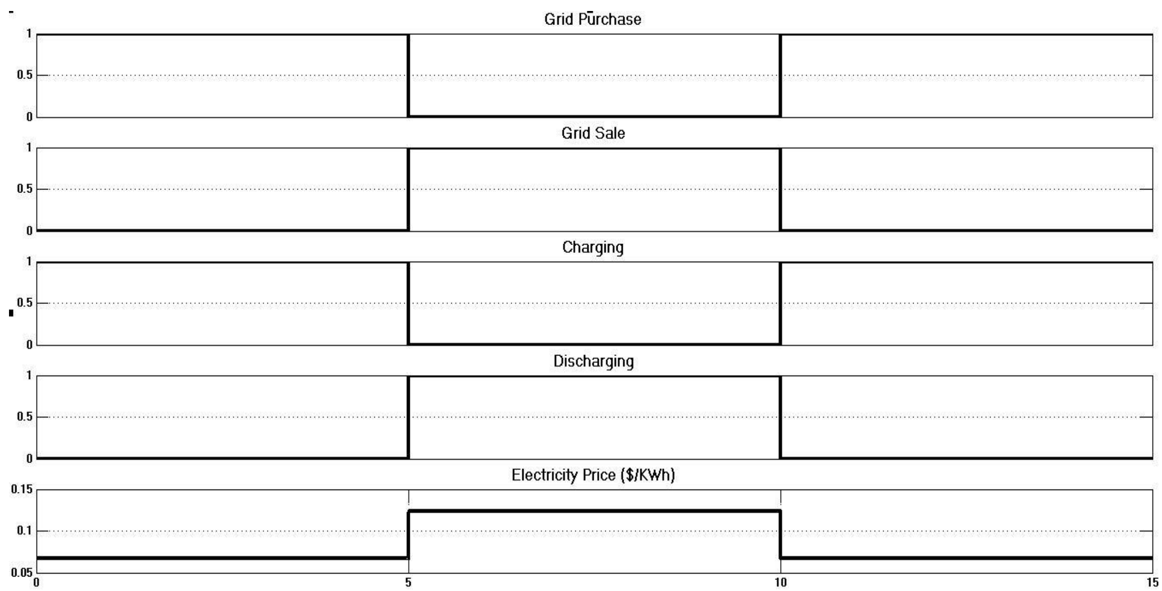

Figure 2.9: Control values with respect to time for SOC=75%

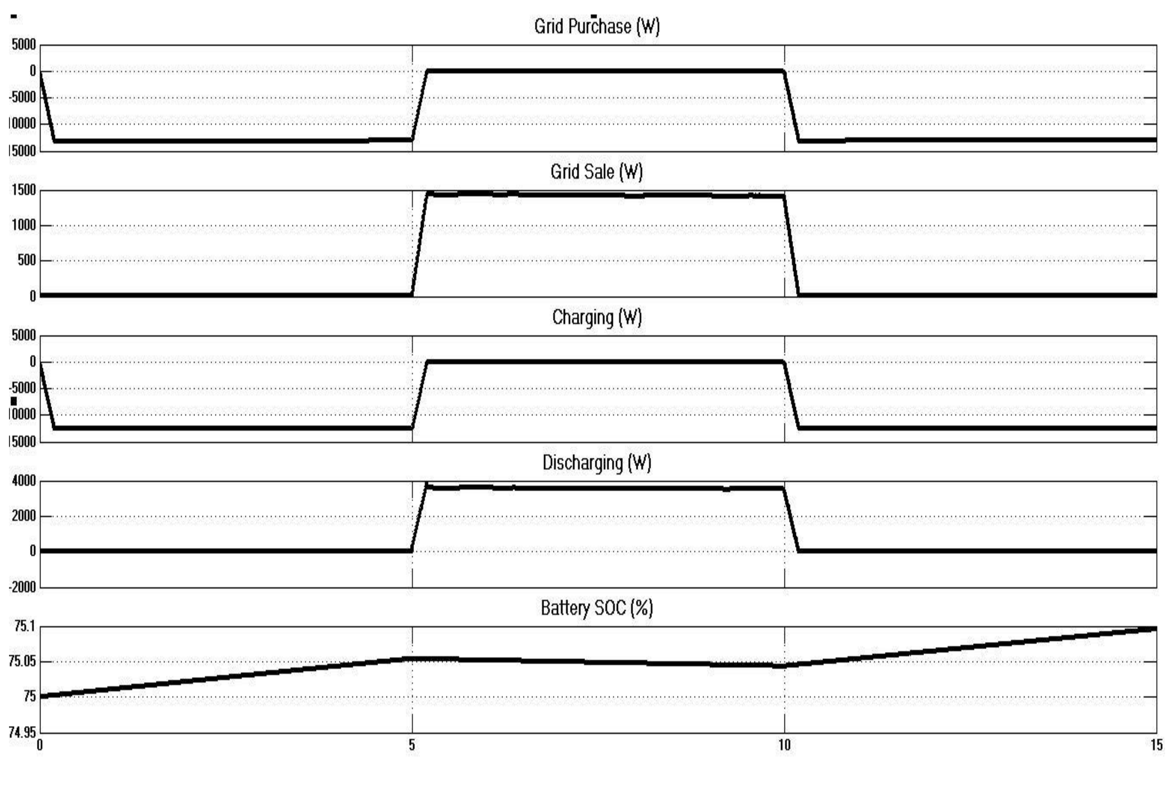

Figure 2.10: Power flow with different electricity rates with respect to time when

SOC=75%

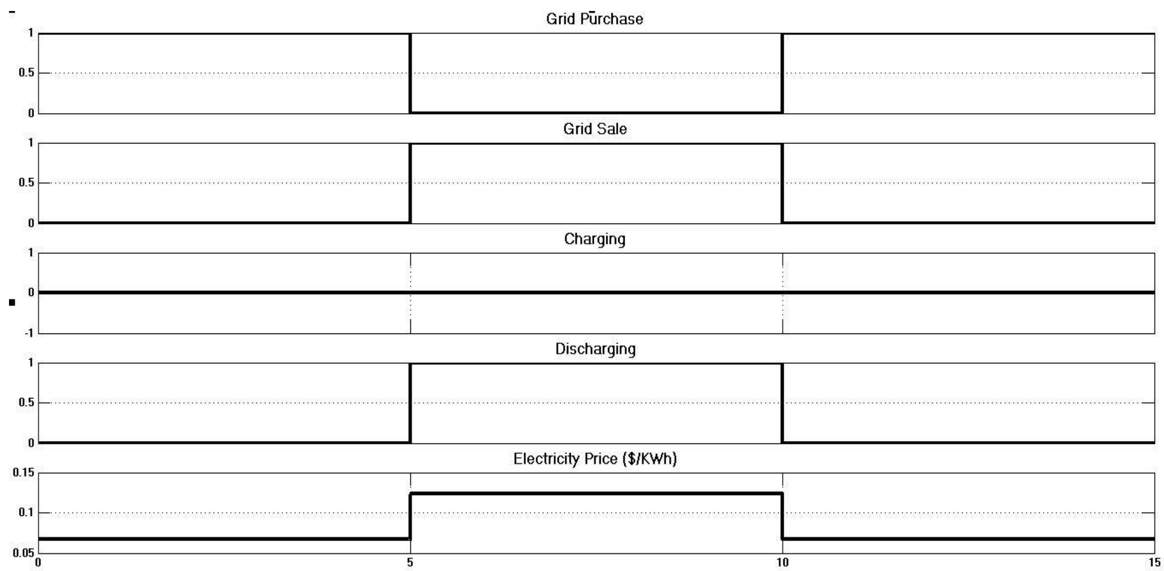

Figure 2.11: Control Values with respect to time for SOC=95%

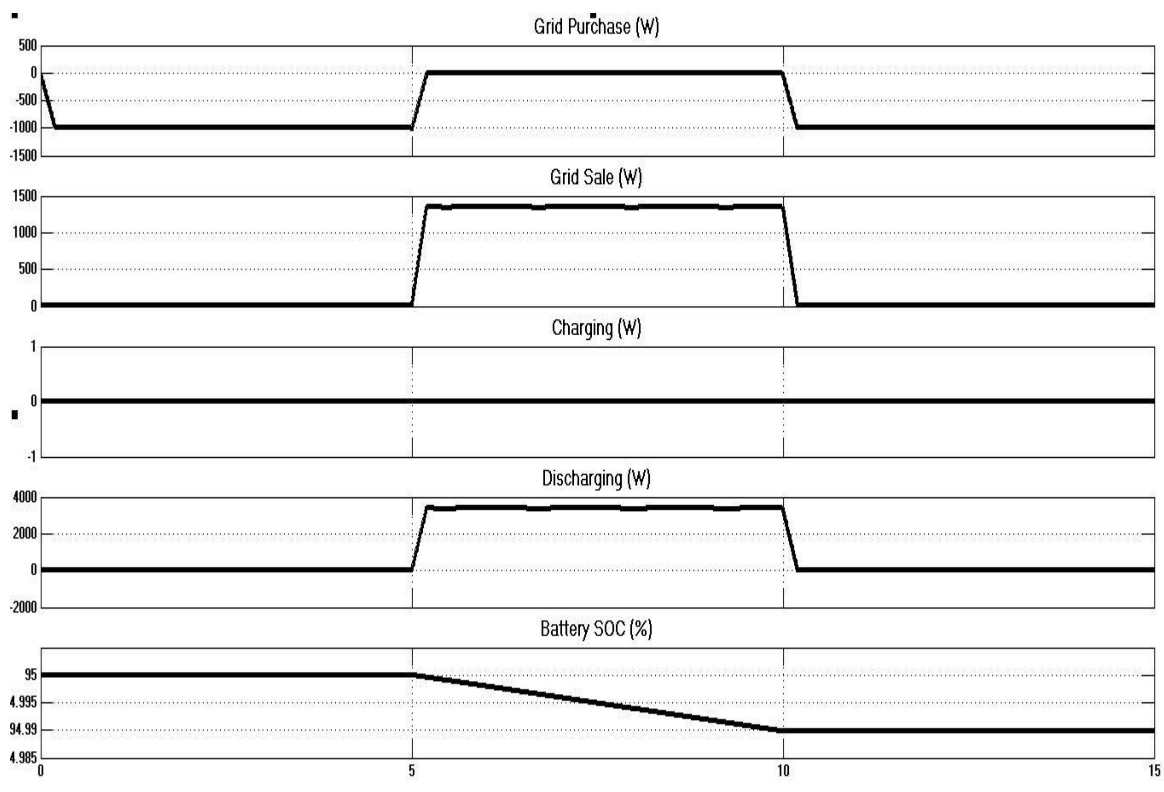

Figure 2.12: Power Flow with different electricity rates with respect to time when SOC=95%

2.5.2 Case 2: when SOC = 75%

Fig. 2.9 shows the control variable values with different electricity prices when battery state of charge is 75%. Battery will be charged from the grid and household load will be connected to the grid when the electricity price is low. Battery is not allowed to be discharged during that time. But during higher price battery is discharged to sell electricity to the grid and to serve the household load as battery has sufficient energy. Fig. 2.10 shows the power flow from/to battery and grid depending on the control values when battery state of charge is 75%.

2.5.3 Case 3: when SOC = 95%

Fig. 2.11 shows the control variable values with different electricity prices when battery state of charge is 95%. During low price battery will not be charged from the grid as battery SOC is already 95% and household load will be connected to the grid. Battery is not allowed to be discharged when price is low. But during higher price battery is discharged to sell electricity to the grid and to serve the household load as battery has sufficient energy. Fig. 2.12 shows the power flow from/to battery and grid depending on the control values when battery state of charge is 95%.

Fig. 2.7 to Fig. 2.12 show that the designed battery storage system would work. Fig. 2.4 shows a supervisory controller which is a simple on/off controller. A microcontroller can be used as a supervisory controller. And as mentioned above the proposed energy storage system will make a profit of about $380/yr.

2.6 Conclusion

This paper discusses the battery based energy storage systems to profit from net metering and variability of electricity price. An energy storage system has been designed in HOMER. Results obtained from HOMER indicate that profit can be made from this energy storage system depending on the peak and off-peak electricity prices. Owners can make more profit by installing more battery and selling more electricity to the grid. A control strategy has been proposed to manage the proposed battery energy storage system. With this control algorithm consumers can decide when to purchase power and how much they consume from the utilities depending on the peak, off-peak prices and battery state of charge. During peak hours consumers can use power from their energy storage and export the power to the grid to make profit. And during off peak consumers can use power from grid and store the energy to the energy storage. This control algorithm has been implemented in Matlab/Simulink. Simulation results show that the proposed control algorithm is able to manage the battery energy storage system.

2.7 Acknowledgement

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Chapter 3

Grid Connected Energy Storage System to Profit from Net-Metering and Variable Rate Electricity

Preface

A version of this manuscript has been published in the conference proceedings of IEEE Canadian Conference on Electrical and Computer Engineering (CCECE) 2014, Toronto, Ontario, Canada. This paper has been presented in that conference. The co-author Dr. Tariq Iqbal supervised the first author Md. Shakhawat Hossain to develop the research and helped him to use the best possible way to implement the idea using existing techniques. Md. Shakhawat implemented the setup, conducted the experiments, analyzed the results and wrote the paper while Dr. Iqbal reviewed the manuscript and provided necessary suggestions. There exists certain amount of overlap of the introductory material as the work of chapter 2 is extended in chapter 3.

Abstract

This article analyses an application of a grid connected battery-based storage system to profit from net-metering and variable rate electricity available in some Canadian provinces. It is possible for customers to manage their energy consumption in response to energy prices variation over a day by integrating an energy storage system in a home. In the present analysis a prototype of the battery based energy storage system has been

designed and implemented. A control algorithm has been proposed to investigate the impacts of different charging and discharging scenarios. The proposed control algorithm is able to control the battery energy system as required in a typical home. Sizing and cost calculations indicate that such a system can profit from variable rate electricity. The outcome of this case study can be extended and used by residents who are interested to generate profit from variable rate electricity.

3.1 Introduction

Storage technologies have added some flexibility to energy systems. Such technologies are essential prerequisite for high penetration of stochastically variable renewable energy sources (RESs) [1]. Proper storage technologies, such as centralised or semi-centralised facilities, are a challenge to implement.

Battery-based energy-storage system for household-demand smoothening is considered to be the most promising one. Other storage technologies at distribution-grid level, such as flywheels, super-capacitors and superconducting magnetic energy storage are designed mainly for peak-power supply/storage [2]. An alternative to batteries could also be hydrogen-based energy-storage systems. But It is not used extensively due to their relatively high cost and low overall efficiency compared to batteries [2]. For this reason batteries are widely used in commercial applications. Their modularity [3] is one of the main factor to install them either at household or at distribution-feeder level. A 30-45% decrease in the variability of the daily demand profile can be achieved when there is 1 kW of peak demand, with a battery system of 0.1 kW rated power and up to 0.6 kWh battery capacity [4].

Demand Side Response (DSR) under time-of-use tariffs [5] can be improved by using appliances after midnight, heating water at night and using technology that would automatically switch off appliances. It would be easy for consumers to manage their energy consumption according to the energy prices by integrating energy storage system.

Future intelligent grid technologies such as smart grids, smart metering, smart pricing, peak load curtailment, demand-side management may create uncertainty for consumers with regards to the price of energy. With a storage system consumers will have control over their power consumption, decide when to purchase power and how much they consume. Utilities may decide peak and off-peak prices and increase them during power shortages [6]. Battery based energy storage systems with effective energy management allow consumers to shift electricity purchases to reduce peak electric demand. It will also lower electricity cost and add value to intelligent grid technologies minimising cost-related uncertainty. Our earlier work [7] presented simulation based results. For this research, the battery based energy storage system has been designed in HOMER and a control algorithm has been implemented in Matlab/Simulink.

The objective of this research is to design and implement a prototype of battery-based energy storage system to profit from net metering and variable rate electricity. Variable rate energy metering is common these days. Customers can generate power using renewable energy sources such as wind, solar etc. to offset the cost of their electricity usage with energy they export to the grid. A specially programmed smart meter is installed to measure the difference between electricity the customer purchases and exports to the grid. The energy will be exported to the grid from a storage system to profit from the variable prices of the electricity.

3.2 Net-Metering and Variable Rate Electricity

3.2.1 Net-Metering

Net-metering is a policy proposed to promote the generation of power from small renewable systems. Under net metering, a system owner receives retail credit for all the electricity they generate when they produce more electricity than they consume during any given billing period.

Under the net metering program, a smart meter is installed. It electronically tracks how much electricity is used and when it is used. This information is used with time-of-use pricing. Smart meters track the energy use in a home on an hourly basis. It also sends this information automatically to the local distribution company (LDC).

Smart meter has some advantages. It supports the implementation of time-of-use prices. By time-stamping the consumption data, local distribution companies can determine how much electricity was used during off-peak times and how much was consumed during peak periods. This capability allows consumers to find electricity savings by shifting their electricity use. A smart meter can also be connected into a wide computer network.

Many companies support the net metering program. Some companies are PG & E, SCE and SDG & E. A criteria must be met to qualify for net energy metering program at PG & E [8].

Some net energy metering (NEM) programs are given below [8]:

- **Standard NEM:** This is a solar and wind energy program for Residential and Small Commercial rate customers whose generator size is 30 kilowatts or less.
- **Expanded NEM:** This is a solar and wind energy program for Agricultural and Demand Rate customers whose generator is of any size and for Residential and Small Commercial rate customers whose generator capacity is over 30 kilowatts
- **NEMVNMA:** This is a solar energy program only for customers living in low income multi-family affordable housing.
- **NEMBIO:** This program is only for customers with generators fuelled from an eligible biogas digester.
- **NEMFC:** This program is only for customers with eligible fuel cell generators.

3.2.2 Time-of-Use Prices

With time-of-use prices, the price of electricity depends on time of use. There are many different time-of-use schemes. It varies with the company and location.

Table. 3.1 shows the rates from the Ontario Energy Board (OEB) website [9]. And table. 3.2 shows the rates from the SDG & E website [10].

Table 3.1: Time-of-use price of OEB

Summer Rates			Winter Rates		
Period	Time	$/kWh	Price	Time	$/kWh
Off-peak	12am-7am	0.067	Off-peak	12am-7am	0.067
Mid-Peak	7am-11am	0.104	On-peak	7am-11am	0.124
On-peak	11am-5pm	0.124	Mid-Peak	11am-5pm	0.104
Semi-Peak	5pm-7pm	0.104	On-peak	5pm-7pm	0.124
Off-peak	7pm-12am	0.067	Off-peak	7pm-12.am	0.067

Table 3.2: Time-of-use price of SDG&E

Summer Rates			Winter Rates		
Period	Time	$/kWh	Price	Time	$/kWh
Off-peak	10pm-6am	0.195	Semi-peak	6am-6pm	0.206
Semi-Peak	6am-11am	0.212			
On-peak	11am-6pm	0.301	Off-peak	6pm-6am	0.197
Semi-Peak	6pm-10pm	0.212			

With a smart meter and time-of-use rates, some customers are able to take advantage of lower rates by switching some of energy use to mid- and off-peak periods. In [11] the authors try to devise a methodology for managing domestic electric energy consumption with storage devices in distribution networks. They investigate the impacts of different charging and discharging scenarios under three types of prices.

3.3 System Design in HOMER and Matlab/Simulink

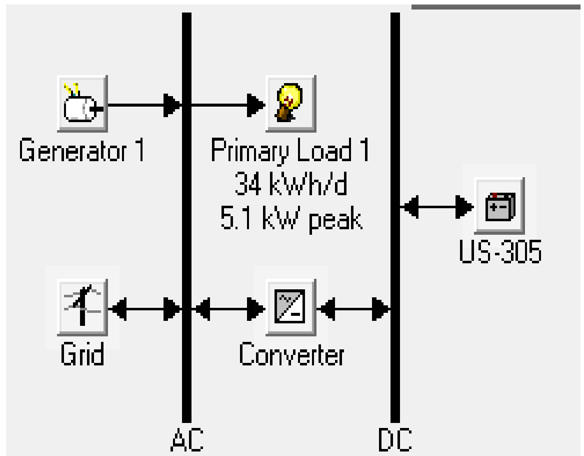

Figure 3.1: Energy Storage system in HOMER [7]

HOMER, a computer model developed by National Renewable Energy Lab (NREL) and distributed by HOMER energy, was used to design the energy storage system. The proposed energy storage system has been designed in HOMER as shown in Fig. 3.1. As the grid always charges the battery to 100% state of charge (SOC) in HOMER, here a diesel generator was used to charge the battery. And the system is connected to the grid so that excess energy can be sold to the grid to generate profit. Peak and off-peak electricity rates used in this study are \$0.124 /kWh and \$0.067/kWh respectively. Sizing details can be found in [7]. A simple energy calculation showed that a customer can generate \$380/year using the designed system.

Fig. 3.2 shows the block diagram of the designed energy storage system. Fig. 3.3 is the control algorithm flow chart for the designed energy system.

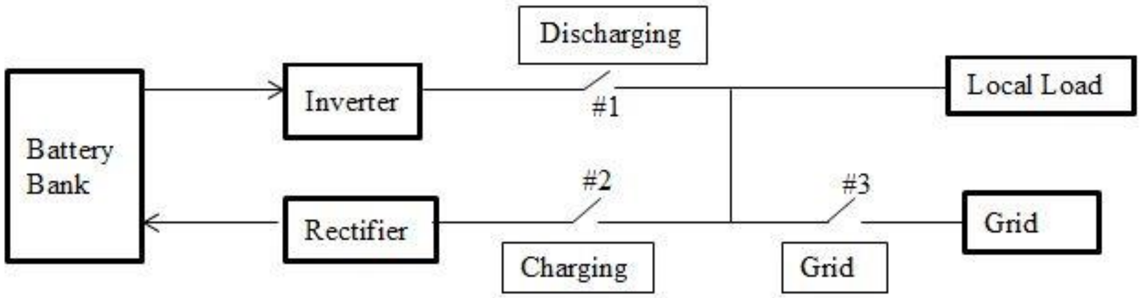

Figure 3.2: Block diagram of the designed energy storage

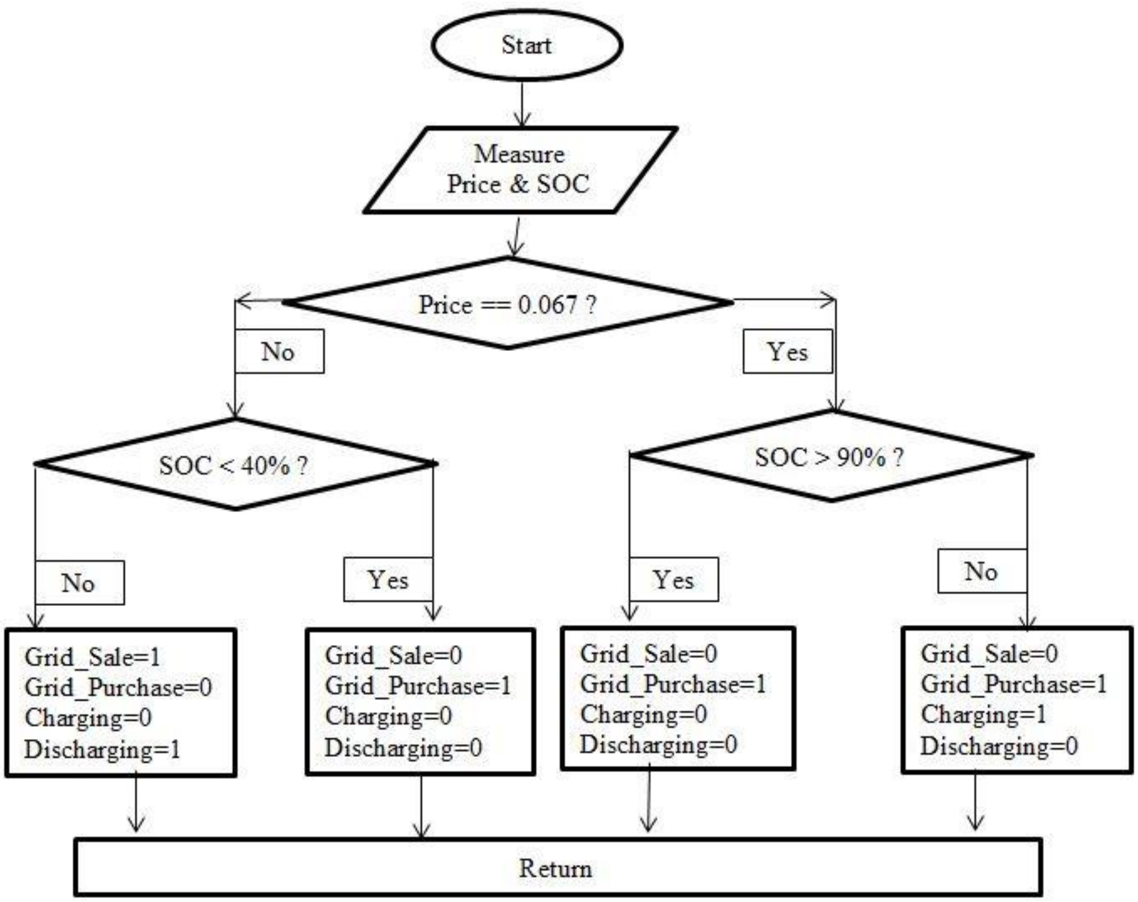

Figure 3.3: Control algorithm of energy storage system

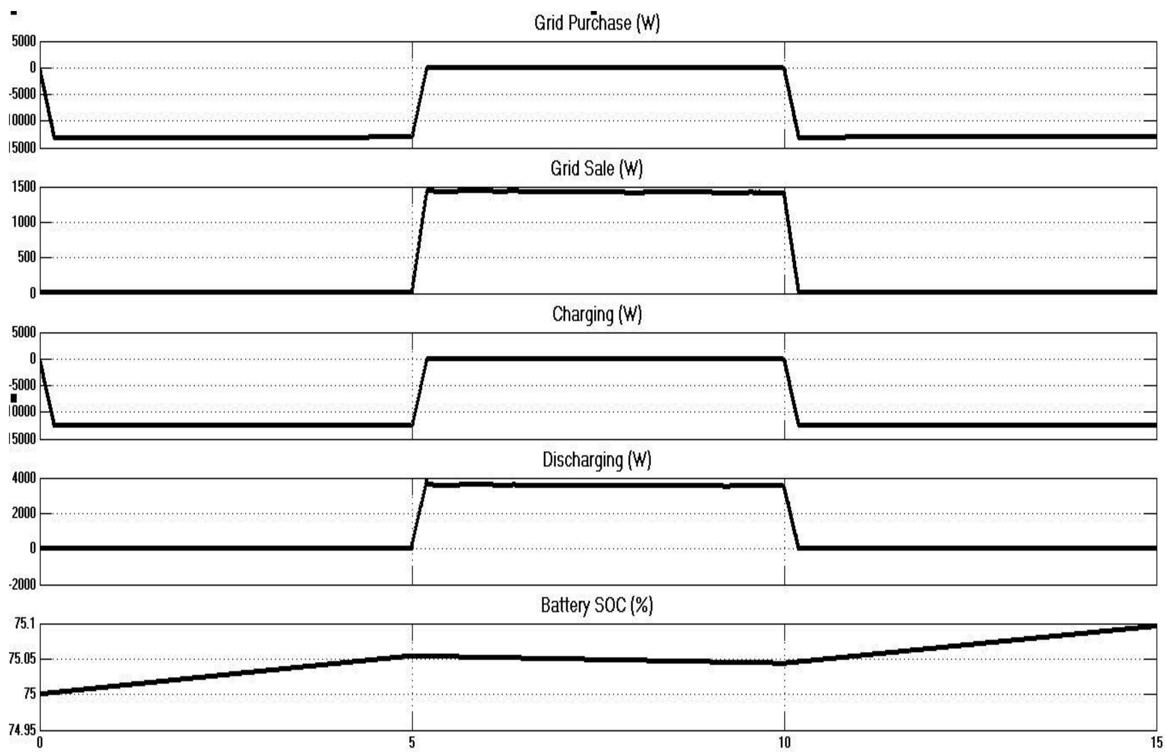

Figure 3.4: Power flow with different electricity rates when SOC=75%

In the control algorithm electricity price and state of charge (SOC) of the battery is measured. Then different actions are taken by checking the system conditions. Depending on the electricity price and SOC of the batteries, the control value of three circuit breakers (shown as #1, #2 and #3 in Fig. 3.2) will be generated. The battery will be charged when charging is 1 and discharged when discharging is 1 and vice versa. The algorithm has been implemented through the m code in Matlab [7]. Fig. 3.4 shows the power flow from/to battery and grid depending on the control values when the battery state of charge is 75%. Here the electricity rate has been changed from low to high and high to low in every 5 seconds for simulation purpose. The battery will be charged from the grid and household load will be connected to the grid when the electricity price is low. The battery is not allowed to be discharged during that time. But during higher price the battery is discharged to sell electricity to the grid and to serve the household load as the battery has sufficient energy.

3.4 Implementation of Battery-Based Storage System

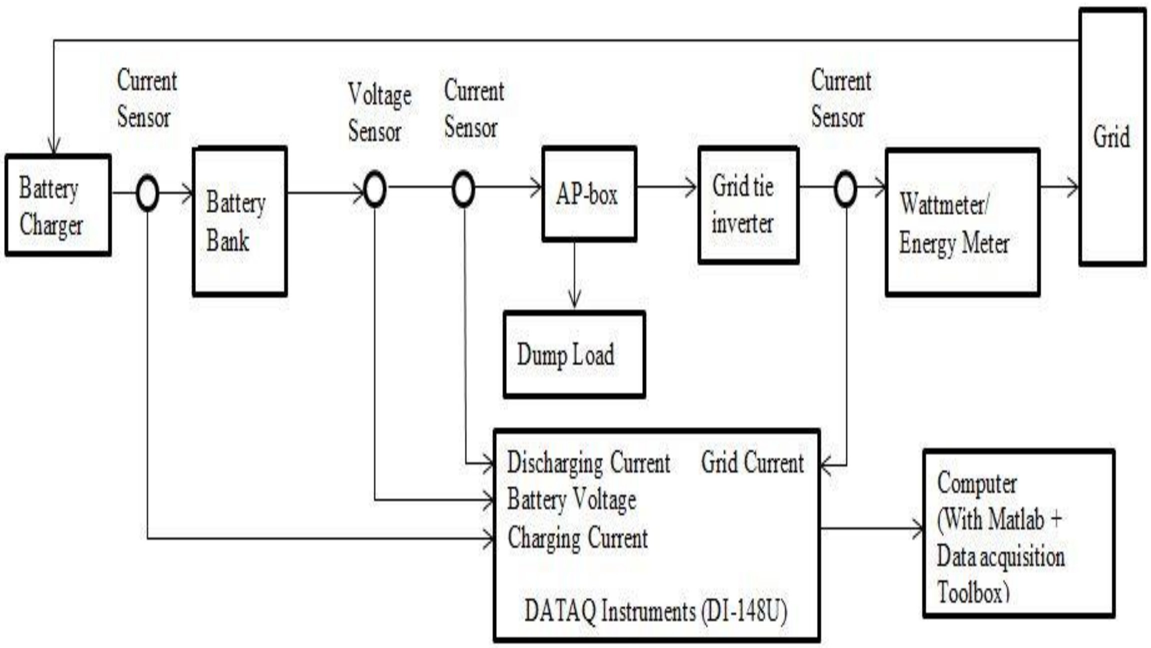

Figure 3.5: Block diagram of experimental setup

Fig. 3.5 shows the block diagram of the designed battery based energy system and Fig. 3.6 shows the experimental setup used in the laboratory for the data collection and analysis. The apparatus used in the experiment are described below:

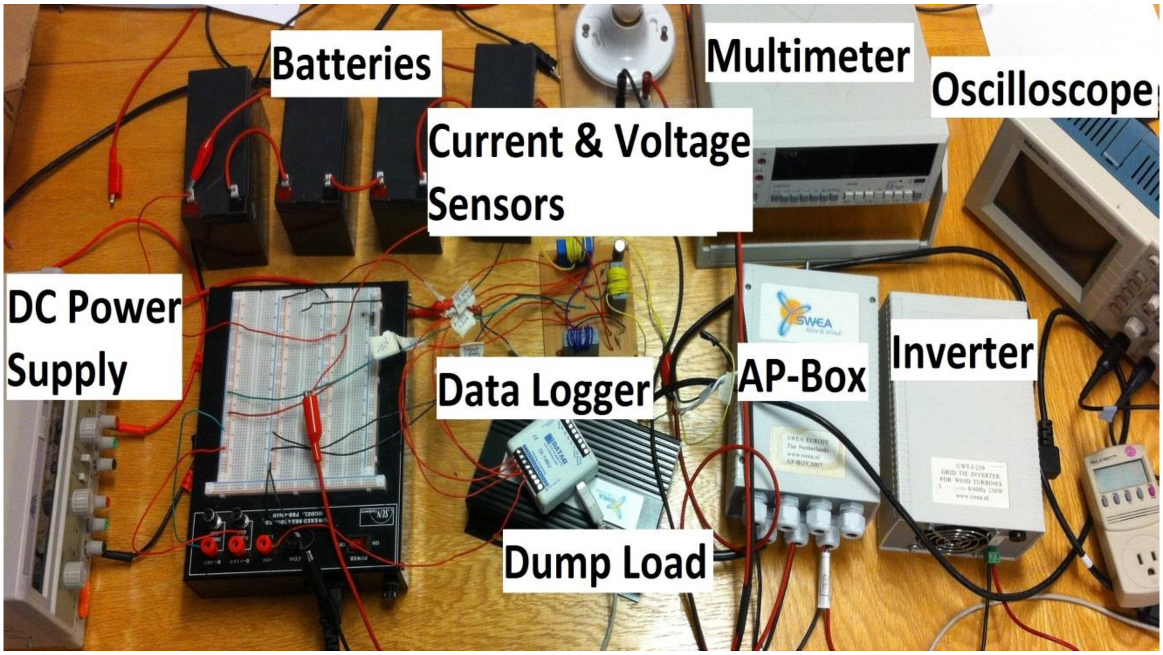

Figure 3.6: Experimental setup in laboratory

3.4.1 Battery Specification

Four 12V 7Ah lead acid batteries have been used in series to get 48V DC output. The manufacturer and the model no. are B.B BATTERY and BP7-12 respectively. The maximum charging current is 2.1 A and the maximum allowed discharge current for 5 sec is 105A.

3.4.2 Grid Tie Inverter UWT-I-250 STARTER KIT

The Grid Tie Inverter UWT-I-250 STARTER KIT [shown in Fig. A.6 and Fig. A.7] consists of AP-box, grid tie inverter and dump load. The description of the components is given below.

3.4.2.1 AP-box with 24 V AC/12 V DC Adaptor

The AP-box is an adaptor box between the batteries and the grid tie inverter UWT-I-250 The AP-box is a connecting and safety box for a typical installation. Four pieces of grid tie inverters UWT-I-250 can be connected (up to 1000 Watt) with one AP-box. It protects the electronics and also the batteries together with the internal safety items and the Dump load. The energy will be absorbed by the Dump load automatically when the input is above 52V DC. It is always connected with a fuse in series with the input supply.

3.4.2.2 Grid Tie Inverter

The grid tie inverter connects the battery storage to the grid. The input of this inverter is 48V DC as four batteries have been used in series. A maximum of four Grid Tie Inverters can be installed with one Starter-Kit. In this case one grid tie inverter has been used.

3.4.2.3 DUMPLOAD DL-2-100

DUMPLOAD DL-2-100 has been connected to the AP-box. The AP-box will switch on the Dump load automatically when the DC-out of the batteries becomes higher than 52 V. Two resistors each rated 100 Watt are installed inside the Dump load.

3.4.3 Voltage and Current Sensors

3.4.3.1 Voltage sensor

A voltage divider circuit has been used to measure the voltage of the battery bank.

3.4.3.2 Current Sensors

Current Transducer LA 55-P has been used to measure the discharging current of the batteries. This is a closed loop (compensated) current transducer using the Hall Effect. This sensor has excellent accuracy and low temperature drift. Current Transducer CLN-50 has also been used to measure the DC charging current of the batteries and output current of the inverter which is AC.

The primary and secondary nominal current (rms) is 50A and 50mA respectively for both sensors. The conversion ratio is 1:1000. Both sensors are calibrated to get the actual current measurements.

3.4.4 Data Acquisition Using the MATLAB Data Acquisition Toolbox

MATLAB's Data Acquisition Toolbox (DAT) allows MATLAB to acquire data from the sensors and to send out electrical signals that can be used to control or drive external devices. DI-148U has been used to acquire the data from sensors. The 32-bit versions of Data Acquisition Toolbox and MATLAB have been installed on a 32-bit Windows OS. Legacy interface is used for DATAQ data acquisition hardware [12].

Four analog input signals have been defined to measure the battery voltage, charging current, discharging current and the grid current from the experimental setup. The sampling time is set to 30s. The mean value of the acquired data from each analog port has been taken as samples per trigger and is set to 1000.

3.5 Experimental Results

The battery will be charged from the grid when the electricity price is low and is not allowed to be discharged during that time. But during higher electricity price, the battery will be discharged through the inverter to generate some profit.

3.5.1 Charging of Batteries

The batteries have been charged with a DC power supply. A DC power supply is less efficient to charge the battery. Typical efficiency of the battery charger is 70-75%. Fig. 3.7 and Fig. 3.8 show the battery voltage (V) and charging current (A) during charging the battery from the grid [sample data shown in Table C.1]. The battery voltage increases for about 10 hours with a constant current of approximately 0.63A. Battery voltage remains constant after that. But current starts decreasing exponentially. The AP-Box and inverter are disconnected from the battery bank during charging. Fig. 3.9 shows the charging power of the battery. Initially the charging power is almost constant but after about 10 hours it starts decreasing exponentially as charging current decreases.

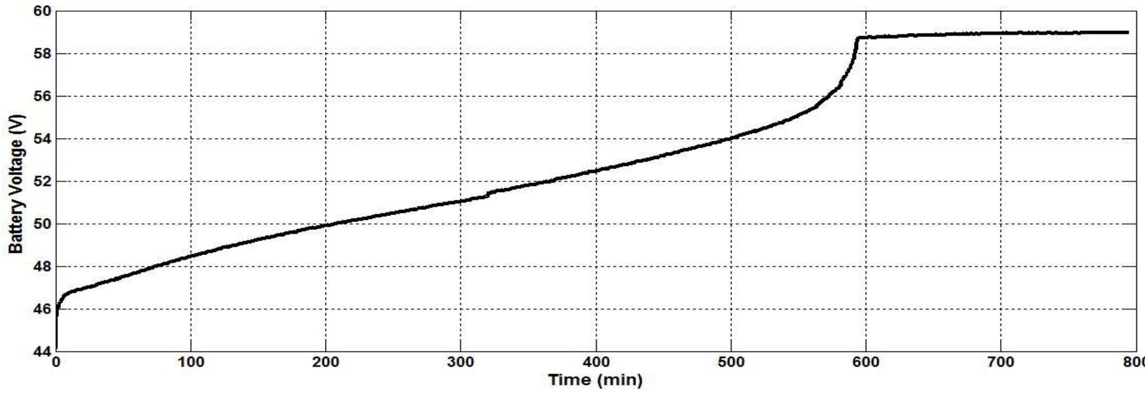

Figure 3.7: Battery voltage during charging of battery

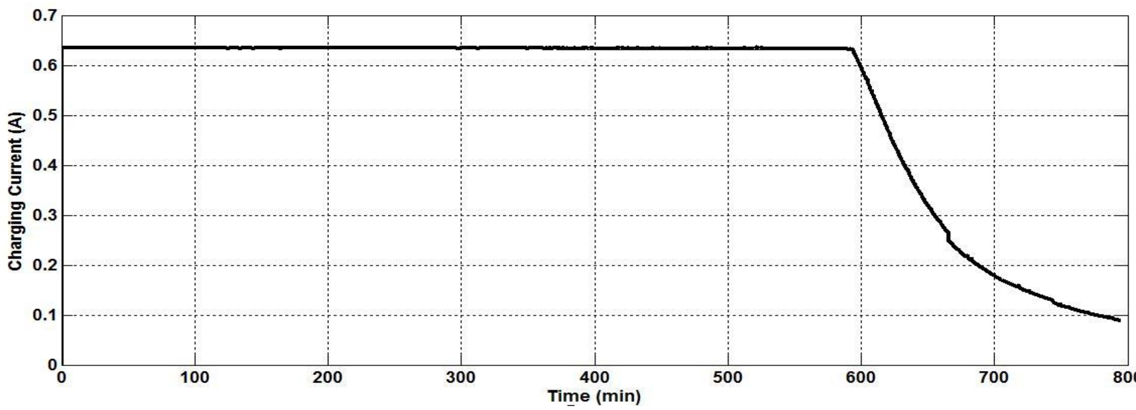

Figure 3.8: Charging current of battery

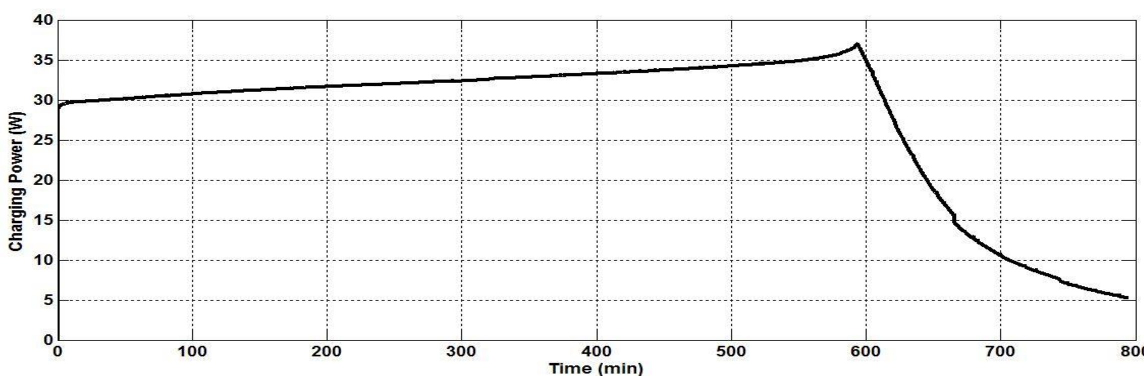

Figure 3.9: Charging power during charging of battery

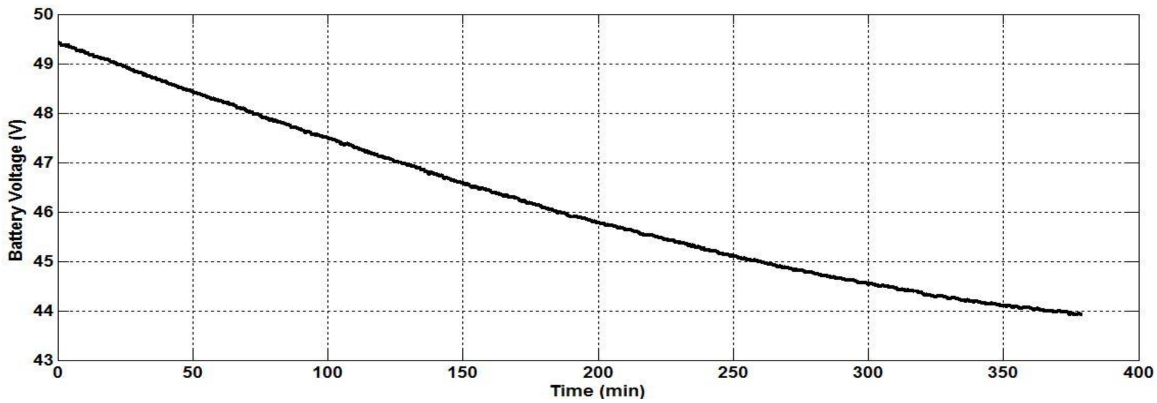

Figure 3.10: Battery voltage during discharging of battery

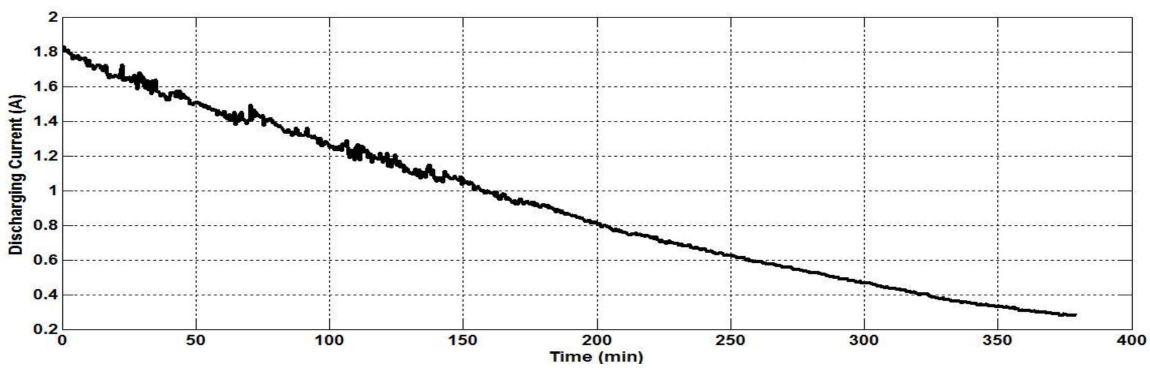

Figure 3.11: Discharging current of battery

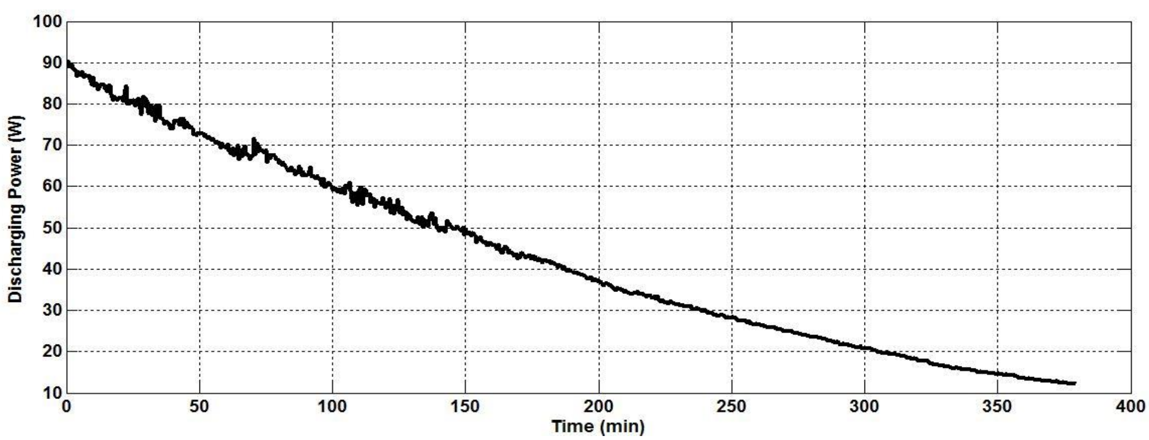

Figure 3.12: Discharging power during discharging of battery

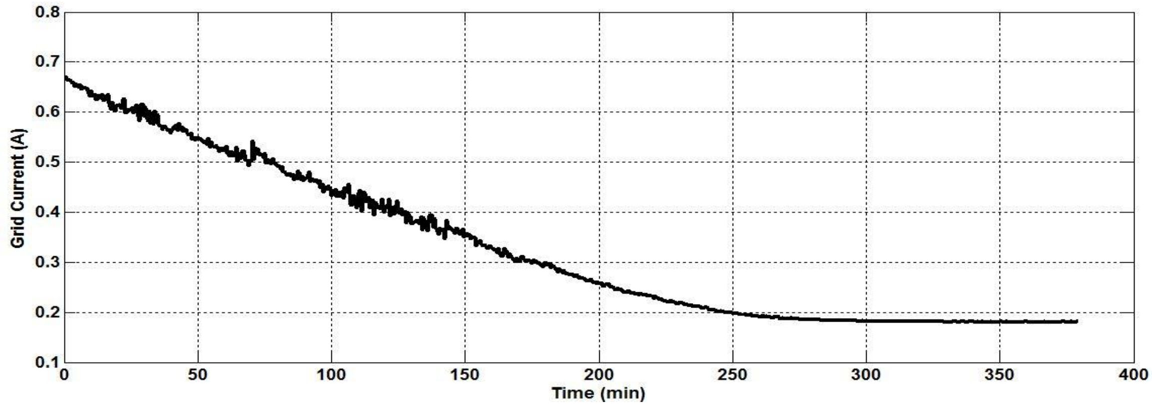

Figure 3.13: Output current of the inverter

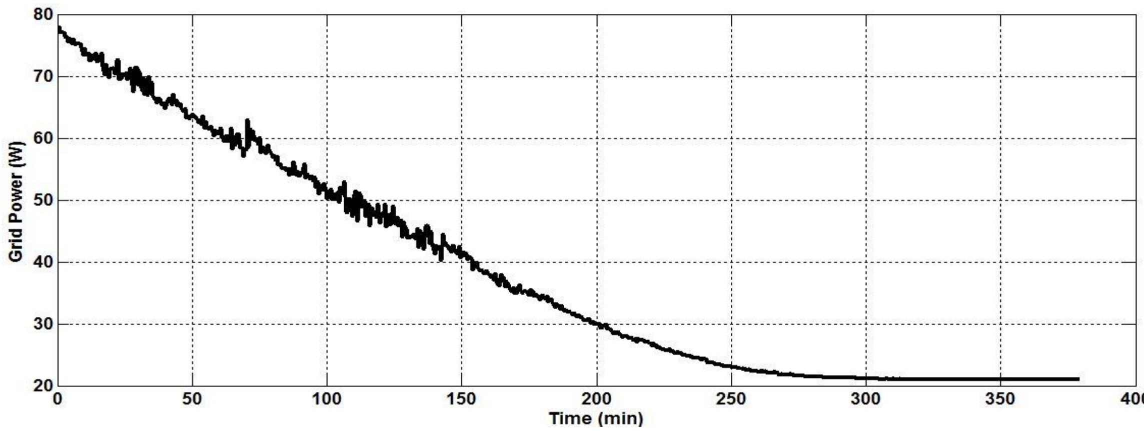

Figure 3.14: Output power of the inverter

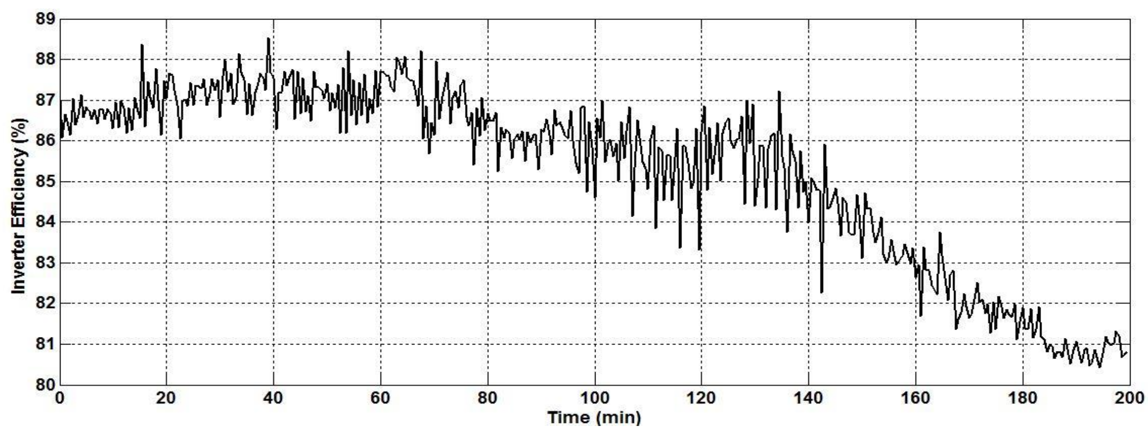

Figure 3.15: Efficiency of the inverter

3.5.2 Discharging of Batteries

Fig. 3.10 and Fig. 3.11 show the battery voltage (V) and discharging current (A) respectively during discharging the battery to sell energy to the grid [sample data shown in Table C.2]. Initially the battery voltage was 49.3V and finally it reaches close to 44V. Batteries have been discharged for more than 6 hours and the discharging current decreases to approximately 0.28A. Only AP-box and inverter is connected to the batteries during this test.

Fig. 3.12 shows the discharging power of the battery. As the voltage and current are decreasing during the battery discharge, the discharging power is also decreasing. Initially the discharging power is close to 90W and finally it reaches to 12W.

3.5.3 Inverter Output

Fig. 3.13 and Fig. 3.14 show the grid current and power sold to the grid respectively. Both are decreasing as it depends on the battery status. The inverter is programmed to supply reduced power to the grid as the battery is discharged. Fig. 3.15 shows that the inverter efficiency during the discharging of the batteries decreases with time as the input power decreases.

Total charging energy is found to be 370.2885 Wh and the discharging energy is found 272.5765 Wh from the experiment. So the battery efficiency is 272.5765/370.2885 =73.6% which can be increased by using better batteries like lithium-ion and using high efficiency charger. The inverter efficiency is 85%, therefore the overall efficiency is 62.6%.

From the actual logged data of a 3 bedroom house in St. John's, it is found that the total household load is 12,483 kWh/yr. [7]. So approximately 12,483/0.626 = 19,941 kWh/yr. energy is needed to buy from the grid to serve the household load of 12,483 kWh/yr. due to the efficiency of the battery and inverter. It can be said that if we charge the battery at low price period and serve the load when electricity price is high, then 12,483×0.124-19,941×0.067 = $212/yr. (approx.) can be earned only from the household load. The energy price ratio for OEB is 0.124/0.067=1.85, while it is 0.301/0.195=1.54 for SDG&E. This indicates that profit could be generated if an efficient energy storage system is employed.

3.6 Conclusion

This paper discusses the battery based energy storage systems to profit from net metering and variability of electricity price. Owners can make profit from the energy storage system depending on the peak and off-peak prices. A control strategy has been used to manage the proposed battery energy storage system. Consumers can decide when to purchase power and how much they consume from the utilities depending on the peak, off-peak prices and battery state of charge with this control algorithm. During peak hours consumers can use power from their energy storage and export the power to the grid to make profit. During off peak consumers can use power from the grid and store the energy in a battery-based energy storage system. A small prototype of the battery-based energy storage system has been designed and implemented. Here charging and discharging control is done manually. Fig. 3.3 shows a supervisory controller which is a simple on/off controller. A microcontroller can be used as a supervisory controller. Battery based energy storage system can be implemented using this kind of low cost supervisory controller to profit from net metering and variability of electricity price.

3.7 Acknowledgement

Authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for funding this research.

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Chapter 4

Wind Energy Based Packet Energy System

Preface

A version of this manuscript has been accepted for publication in the International Journal of Energy Science. The co-author Dr. Tariq Iqbal supervised the first author Md. Shakhawat Hossain to develop the research and helped him to use the best possible way to implement the idea using existing techniques. Md. Shakhawat developed the model, implemented the setup, conducted the experiments, analyzed the results and wrote the paper while Dr. Iqbal reviewed the manuscript and provided necessary suggestions. There exists certain amount of overlap from previous chapter.

Abstract

This paper proposes a wind turbine and battery storage based packet energy system. The proposed energy packet network can be used to make renewable energy sources more practical and supply energy on demand. The flow of energy in the energy packet network is controlled by a Smart Energy Dispatching Center (SEDC). SEDCs receive the energy requests from the customers and it tries to optimize the energy flows by making the best use of renewable energy resources, existing price and policies. The proposed energy system can take energy flow instructions from a SEDC. In the present analysis, a small wind energy system with battery storage has been simulated in Matlab/Simulink. The

system has been modeled using low order transfer functions. Random switching has been employed to provide energy packets from the model. A prototype of the battery-based energy storage system has been designed and implemented. Lab tests and simulation results indicate that the designed packet energy network system is able to provide energy packet as required by the grid. Additionally the output power from a very large energy packet network is found to be stable with the existence of large load fluctuation.

Keywords: Smart Grid; Smart Meter; Packet Energy; Battery Storage; Wind Energy

4.1 Introduction

The Smart Grid is considered as the next generation energy grid. Two-way flows of electricity and information make it a widely distributed and automated energy delivery network. The smart infrastructure system, the smart management system, and the smart protection system are the three major parts of a smart grid [1]. Renewable sources of energy, such as wind and solar, have gained attention over the last few decades. Presently, these are the key components to build a clean electric grid. Renewable energy resources such as solar, wind, wave, small hydroelectric and marine current all are typically unpredictable and sometimes aperiodic. Here renewable energy sources are unpredictable elements on the supply side. The demand side of the energy market is also unpredictable. Energy storage systems such as battery storage can offer new opportunities to improve the interaction between varying supply and demand.

Smart grid is designed with extensive interconnections. Reliability is the main concern of these interconnections. Interconnection also increases the risk of failure. Any imbalance can spread to the wide area. If large proportions of renewable energy generation need to be connected to the grid without the risk of wide area failures, a new electric power grid needs to be developed. In [2]-[3], various approaches to coordinate the operation and control of distributed generators have been proposed. A smart grid can also be designed where demand-side management of power usage is put into effect through a parallel information network [4]. The problems of power flow cannot be solved by only demand-side management. Impedance is relatively static in the traditional grid but it is dynamic in a distributed generation grid. Integration of large proportion of renewable energy sources is also challenging because it is difficult to maintain synchronization over a wide area.

In [5], a new type of power system referred to as a digital grid is proposed. Here, a wide-area synchronized power system is subdivided into smaller or medium sized cells. And these cells are connected through asynchronous coordination control. By separating the power grid into cells, the fluctuations of renewable power can be managed within the cell. The fluctuations of one cell cannot affect other cells because each cell is separated by ac/dc/ac conversion. In this way, a digital grid can accept high penetrations of renewable energy. It can also help to prevent wide area blackout. If fault occurs in a line, power can flow through other paths because a number of such paths are available among cells.

In [6], plug-in vehicle charging has been proposed using charge packets which are analogous to discrete data packets used in communication system. Here, packetized charging breaks the required charge time into many small intervals or packets. A charge management coordinator device at the distribution substation determines whether additional load on the system can be served. If charging is not possible with existing resources, the PEV resubmits a request after a certain time. If charging is possible, the PEV will charge for the duration of the packet. PEV will submit new requests for subsequent packets until the battery is fully charged. Here, it is also recommended that 5s request interval and 5s packet in length is superior in terms of both total cost and equal access.

The objective of this research is to design a small wind energy based packet energy system. The system is based on wind turbines and battery storage. The wind turbines will charge the batteries depending upon wind availability. The smart energy dispatch center will send request to the energy storage system through advanced metering infrastructure to provide energy packet of a fixed duration. The duration of energy packet will be decided by the dispatch center depending on the energy demand from customers, load forecast and energy production. The magnitude of each packet will be the name plate rating of the grid-tie inverter. In other words, the grid-tied inverter on/off time and duration will be decided by the SEDC. A SEDC will always have an updated status of the battery-inverter system that could supply energy packets. The proposed system is modeled and simulated in Matlab/Simulink. Simulation results indicate that the proposed

Energy Packet Network (EPN) is able to provide power as needed with the presence of renewable energy sources. The EPN can store energy originating from the renewable energy sources, and the stored energy can complement the traditional sources of energy in pulsed form when demand is high. A prototype of the battery based energy storage system has been designed and implemented in this research to demonstrate the system and its ability to provide energy packets without any issue.

The rest of the paper is organized as follows: The concept of energy packet network is discussed in the next section. The modeling and simulation outputs are shown in successive sections. The output of the experimental setup is shown in the experiment section.

4.2 Energy Packet Network

Energy packet network offers smart management of energy flow. Here energy flows like a packet in the internet rather than the continuous instantaneous flow of current towards points of energy consumption. Energy packet can be described as a pulse of power which lasts for a certain time. So the unit of the energy packet is kWh. The duration of the energy packet is determined by the grid according to the requirement of energy. The flow of energy in energy packet network is controlled by a Smart Energy Dispatching Centers (SEDCs) which is basically a computer control center. SEDCs receive the current state of all energy storage systems from the consumers and estimate the energy requirement based on forecast. It tries to optimize the energy flows by making the best use of available renewable energy sources and existing pricing policies. From the customer point of view, essentially a SEDC sends random demand pulses (turn on duration and time) to a renewable energy system with storage and collects current status of battery charge. SEDCs use data communication networks to receive and send information and make optimal dispatching decisions. It will also have the updated status of every component connected to it.

An energy packet network can serve different purposes [7]:

- Provide real-time information about the requests on the one hand, and the sources of energy on the other.
- Schedule the flow of current to and from electricity storage units depending on the availability and demand of energy.
- Real-time scheduling of energy demand so as to meet certain desirable objectives, e.g. scheduling electric heating in a large building.

In [8], the authors proposed two in-home power distribution systems. Information is added to the electric power distribution and electricity is distributed according to the supplied information. A switching circuit system based on alternating current (AC) power distribution and a switching circuit based on direct current (DC) power dispatching system via power packets are proposed. But it requires high power switching devices.

An internet-based energy provisioning concept has been proposed in [9]. Customers can order and request future power demands through a system called Online Purchase

Electricity Now (OPEN). It will encourage customers to order the electricity they need and consume or store locally exactly what they ordered.

The paper indicates that reliability of the electric grid can be improved with this kind of virtual energy provisioning system. System concepts and implementation strategies are also discussed in the paper. Several methods have been proposed to represent the demand orders for the customers [9].

4.2.1 Average Demand Orders

In this method, customers can order the average electricity demand that will be needed in hourly, daily, weekly, or monthly basis based on the historical consumption. Let d(t) be the demand order in kWh units from customer i at time t, then the total required generation, g(t), is

$$g(t) = \sum_{i=1}^{n} d_i(t) \tag{4.1}$$

where n is the number of customers and t represents a specific hour, day, week, or month.

4.2.2 Lower and Upper Bounds Demand Orders

In this method, customers can order the minimum and maximum energies that will be consumed in the future. It will give customers more flexibility to estimate their future energy consumptions. Let d_L and d_U be the lower and upper demands from customer i, respectively, then the lower and upper generations is estimated by

$$g_L(t) = \sum_{i=1}^{n} d_{Li}(t) \tag{4.2}$$

$$g_U(t) = \sum_{i=1}^{n} d_{Ui}(t) \tag{4.3}$$

With this the supplier can plan for the worst or the best scenario of the future energy demand. If maximum energy demand of all customers is considered, it will be worst scenario which rarely occurs in reality.

4.2.3 Demand Orders with Power and Time Duration

In this method, customers can order in terms of electric power plus the time duration.

The Smart energy dispatching center can control the energy flow after getting the customer's order. For sources such control is effectively random requests of energy packets.

4.3 Simulation of a Wind Energy System with Storage in Matlab/Simulink

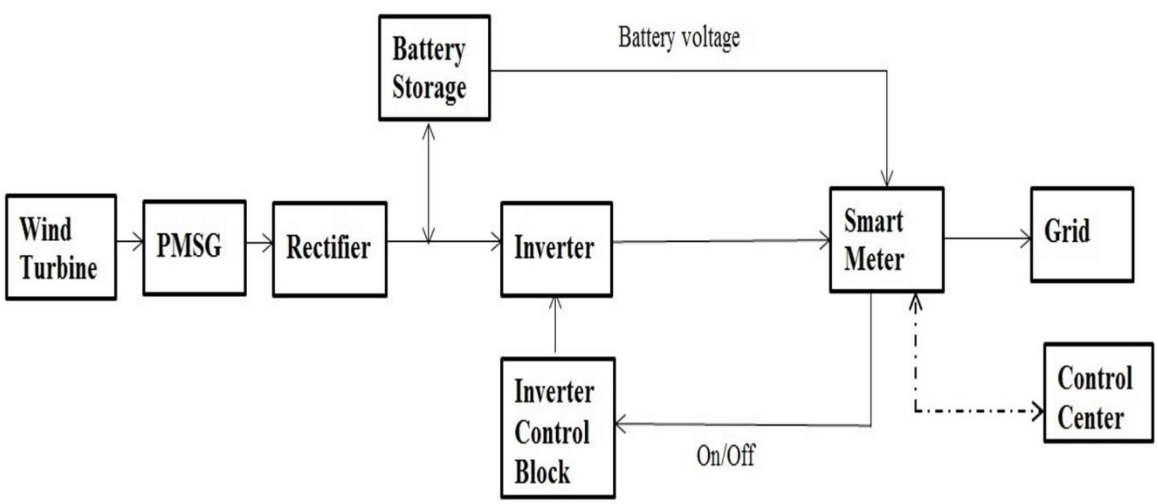

Figure 4.1: Small wind turbine with energy storage

Fig. 4.1 shows the block diagram of a grid connected small wind energy system with battery storage. This system has been modeled in the Matlab/Simulink without the PID controller to obtain the open loop response of the system. A 7.5 kW wind turbine is coupled with a 24 pole 300 rpm permanent magnet synchronous generator (PMSG). The base wind speed and pitch angle is set to 12 m/s and 0 degree respectively. Here the 6V, 305 Ah batteries are used. Two strings of batteries are used in total. Each string has 8 batteries to make 48V DC bus voltage. For AC to DC conversion an uncontrolled rectifier has been used. The output of the rectifier is connected to the battery storage through a LC filter. Depending on the wind speed, the battery bank will be charged from the wind turbine.

The battery and the output of the rectifier are connected to an inverter for DC to AC conversion. The output of the inverter is connected to the grid through three phase LC filter and transformer. The inverter will be controlled with a PID controller and PWM generator. The output of the PID controller is connected to the inverter through the PWM generator. The whole system has been implemented in Matlab/Simulink without the PID controller. The full system has been converted into simple first order transfer function as the full system simulation takes a long time to complete in Matlab. The transfer function model of the system was obtained using the step response of the full system model.

In the next section the open loop system has been used to design an energy packet network.

4.4 Modeling of Packet Energy System

In this section the transfer function of the above described wind energy system with battery storage has been determined to design a packet energy network. The whole system has been divided into two parts to calculate the transfer function.

The first part consists of the wind turbine, PMSG, rectifier and battery [shown in Fig A.1]. For the first part the response of the battery voltage is calculated for different wind speeds such as 7, 8, 9, 10, 11 m/s. From the output response, the transfer function of the battery charging current is found as equation (4.4).

$$\frac{I_b(s)}{W_s(s)} = \frac{8}{0.72s + 1} \tag{4.4}$$

$$\frac{P_{out}(s)}{V_b(s)} = \frac{40}{0.125s + 1} \tag{4.5}$$

Here I_b is battery charging current (A) and W_s is the wind speed. From the output response, the steady state gain and time constant have been calculated. The steady state gain is determined to be 8 and the time constant is 0.72 s. It is then multiplied by the internal resistance of the battery to calculate the response of the battery voltage for different wind speeds. The output of the first part has been used as the input to a voltage controlled voltage source. And that voltage controlled voltage source is connected to the inverter. Another transfer function has been determined to include the effect of voltage change of the voltage source inverter on the output power, which is shown in equation

(4.5) with the time constant 0.125s and steady state gain of 40. Here, P_{out} is the output power of the inverter (W) and V_b is the battery voltage.

The second part of the system model [shown in Fig. A.2] consists of the voltage source inverter and the rest of the components of Fig. 4.1. Two more transfer functions have been determined for this model. One is to get the effect of the load change and another one is to get the effect of modulation index change on the output power of the inverter. Step input has been provided to the circuit breaker in Matlab/Simulink to increase the load, which helps to find the effect of load change on the output power of the inverter. The transfer function due to the load change is shown in equation (4.6). Here, C_{load} stands for change of load. Step input has been provided to the PWM generator to find the effect of different modulation index on the output power of the inverter. From the output response, the steady state gain and time constant have been calculated. The transfer function due to the modulation index change is shown in equation (4.7). Here, C_{PWM} stands for the change in PWM change.

$$\frac{P_{out}(s)}{C_{load}(s)} = \frac{1100}{0.125s + 1} \tag{4.6}$$

$$\frac{P_{out}(s)}{C_{PWM}(s)} = \frac{1200}{0.125s + 1} \tag{4.7}$$

Fig. 4.2 shows the transfer function model of the wind energy system with storage shown in Fig. 4.1.

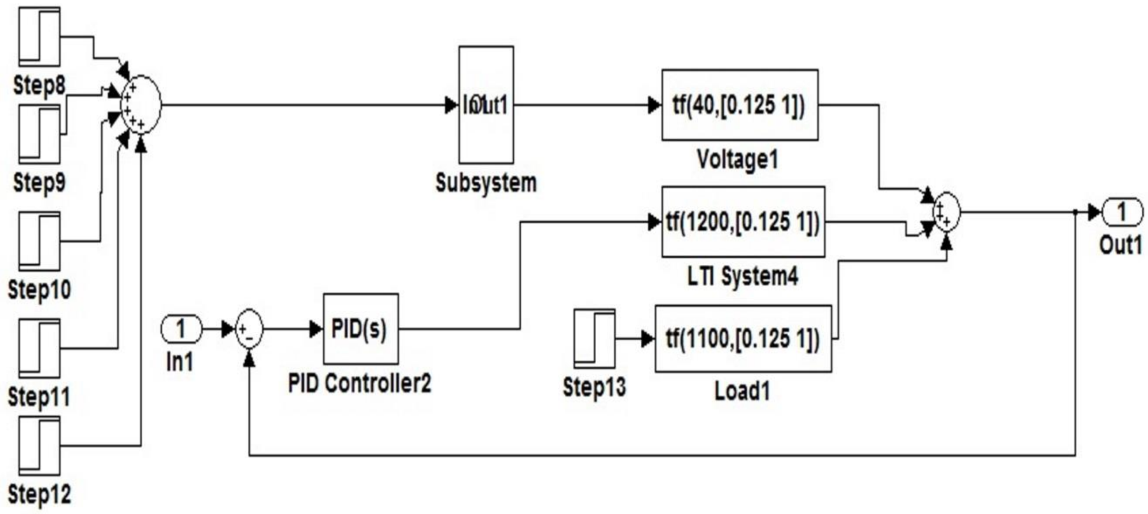

Figure 4.2: Transfer function model of the wind energy system

After getting the open loop transfer function of the system in Fig. 4.1, a PID controller is used to get constant active power from the wind energy system, which is determined by the reference power. Controller gains have been adjusted using the automatic tuning method in Matlab/Simulink.

The energy dispatch center selects the storage system depending on the energy demand, energy production and status of the battery storage. This is random selection from the customer point view. Random switching is done to produce power packet from the designed packet energy system to implement this idea. Fig. 4.2 is considered as one block in the packet energy network. The first plot of Fig. 4.4 shows the output power of one block where the reference power is set to 2 kW. The duration of each packet depends on the command from the smart energy dispatching center. The smart energy dispatching center will make this decision depending on the request from the customers and availability of the power in the power stations.

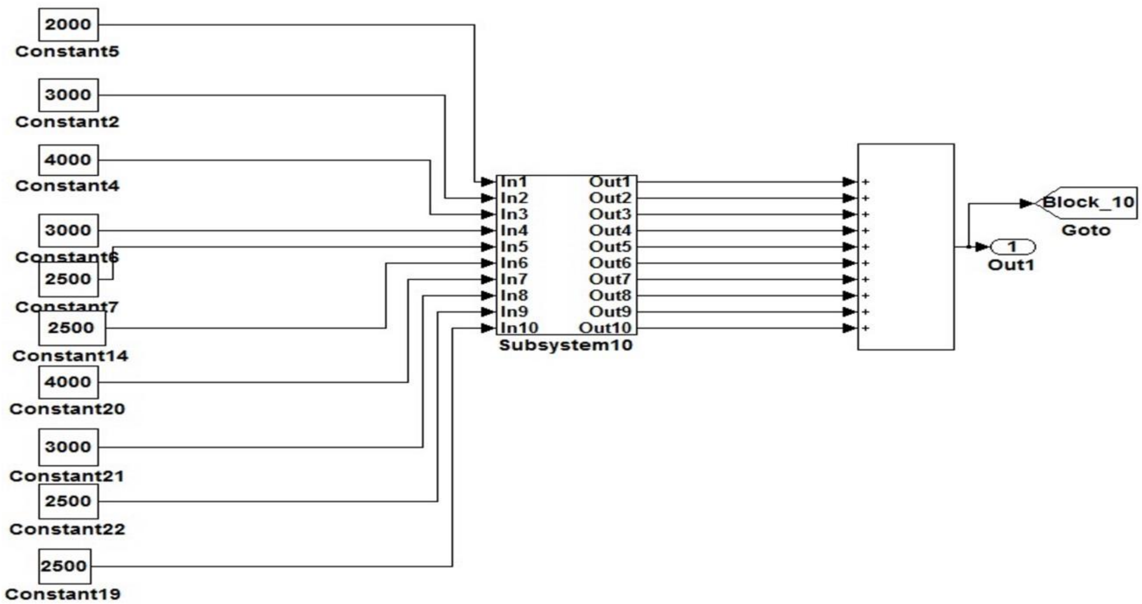

Figure 4.3: Blocks with different reference power

Fig. 4.3 shows a bit more complicated system where 10 blocks have been added with different reference power. Here, it is assumed that each cell has different amount of power generation. The second plot of Fig. 4.4 shows the total output power from the ten blocks where all blocks generate power randomly in energy packets form.

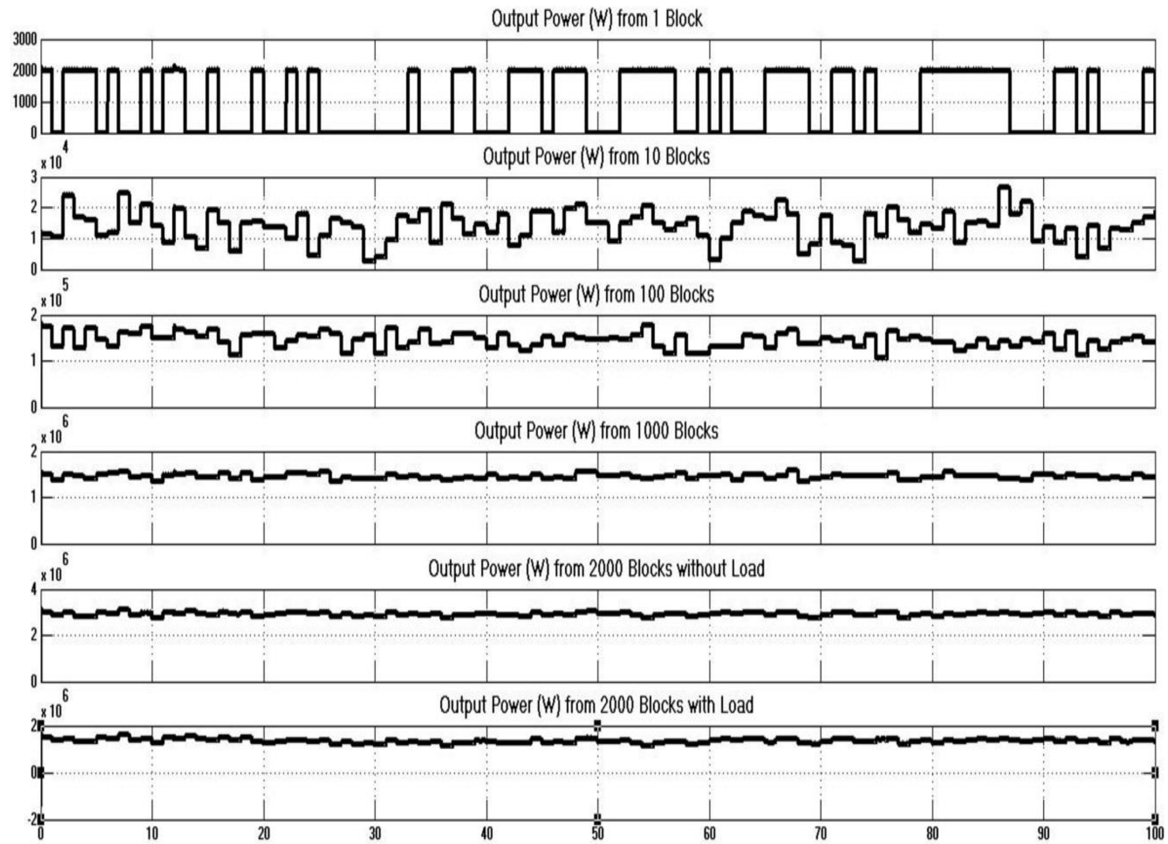

Figure 4.4: Output power from different number of blocks with respect to time

A large number of this kind of blocks can be considered to form a grid that constitutes a packet energy network. First only 10 blocks have been used with different output power level. Then those 10 blocks are used to make 2000 blocks to behave like a practical digital grid system consisting of effectively 2000 sources switching randomly and injecting energy packets [shown in Fig. A.3]. Fig. 4.4 shows the total output power from different blocks. From the simulation plots it can be said that the designed packet energy system can provide stable output power with the presence of large number of blocks switching or injecting energy packets to the grid randomly.

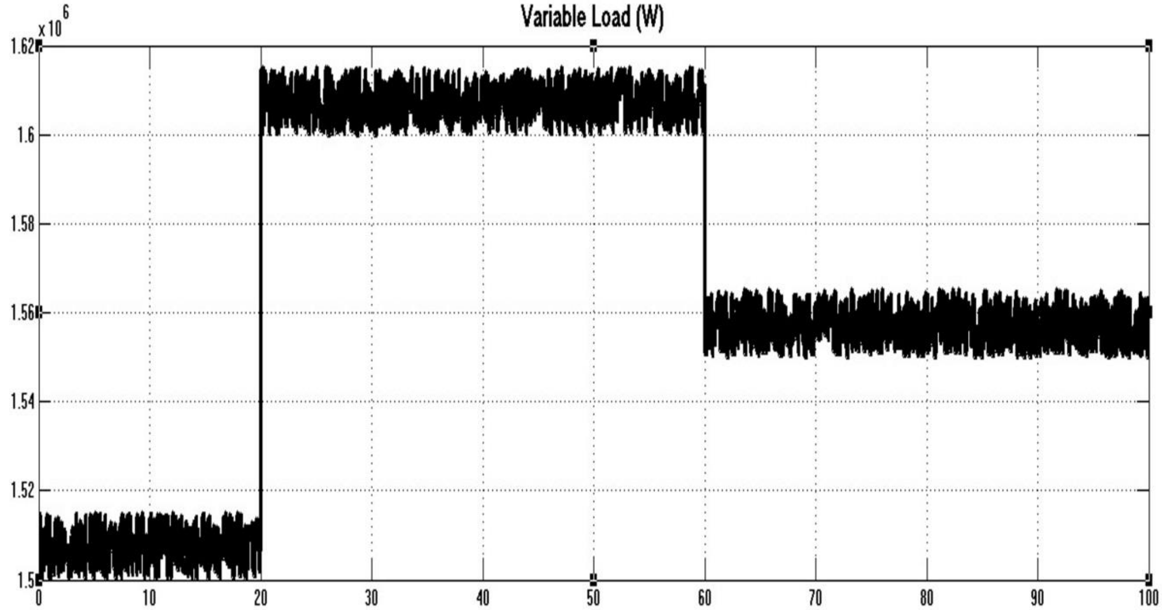

Figure 4.5: Variable load used in the system with respect to time

Large variable load with the presence of random fluctuations is applied in simulation to check the stability of the designed packet energy system. The variable load consists of 1,500 kW constant load, 100 kW step load and maximum 15 kW random load fluctuations [shown in Fig. A.4]. Fig. 4.5 shows the load that has been applied to the system in simulations.

The mean output power from 10 blocks is found as 1.38×10^4 W. As the sum of independent normally distributed random variables is also normal, the mean of the sum of independent variables is the sum of the means of individual variables. Here, the mean output power from the 100 blocks is found as 1.44×10^5 W which is 10 times the mean output power of 10 blocks. Similarly, the mean output power of 1000 blocks and 2000 blocks are 1.44×10^6 W and 2.89×10^6 W. The mean output power of 1000 blocks is 100 times the mean output power of the 10 blocks. The mean output power of 2000 blocks is double the mean output power of 1000 blocks.

Comparing the last two plots of fig. 4.4, it could be concluded that random sources and random load fluctuations still lead to an almost steady output.

4.5 Implementation of Battery-Based Storage System

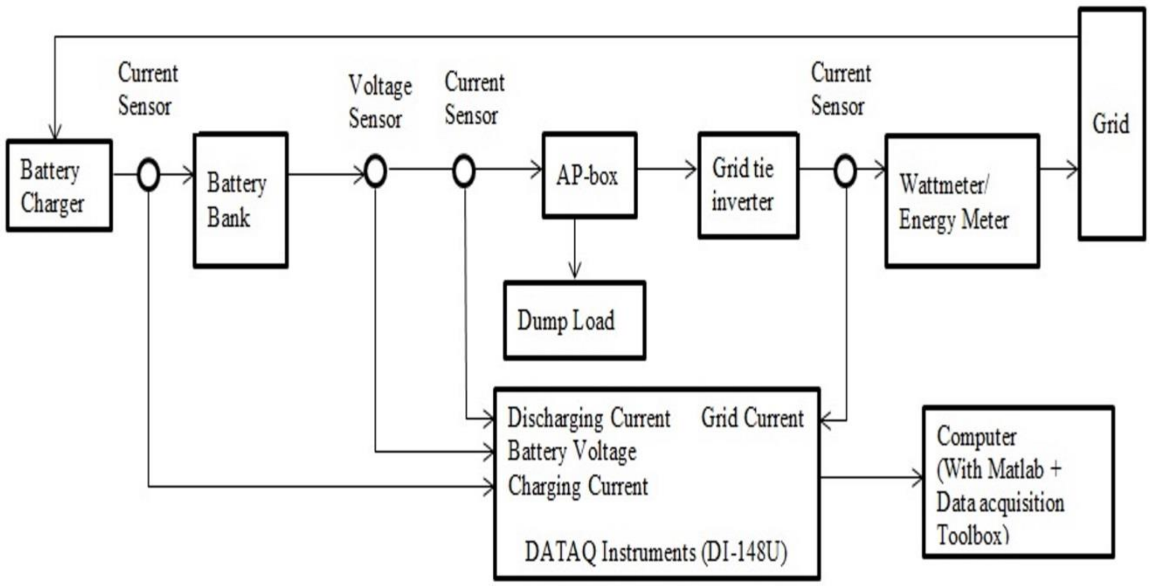

Figure 4.6: Block diagram of experimental setup

Fig. 4.6 shows the block diagram of the designed battery based energy storage system [10] and Fig. 4.7 shows the experimental setup used in the laboratory for the data collection and analysis [10]. The apparatus used in the experiment are described below:

4.5.1 Battery Specification

Four 12V 7Ah lead acid batteries have been used in series to get 48V DC output. The manufacturer and the model no. are B.B BATTERY and BP7-12 respectively. The maximum charging current is 2.1 A and the maximum allowed discharge current for 5 sec is 105A.

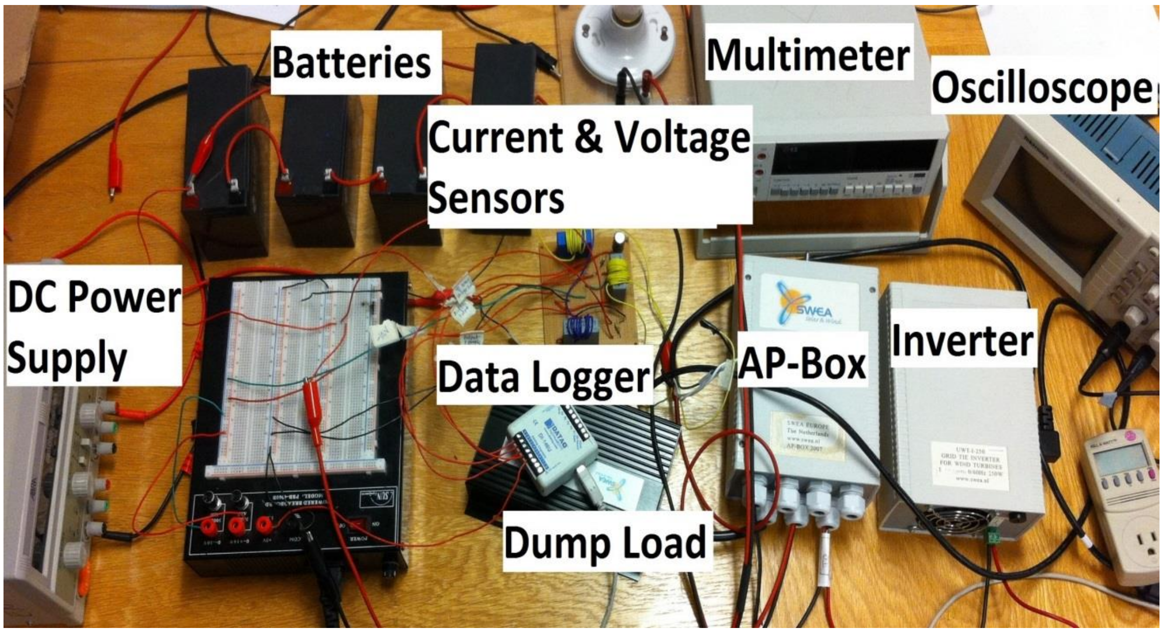

Figure 4.7: Experimental setup in laboratory

4.5.2 Grid Tie Inverter UWT-I-250 STARTER KIT

The Grid Tie Inverter UWT-I-250 STARTER KIT consists of AP-box, grid tie inverter and dump load. The description of the components is given below.

4.5.2.1 AP-box with 24 V AC/12 V DC Adaptor

The AP-box is an adaptor box between the batteries and the grid tie inverter UWT-I-250 The AP-box is a connecting and safety box for a typical installation. Four pieces of grid tie inverters UWT-I-250 can be connected (up to 1000 Watt) with one AP-box. It protects the electronics and also the batteries together with the internal safety items and the Dump load. The energy will be absorbed by the Dump load automatically when the input is above 52V DC. It is always connected with a fuse in series with the input supply.

4.5.2.2 Grid Tie Inverter

the grid-tie inverter connects the battery storage to the grid. The input of this inverter is 48V DC as four batteries have been used in series. A maximum of four Grid Tie Inverters can be installed with one Starter-Kit. In this case, one grid tie inverter has been used.

4.5.2.3 DUMPLOAD DL-2-100

DUMPLOAD DL-2-100 has been connected to the AP-box. The AP-box will switch on the Dump load automatically when the DC-out of the batteries becomes higher than 52 V. Two resistors of 100 Watt are installed inside the Dump load.

4.5.3 Voltage and Current Sensors

4.5.3.1 Voltage sensor

A voltage divider circuit has been used to measure the voltage of the battery bank.

4.5.3.2 Current Sensors

Current Transducer LA 55-P has been used to measure the discharging current of the batteries. This is a closed loop (compensated) current transducer using the Hall Effect. This sensor has excellent accuracy and low temperature drift. Current Transducer CLN-50 has also been used to measure output current of the inverter which is AC.

The primary and secondary nominal current (rms) is 50A and 50mA respectively for both sensors. The conversion ratio is 1:1000. Both sensors are calibrated to get the actual current measurements.

4.5.4 Data Acquisition Using the MATLAB Data Acquisition Toolbox

MATLAB's Data Acquisition Toolbox (DAT) allows MATLAB to acquire data from the sensors and to send out electrical signals that can be used to control or drive external devices. DI-148U has been used to acquire the data from sensors. The 32-bit versions of Data Acquisition Toolbox and MATLAB have been installed on a 32-bit Windows OS. Legacy interface is used for DATAQ data acquisition hardware [11].

Three analog input signals have been defined to measure the battery voltage, discharging current and the grid current from the experimental setup. The sampling time is set to 1s. The mean value of the acquired data from each analog port has been taken as samples per trigger and is set to 1000.

4.5.5 Smart Meter

In the present analysis, a modification has been assumed in a smart meter. The existing smart meter can communicate with the following communication channels:

- Optical port – IR communication interface
- DLC modem
- GSM/GPRS communication interface with antenna

- RS 485 comm. interface
- M-Bus communication interface

The existing smart meter can perform the following functions using these communication channels [12]

- Collection of energy consumption information
- Reading of energy consumption information on request.
- Collection of supply quality information (e.g. sags, voltage measurements) of individual customers.
- Collection of information saved in profiles of individual customers and/or a (larger) number of customers.
- Collection of power failure duration information of individual customers and/or a (larger) number of customers.
- Setting and retrieving different tariff structures
- Retrieving device status.
- Remote connection and disconnection of the energy supply of individual customers.

A small block can be added to the existing smart meter to use with the battery storage system. The modified smart meter will measure the battery voltage and obtain a simple approximation by calculating the state of charge of the battery storage from the measured battery voltage using equation (4.8). A complicated method can also be implemented in the microcontroller of the smart meter to determine the state of charge of the battery.

$$SOC = \frac{V_{present}}{V_{full}} \times 100\% \tag{4.8}$$

In this research it is proposed that smart meter will send the battery storage status information to the smart energy dispatch center. After getting the energy storage status, the control center will randomly select the energy system depending on the energy demand and energy production.

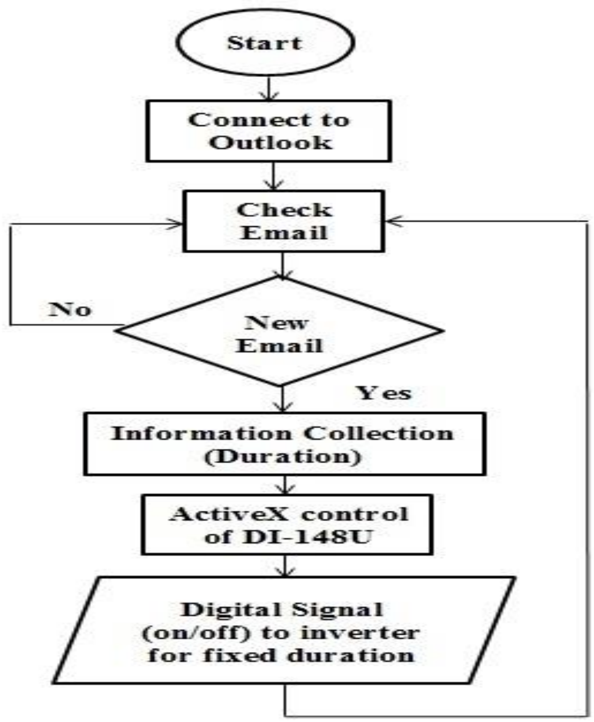

Figure 4.8: Flowchart to control inverter on/off using Matlab

In this experiment it is assumed that the energy dispatch center will communicate with the smart meter through GSM network. To implement this idea, it is assumed that the control center will send request for energy packet to the smart meter through an email. Fig. 4.8 shows the algorithm to implement this idea in Matlab. In the email there are two information [shown in Fig. A.5]. One is the request for the inverter to be turned on and another is the duration of the energy packet. The inverter will run at full power during that duration. After getting the request of the energy packet from the dispatch center, the information has been collected by the Matlab. Using the ActiveX control in Matlab for the DI-148U, an on/off digital signal is generated for the specified duration determined by the dispatch center. This digital signal is provided to the inverter. As the inverter starter kit used in this experiment doesn't allow the grid side to be disconnected, the connection and disconnection of the input side of the inverter has been done to produce a power packet. If the inverter allows disconnection of the grid side, a relay can be used which can be controlled with the digital output from the DI-148U. A solid state relay can also be used to control the energization of the winding depending on the digital signal from the DI-148U.

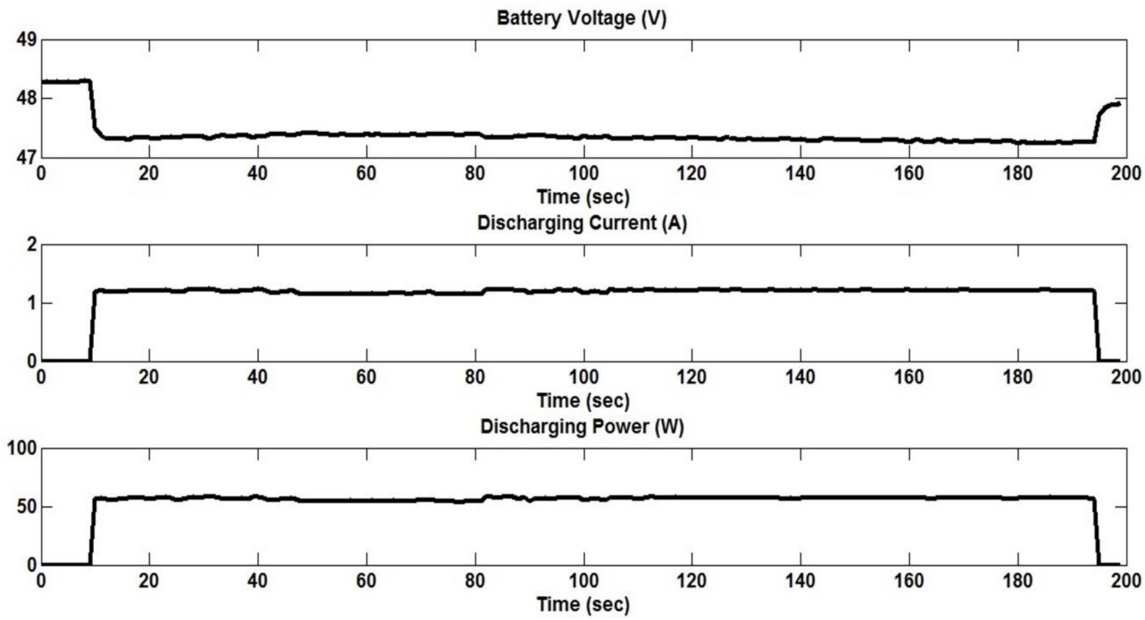

Figure 4.9: Battery voltage, discharging current and discharging power with respect to time

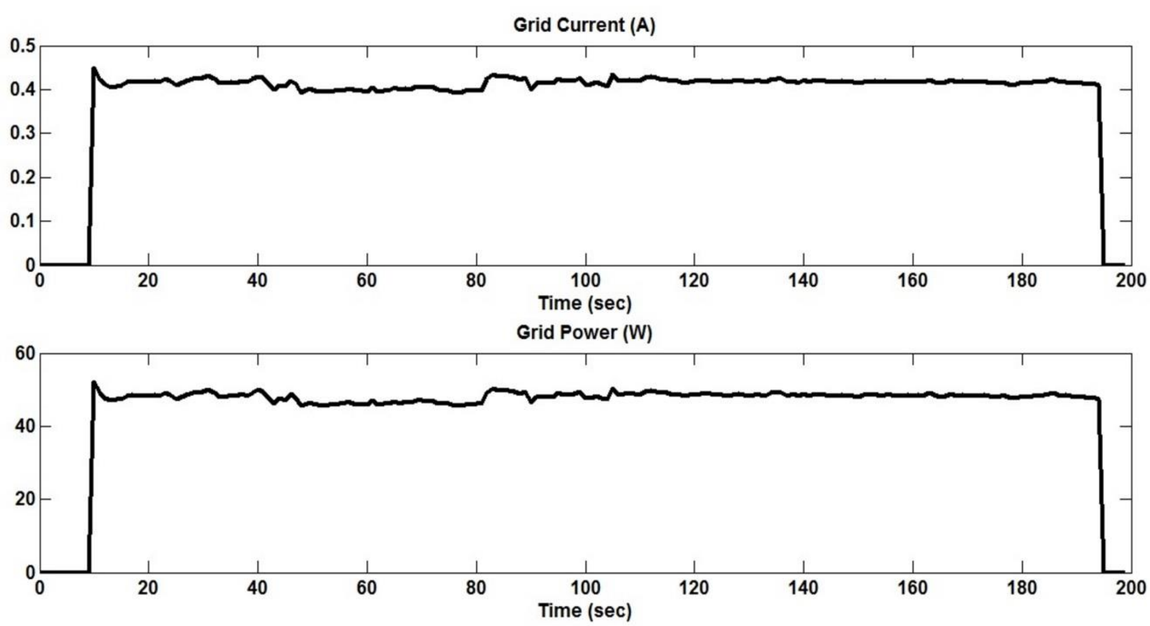

Figure 4.10: Inverter output current and power going to grid with respect to time

4.6 Experimental Results

Fig. 4.9 shows the battery voltage (V), discharging current (A) and discharging power (W) during discharging the battery to sell energy to the grid. Initially the battery voltage was 48.26V. It reaches 47.3V when inverter is on and it reaches back to 47.9V when the inverter is off. Batteries have been discharged for approximately 180 seconds and the discharging current from the battery is approximately 1.2A. During this test the discharging power is approximately 56W for demonstration.

Fig. 4.10 shows the grid current and power sold to the grid. The grid current and the power sold to the grid are found as 0.43A and 49W respectively. So the inverter efficiency is calculated as 49/56= 87.5%.

From Fig. 4.10, it can be said that the implemented system can supply energy packet of variable duration as determined by the energy dispatch center.

4.7 Conclusions

This paper discusses a wind energy based packet energy system. The grid connected wind energy system with battery storage has been simulated in Matlab/Simulink. The basic system has been converted into transfer function model to design the energy packet network. After determining the transfer function model of the wind energy system, a PID controller has been used to obtain a constant output power from the basic system. A large number of blocks have been considered with different constant output power similar to a practical system. Random switching has been used to obtain the power in packets from the model. Simulation results indicate that the designed packet energy network system consisting of thousands of smaller packet energy system is able to provide a flexible and stable power. A small prototype has been implemented with battery storage to demonstrate control to produce an energy packet. Experimental results show that it is possible to make such energy packet in the existing system. The proposed packet energy system is based on renewable energy sources with local storage. With the help of energy packet network, a smart energy dispatching centers can take full advantage of renewable energy sources. The proposed packet energy network could be implemented using already available commercial technology.

4.8 Acknowledgement

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Chapter 5

Conclusions and Future Works

5.1 Summary of research and contributions

Design and analysis of a small wind turbine based packet energy system has been presented in this thesis. Experimental and simulation results presented in this thesis clearly demonstrate that such a system could be implemented using available technology. One of the objectives of this research was to design a grid connected battery based energy storage system to profit from net-metering and variable rate electricity available in some Canadian provinces. In this research, an energy storage system has been designed using the NREL HOMER software. HOMER was used for battery sizing and cost calculations. A control strategy has been proposed to manage the designed battery storage system. The proposed control algorithm, which is a simple supervisory controller, has been simulated in Matlab/Simulink. This control algorithm takes the peak, off peak prices and battery state of charge (SOC) as input to generate control values. During peak hours, consumers can use power from their energy storage and export the power to the grid to make some profit. During off peak, consumers can use power from the grid and store the energy to the energy storage. A small prototype has been designed and implemented in the lab to demonstrate how the system works. The feasibility of the system has also been demonstrated. MATLAB's Data Acquisition Toolbox (DAT) and DI-148U has been used to acquire data from the current and voltage sensors. The whole system efficiency has been calculated from the acquired sensor data to determine the profit from the energy storage system.

The outcomes from this research are listed below:

- The proposed control algorithm is able to manage the battery energy storage system. With this algorithm, consumers can decide when to purchase power and how much they can consume from the utility depending on the peak, off peak electricity prices and battery state of charge (SOC).
- A microcontroller can be used as a supervisory controller. A battery based energy storage system can be implemented using this kind of low cost supervisory controller to profit from net metering and variability of electricity price.
- Owners can make profit from the designed energy storage system using net-metering and peak and off-peak prices. They can make more profit by installing high efficiency batteries like lithium-ion and using high efficiency charger and selling electricity to the grid during peak hours.

Another objective of this research was to propose a small wind turbine and battery storage based packet energy system. A small wind turbine with battery storage has been simulated in Matlab/Simulink. The system has been modeled using low order transfer functions. This model provides faster simulation than the built in Simulink blocks. Energy packets have been produced from the model using random switching. A prototype of the battery based energy storage system has been designed and implemented. This prototype can take instructions from the energy dispatch center and provide energy packet according to the instruction from the dispatch center. Lab tests and simulation results indicate that the designed packet energy network is able to provide energy packets as required by the grid. Additionally, the output power from a very large energy packet network is also found to be stable with the existence of large load fluctuation.

The outcomes of the analysis presented in the thesis are listed below:

- A designed packet energy network system, consisting of thousands of smaller packet energy system, is able to provide stable power.
- With the help of energy packet network, smart energy dispatching centers can take full advantage of renewable energy sources.
- Experimental results show that it is possible to implement such an energy packet system in the existing grid. The proposed packet energy network could be implemented using already available commercial technology.

5.2 Future Works

- In the present analysis, the battery based energy storage system has been designed and a small prototype has been implemented in the lab. Lead acid batteries have been used as energy storage system. Lithium-ion batteries and a high efficiency charger can be used to increase the efficiency of the packet energy system.
- A battery charger has been used to charge the batteries from the grid. An inverter has been used to convert dc to ac. A bidirectional inverter can be used to analyze the effect of the battery-based energy storage system in real life situations.
- Low order transfer functions have been used to model the wind turbine based packet energy system. The model can be developed further by using higher order transfer function to investigate the effect of the packet energy system.
- In this research, only wind energy has been used to model the energy packet network. PV modules can also be integrated to the energy packet network model.
- In the present experimental investigation, the designed prototype was not connected to the wind turbine. Further experimental investigation of a system including wind turbine and PV modules connected to the battery storage system to demonstrate the whole energy packet network system with variable load is required.
- A detailed economic analysis can also be done.

Appendix A

Table A.1: Simulink Block Parameters

Simulation Block	Parameter	Value
Battery	Battery type	Lead-acid
	Nominal Voltage	6×8 V
	Rated Capacity	305×2 Ah
	Internal Resistance	0.00019672×8/2
	Initial State of Charge (%)	80
Inverter	Power Electronic Device	IGBT/Diodes
PWM Generator	Carrier Frequency	1080 Hz
	Modulation Index, m	1
	Frequency of output voltage	60Hz
Rectifier	Power Electronic Device	Diodes
Transformer	Rating	10 KVA, 60 Hz
Single Phase LC Filter	L1	2 mH
	C1	1 mF
	C2	5 mF
Three Phase LC Filter	L	3 μH
	Capcitive reactive power	10 kvar
Grid	Voltage (p-p)	600 Vrms
Powergui	Sample Time	5×10^{-5} *sec.*

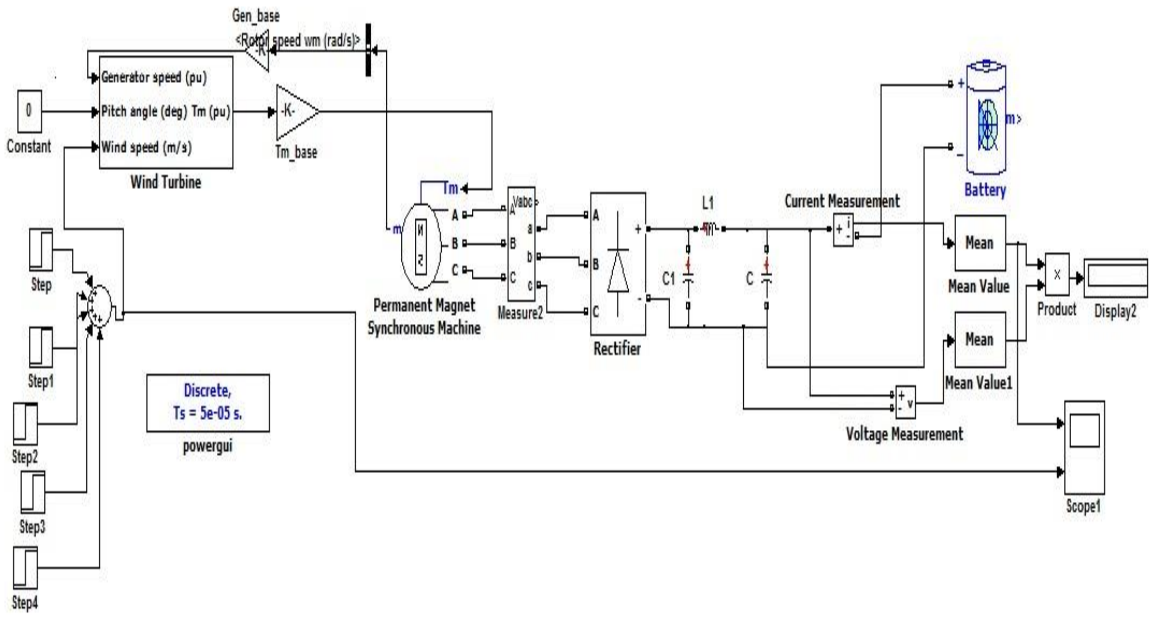


Figure A.1: First part of Simulink diagram used to model energy packet network in chapter 4

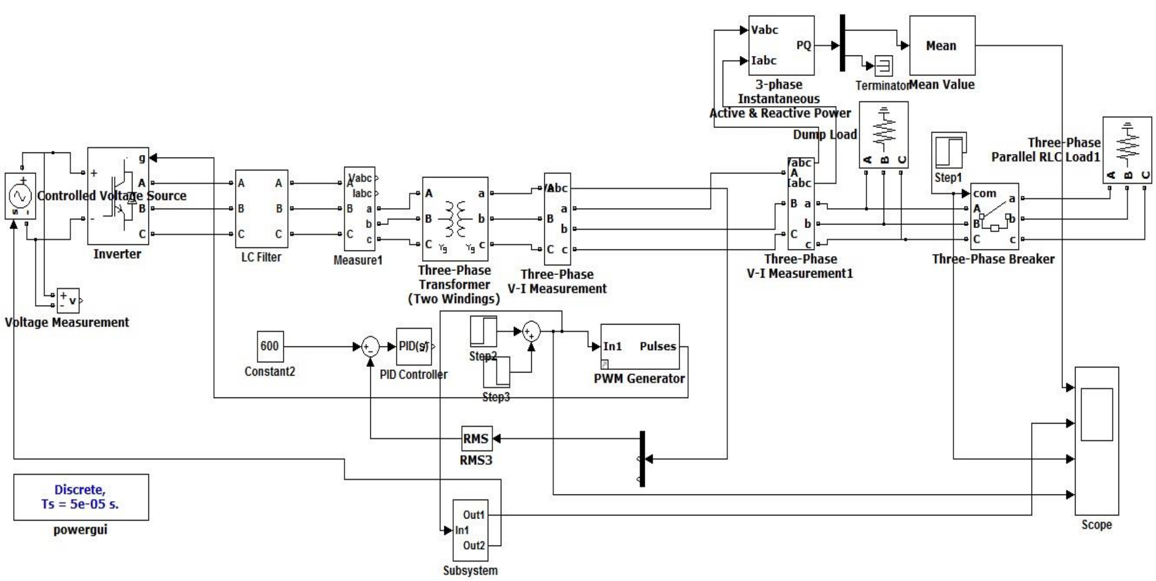


Figure A.2: Second part of Simulink diagram used to model energy packet network in chapter 4

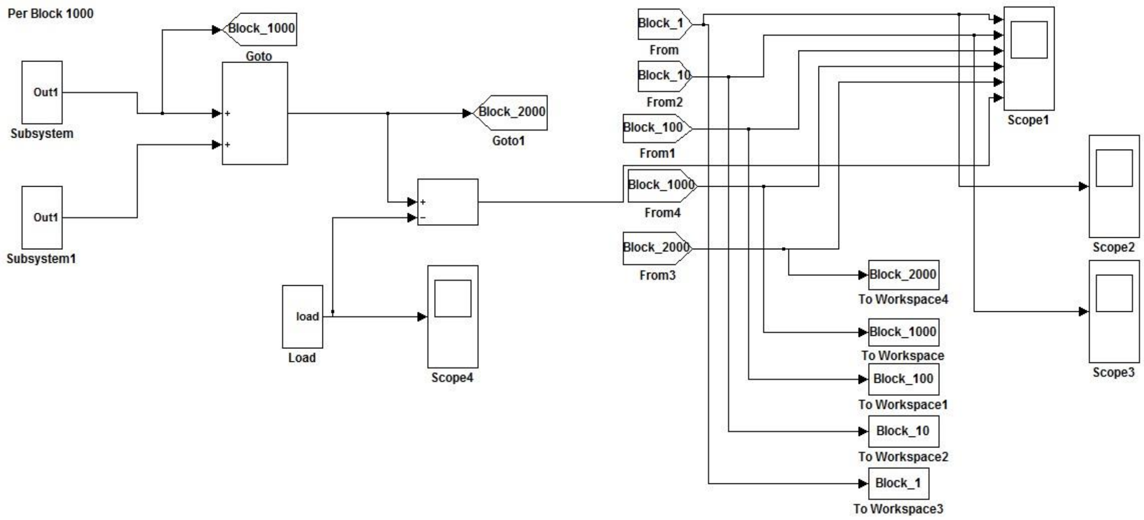


Figure A.3: Simulink Diagram of Energy Packet Network used in chapter 4

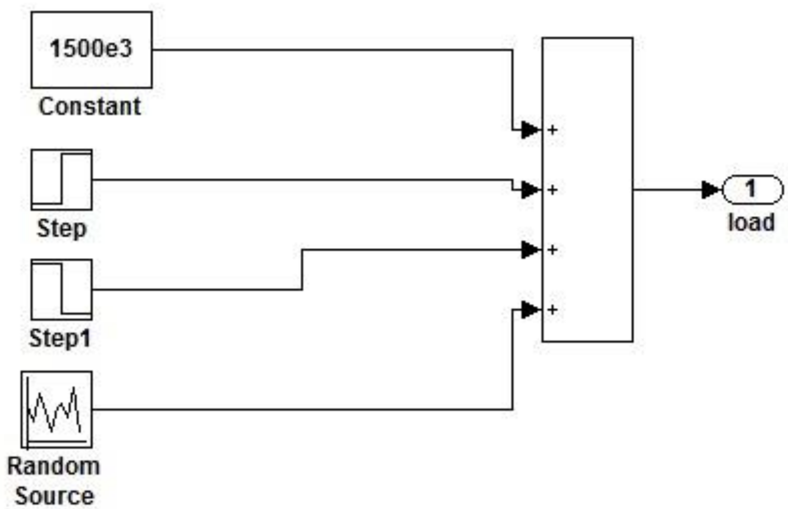


Figure A.4: Load model used in chapter 4


Inverter
Md Shakhawat Hossain <msh358@mun.ca>
Sent: Fri 07/03/2014 12:18 PM
To: Hossain Md. Shakhawat

Inverter on
Duration 30 (sec)

Figure A.5: Email format to control inverter on/off used in chapter 4

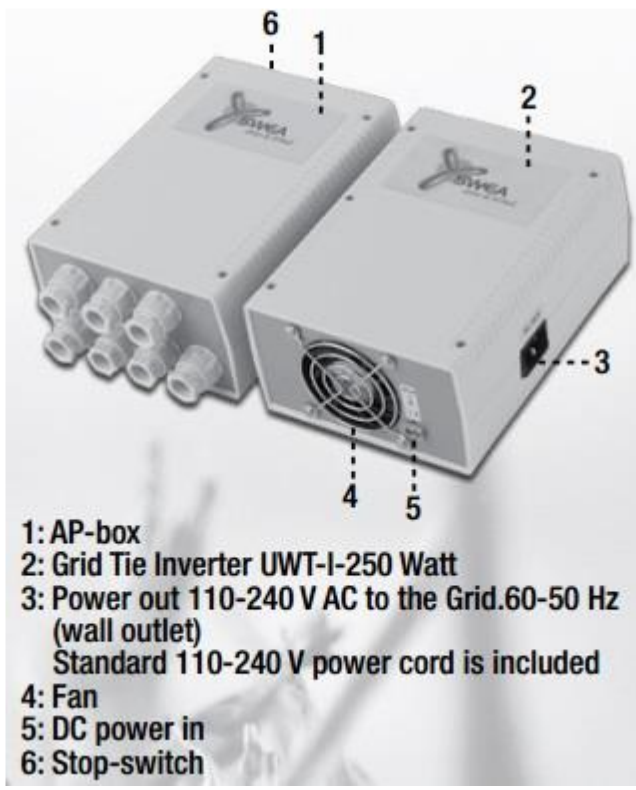
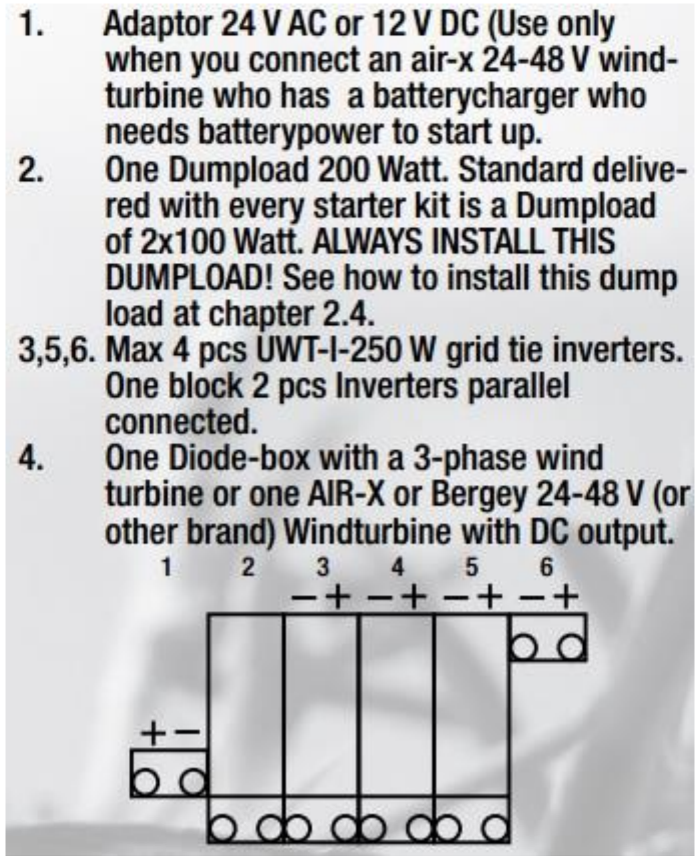


Figure A.6: Grid Tie Inverter & AP Box used in chapter 3 & chapter 4



1. Adaptor 24 V AC or 12 V DC (Use only when you connect an air-x 24-48 V wind-turbine who has a batterycharger who needs batterypower to start up.
2. One Dumpload 200 Watt. Standard delive-red with every starter kit is a Dumpload of 2x100 Watt. ALWAYS INSTALL THIS DUMPLOAD! See how to install this dump load at chapter 2.4.

3,5,6. Max 4 pcs UWT-I-250 W grid tie inverters. One block 2 pcs Inverters parallel connected.

4. One Diode-box with a 3-phase wind turbine or one AIR-X or Bergey 24-48 V (or other brand) Windturbine with DC output.

Figure A.7: Connection Block Number of AP-Box from the manual [Ref: SWEA Solar & Wind]

Appendix B

Matlab Code used for data collection from DI- 148U:

```
clear all;

analog_port=5;
ai=analoginput('dataq',0);
addchannel(ai,0:analog_port-1);
set(ai,'SampleRate',1000);
ActualRate = get(ai,'SampleRate');
set(ai,'SamplesPerTrigger', ActualRate);


% Save date and time as a file name

time=datestr(clock,'yyyymmdd-HHMMSS');
%filename=strcat('Charging_',time, '.txt');
filename=strcat('Discharging_',time, '.txt');
fid=fopen(filename, 'wt'); % create file in current directory

fprintf(fid,'%s\t %s\t %s\t %s\t %s\n', 'Battery Voltage','Charging
Current','Discharging Current','Grid Current','Test');


sensor_1_cal=1.1361;
sensor_2_cal=1.1026;
grid_voltage=115.5;

for i=1:10

    start(ai)
    %sampling time is 10s
    pause(30)
    it= get(ai,'SamplesAvailable')
    raw_data=getdata(ai,it);

    data_1=raw_data(:,1);
    data_2=raw_data(:,2);
    data_3=raw_data(:,3);
    data_4=raw_data(:,4);
    data_5=raw_data(:,5);

    d1=mean(data_1);
    d2=mean(data_2);
    d3=mean(data_3);
    d4=mean(data_4);
```

```
    d5=mean(data_5);

    battery_voltage=10.725*d1;
    charging_current=sensor_1_cal*d2;
    discharging_current=sensor_2_cal*d3;
    grid_current=-0.20535*d4^2+0.87902*d4+0.16941;

    x=[i battery_voltage]

    fprintf(fid,'%6.4f\t  %6.4f\t %6.4f\t %6.4f\t %6.4f\n',
battery_voltage,charging_current,discharging_current,grid_current,d5);


end

fclose(fid);

% Cleanup workspace
delete(ai)
clear ai
```

Matlab Code used for data processing

```
%%%%%%% Data Processing%%%%%%%%%%%%%%%%%%%%%%%
clear all
grid_voltage=116;
%modified_data=importdata(filename);
modified_data=importdata('Charging_desk_1.txt');
modified_data=importdata('Discharging_desk_1.txt');
[m,n]=size(modified_data.data);
battery_voltage=modified_data.data(:,1);
charging_current=modified_data.data(:,2);
discharging_current=modified_data.data(:,3);
grid_current=modified_data.data(:,4);




prompt = {'Charging[1] & Discharging[2]'};
dlg_title = 'Input';
num_lines = 1;
def = {'0'};
options.Resize='on';
options.WindowStyle='normal';
options.Interpreter='tex';
answer =inputdlg(prompt,dlg_title,num_lines,def,options);
state=str2double(answer);
```

```
if state==1
    %During Charging
    discharging_current=zeros(m,1);
    grid_current=zeros(m,1);
else
    %During Discharging
    charging_current=zeros(m,1);
end


charging_power=battery_voltage.*charging_current;
discharging_power=battery_voltage.*discharging_current;
grid_power=grid_current*grid_voltage;

Battery_Charging_Energy_Wh=sum(charging_power*0.5/60)
Battery_Discharging_Energy_Wh=sum(discharging_power*0.5/60)
Grid_Energy_Wh=sum(grid_power*0.5/60)

battery_efficiency=discharging_power/charging_power;
inverter_efficiency=(grid_power./discharging_power)*100;

t=0:0.5:m/2-0.5;

figure(1)

plot(t,battery_voltage);
title('Battery Voltage')
xlabel('Time (min)')
ylabel('Battery Voltage (V)')

figure(2)

plot(t,charging_current);
title('Charging Current')
xlabel('Time (min)')
ylabel('Charging Current (A)')

figure(3)

plot(t,discharging_current);
title('Discharging Current');
xlabel('Time (min)')
ylabel('Discharging Current (A)')

figure(4)

plot(t,grid_current);
title('Grid Current');
xlabel('Time (min)')
ylabel('Grid Current (A)')
```

```
figure(5)

plot(t,charging_power);
title('Charging Power')
xlabel('Time (min)')
ylabel('Charging Power (W)')

figure(6)

plot(t,discharging_power);
title('Discharging Power')
xlabel('Time (min)')
ylabel('Discharging Power (W)')

figure(7)
plot(t,grid_power);
title('Grid Power');
xlabel('Time (min)')
ylabel('Grid Power (W)')

figure(8)

plot(t(1:400),inverter_efficiency(1:400))
title('Inverter Efficiency');
xlabel('Time (min)')
ylabel('Inverter Efficiency (%)')
```

Matlab Code used to control the inverter on/off from smart energy dispatch center

```
clear all;

% Connecting to Outlook
outlook = actxserver('Outlook.Application');
mapi=outlook.GetNamespace('mapi');
INBOX=mapi.GetDefaultFolder(6);

% Connecting to DATAQ
dataqsdk1 = actxcontrol('DATAQSDK.DataqSdkCtrl.1');
set(dataqsdk1, 'DeviceID', 'COM04 148 460800');
set(dataqsdk1, 'DeviceDriver', 'DI104NT.DLL');
set(dataqsdk1,'EventPoint',20)
set(dataqsdk1,'SampleRate',240)
set(dataqsdk1,'ADChannelCount',4)
set(dataqsdk1,'MaxBurstRate',200000)
set(dataqsdk1,'DigitalOutput',-32765)
led=0;

for i=1:50
```

```
    pause(2)

    % Retrieving last email
    count = INBOX.Items.Count; %index of the most recent email.
    firstemail=INBOX.Items.Item(count); %imports the most recent email
    subject = firstemail.get('Subject');
    body = firstemail.get('Body');
    duration=str2double(body(22:strfind(body,'(')-1));
    if count > led
        if size(strfind(body,'Inverter on'))==0
            set(dataqsdk1,'DigitalOutput',0)


        else
            set(dataqsdk1,'DigitalOutput',4)
            pause(duration)
            set(dataqsdk1,'DigitalOutput',0)
        end

        led=count;
    end

    i

end
release(dataqsdk1)
```

Appendix C

Table C.1: Sample experimental data of battery voltage, charging current and grid current during charging cycle

Battery Voltage (V)	Charging Current (A)	Discharging Current (A)	Grid Current (A)
44.1137	0	0	0.181
45.6388	0.6341	0	0.1809
45.8715	0.6345	0	0.1809
45.9874	0.6349	0	0.181
46.0471	0.6346	0	0.1811
46.167	0.6349	0	0.1809
46.2359	0.6346	0	0.181
46.3	0.6349	0	0.1811
46.3601	0.6349	0	0.1808
46.4172	0.6349	0	0.1809
46.4453	0.6349	0	0.1809
46.5135	0.6349	0	0.1809
46.5491	0.6349	0	0.1809
46.5844	0.635	0	0.1808
46.591	0.6351	0	0.1809
46.6443	0.6371	0	0.1808
46.6688	0.6348	0	0.1809
46.6693	0.6348	0	0.1808
46.6847	0.635	0	0.181
46.7259	0.635	0	0.1808
46.7429	0.6349	0	0.1809
46.7539	0.6349	0	0.1809
46.7446	0.6349	0	0.1809
46.7731	0.6349	0	0.1808
46.7909	0.6349	0	0.1809
46.7947	0.6349	0	0.1809
46.8058	0.635	0	0.1808
46.8153	0.6351	0	0.1808
46.8001	0.6349	0	0.1809
46.8368	0.635	0	0.181
46.823	0.6351	0	0.1809
46.8608	0.6351	0	0.1809
46.8698	0.6349	0	0.1808
46.8751	0.6349	0	0.1809
46.8595	0.6349	0	0.181
46.8899	0.6348	0	0.181
46.9015	0.6348	0	0.1809
46.8853	0.6348	0	0.1807
46.9123	0.6348	0	0.181
46.924	0.6346	0	0.1808
46.9265	0.6345	0	0.1809
46.9378	0.6347	0	0.1808
46.9452	0.6348	0	0.1809
46.9577	0.6346	0	0.181
46.9609	0.6346	0	0.1809
46.9689	0.6347	0	0.1809

Battery Voltage (V)	Charging Current (A)	Discharging Current (A)	Grid Current (A)
46.98	0.6347	0	0.1808
46.9909	0.6348	0	0.1809
46.9989	0.6347	0	0.1809
47.0106	0.6347	0	0.1809
47.0209	0.6347	0	0.1808
47.032	0.6347	0	0.1809
47.0125	0.6346	0	0.1809
47.0433	0.6347	0	0.1808
47.0559	0.6349	0	0.1808
47.0656	0.6347	0	0.181
47.0736	0.6346	0	0.181
47.0584	0.6348	0	0.1809
47.0925	0.6368	0	0.1808
47.102	0.6346	0	0.1808
47.0926	0.6346	0	0.1809
47.1271	0.6347	0	0.1809
47.1321	0.6346	0	0.1809
47.1487	0.6346	0	0.1808
47.1561	0.6346	0	0.1809
47.1437	0.6347	0	0.1809
47.1484	0.6347	0	0.1809
47.1844	0.6346	0	0.1809
47.1933	0.6347	0	0.1809
47.2004	0.6346	0	0.1809
47.1869	0.6345	0	0.1809
47.2205	0.6346	0	0.1809
47.229	0.6347	0	0.1809
47.2118	0.6366	0	0.1808
47.2459	0.6345	0	0.1808
47.2542	0.6346	0	0.1808
47.242	0.6344	0	0.1809
47.2494	0.6346	0	0.1808
47.2839	0.6347	0	0.1808
47.2944	0.6349	0	0.1809
47.3036	0.6347	0	0.1809
47.3083	0.6346	0	0.1809
47.2962	0.6345	0	0.1809
47.3338	0.6345	0	0.1808
47.3401	0.6344	0	0.1808
47.3541	0.6343	0	0.1809
47.3644	0.6346	0	0.1808
47.3458	0.6346	0	0.1809
47.3837	0.6344	0	0.1808
47.3938	0.6348	0	0.1809
47.4016	0.6345	0	0.1808
47.3866	0.6346	0	0.1808

Battery Voltage (V)	Charging Current (A)	Discharging Current (A)	Grid Current (A)
47.423	0.6346	0	0.1809
47.4305	0.6346	0	0.1809
47.444	0.6344	0	0.1809
47.4237	0.6344	0	0.1809
47.432	0.6343	0	0.1809
47.4671	0.6344	0	0.1809
47.4811	0.6345	0	0.1809
47.4903	0.6346	0	0.1809
47.4935	0.6347	0	0.1809
47.5072	0.6346	0	0.1808
47.5137	0.6345	0	0.1809
47.5244	0.6346	0	0.1808
47.5344	0.6345	0	0.1808
47.5188	0.6341	0	0.1808
47.5541	0.6342	0	0.1809
47.5438	0.6344	0	0.1808
47.5533	0.6345	0	0.1808
47.5869	0.6344	0	0.1809
47.5766	0.6344	0	0.181
47.6106	0.6344	0	0.1808
47.597	0.6345	0	0.1807
47.6031	0.6344	0	0.1808
47.64	0.6344	0	0.1807
47.6473	0.6344	0	0.1808
47.6583	0.6345	0	0.1809
47.6403	0.6344	0	0.1809
47.673	0.6347	0	0.1808
47.6603	0.6344	0	0.1808
47.6945	0.6345	0	0.1809
47.7019	0.6345	0	0.1809
47.7081	0.6347	0	0.1809
47.7181	0.6345	0	0.1808
47.7063	0.6346	0	0.1809
47.7405	0.6346	0	0.1808
47.7474	0.6346	0	0.1808
47.7567	0.6347	0	0.1808
47.7684	0.6347	0	0.1809
47.7482	0.6346	0	0.1808
47.7577	0.6345	0	0.1809
47.7917	0.6347	0	0.1809
47.7799	0.6346	0	0.1808
47.8146	0.6347	0	0.1809
47.8274	0.6346	0	0.1809
47.8388	0.6348	0	0.1808
47.8453	0.635	0	0.181
47.8599	0.6347	0	0.1808

Table C.2: Sample experimental data of battery voltage, charging current and grid current during discharging cycle

Battery Voltage V)	Charging Current (A)	Discharging Current (A)	Grid Current (A)
49.425	0	1.8043	0.6688
49.4263	0	1.831	0.6715
49.427	0	1.8005	0.6648
49.3829	0	1.8056	0.6648
49.3749	0	1.8116	0.6643
49.3696	0	1.7933	0.6643
49.3819	0	1.7927	0.6594
49.3491	0	1.786	0.6582
49.3757	0	1.7546	0.6507
49.3495	0	1.7812	0.656
49.3247	0	1.7674	0.6525
49.3344	0	1.7601	0.6491
49.3159	0	1.7794	0.6546
49.3162	0	1.7533	0.6467
49.2695	0	1.7675	0.6488
49.2661	0	1.7611	0.6489
49.2806	0	1.7587	0.6484
49.2474	0	1.7656	0.6486
49.2622	0	1.7442	0.6428
49.2611	0	1.718	0.6324
49.2384	0	1.7538	0.6425
49.2109	0	1.7164	0.6331
49.2211	0	1.7271	0.6327
49.1923	0	1.7227	0.6354
49.1886	0	1.6985	0.6252
49.1728	0	1.7136	0.626
49.1811	0	1.7201	0.6331
49.1465	0	1.7267	0.6311
49.1401	0	1.7216	0.635
49.1559	0	1.7002	0.6255
49.1428	0	1.7007	0.6237
49.1318	0	1.6886	0.632
49.1128	0	1.7209	0.6292
49.101	0	1.7182	0.636
49.1069	0	1.6758	0.6176
49.1058	0	1.6474	0.6054
49.0846	0	1.6685	0.6196
49.0813	0	1.6622	0.612
49.0744	0	1.6504	0.6015
49.0377	0	1.6554	0.6122
49.0476	0	1.6644	0.6126
49.0348	0	1.6577	0.6142
49.0287	0	1.6596	0.6145
49.0201	0	1.6465	0.607
48.9863	0	1.7036	0.625
48.9689	0	1.7249	0.6265

Battery Voltage V)	Charging Current (A)	Discharging Current (A)	Grid Current (A)
48.9901	0	1.632	0.5994
48.9778	0	1.6352	0.6008
48.9659	0	1.6538	0.6063
48.9549	0	1.6387	0.6046
48.9449	0	1.6519	0.6055
48.9297	0	1.6515	0.6086
48.9245	0	1.6272	0.5993
48.9081	0	1.6391	0.6032
48.8841	0	1.6647	0.614
48.8837	0	1.6426	0.6014
48.8726	0	1.5863	0.5824
48.8407	0	1.6477	0.6072
48.8343	0	1.6773	0.616
48.8284	0	1.668	0.6144
48.8323	0	1.6219	0.5912
48.8066	0	1.6541	0.6096
48.8174	0	1.598	0.5917
48.8096	0	1.5908	0.5836
48.7615	0	1.6334	0.6019
48.7881	0	1.5811	0.5779
48.7651	0	1.6274	0.5956
48.7467	0	1.5555	0.5761
48.7403	0	1.635	0.6024
48.7442	0	1.5934	0.5858
48.7137	0	1.6369	0.5956
48.7062	0	1.5705	0.5763
48.7185	0	1.5714	0.5717
48.7086	0	1.5635	0.5724
48.6776	0	1.5434	0.5656
48.6894	0	1.5554	0.5723
48.6781	0	1.5548	0.5712
48.6704	0	1.5465	0.5661
48.6413	0	1.5194	0.5641
48.6258	0	1.5395	0.5658
48.644	0	1.5211	0.5584
48.6184	0	1.5649	0.5659
48.5931	0	1.5598	0.5696
48.5947	0	1.5639	0.5713
48.5869	0	1.5606	0.5733
48.5868	0	1.5399	0.5635
48.5651	0	1.5744	0.5774
48.5615	0	1.5404	0.5659
48.5421	0	1.5745	0.5702
48.5437	0	1.5309	0.5619
48.5052	0	1.5582	0.5647
48.5084	0	1.5421	0.5645

Battery Voltage V)	Charging Current (A)	Discharging Current (A)	Grid Current (A)
48.5091	0	1.5449	0.5602
48.5045	0	1.5296	0.5571
48.4698	0	1.5337	0.5543
48.4847	0	1.5243	0.5587
48.4636	0	1.4966	0.5459
48.4489	0	1.504	0.5485
48.4689	0	1.4925	0.5439
48.452	0	1.5021	0.5461
48.4387	0	1.5069	0.55
48.4106	0	1.5108	0.5469
48.4232	0	1.5055	0.5479
48.4089	0	1.5036	0.5447
48.4043	0	1.4889	0.5429
48.3921	0	1.4986	0.5388
48.3806	0	1.4811	0.5424
48.3737	0	1.4912	0.536
48.3632	0	1.4884	0.5474
48.3566	0	1.4701	0.5308
48.3425	0	1.482	0.5404
48.3136	0	1.4772	0.5315
48.3096	0	1.4595	0.5314
48.3197	0	1.4696	0.5303
48.2833	0	1.464	0.534
48.3006	0	1.4606	0.5257
48.2994	0	1.4361	0.5204
48.2653	0	1.4603	0.5266
48.2813	0	1.4448	0.5276
48.2445	0	1.4478	0.5229
48.2627	0	1.4357	0.5239
48.2416	0	1.4572	0.5314
48.2453	0	1.4206	0.5176
48.2139	0	1.4231	0.5181
48.2284	0	1.4107	0.5123
48.198	0	1.4378	0.5209
48.2162	0	1.4002	0.5124
48.1709	0	1.4288	0.5219
48.1696	0	1.4089	0.5127
48.1641	0	1.452	0.5309
48.1787	0	1.3816	0.5025
48.1548	0	1.4178	0.5148
48.1552	0	1.3961	0.507
48.1102	0	1.4363	0.5199
48.0899	0	1.4513	0.5226
48.1167	0	1.4063	0.5145
48.0826	0	1.4131	0.504
48.104	0	1.3976	0.5034