COORDINATED OPERATIONS OF DISTRIBUTED WIND GENERATION IN A DISTRIBUTION SYSTEM USING PMUS

by

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B.E., ANNA UNIVERSITY, CHENNAI, INDIA, 2010

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Electrical and Computer Engineering
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2012

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Abstract

Wind energy is becoming one of the most widely implemented forms of renewable energy worldwide. Traditionally, wind has been considered a non-dispatchable source of energy due to the uncertainty of wind speed and hence the variable availability of wind power. Advances in technology allow the consideration of the impact of distributed wind turbines and farms on distribution systems. It is possible to combine the clean energy attributes of wind with the quickly dispatchable nature of a storage facility in order to provide the maximum amount of locally available power economically to the loads present on the distribution feeder. However, a monitoring and control system needs to be provided that is capable of detecting the changes associated with the distribution feeder load and also the variable generation output from the wind farms. This task can be accomplished using a Phasor Measurement Unit (PMU) which has very high sampling rates and hence can measure very rapid and dynamic changes in power levels associated with distribution feeder load and wind generation. The data which is obtained from these PMUs can be used to calculate the amount of distributed generation and storage that can be dispatched locally at the distribution feeder, thus resulting in a reduction in the peak load levels associated with the distribution feeder as seen by the substation monitoring system. Simulations will work to balance load requirements, wind generation output, and distributed storage providing a stable system utilizing maximum renewable resources. The standard IEEE 37-node distribution test feeder is used in the study. Probabilistic models are implemented for distribution feeder load, and the models are analyzed through simulations. Four different combinations of charging and discharging methods have been investigated. Two analytically different algorithms have been used for wind and battery dispatch, one based on forecasted load information and the other based on historical measurements obtained from PMUs. The strategies being investigated can also be used to implement other important applications such as distribution system state estimation, protection and instability prediction.

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Acknowledgements

I would like to thank the members of my master's thesis committee Dr. Noel Schulz, Dr. Anil Pahwa and Dr. Shelli Starrett for their valuable contributions, advice, guidance, encouragement, and corrections during the entire study and research of this work.

I would like to thank Dr. Ruth Miller and my friend and colleague Dulan Weerasinghe for their valuable inputs, contributions, and guidance during the study and research of this work. I would like to thank the department of Electrical and Computer Engineering for funding this research work.

Dedication

I would like to dedicate this research work to my parents who have always been there to support and encourage me.

Chapter 1 - Introduction

1.1 Introduction and Motivation

The electric power distribution network is often the most overlooked but also the most complex part of the entire power system. While the measurements currently available from the power system are sufficient to ensure the proper working of the generation and transmission system infrastructure, under contingency issues, the distribution system often bears the brunt of all emergency measures taken to bring the system back to its original stable state. This includes measures such as load shedding leading to branch outages, and more recently, islanding of certain parts of the distribution grid to local distributed generation. For quite a few years now, there has been an increasing interest in the installation of renewable energy generation at the transmission as well as the distribution levels, but these still constitute a very small percentage of all the power generated in North America [28]. Under current NERC regulations [29], all forms of renewable generation are currently required to disconnect from the system under abnormal or emergency conditions. The main reason for this regulation is that most renewable energy resources, such as wind and solar, are non-dispatchable due to uncertainty associated with the respective natural resources of wind and sunlight. This leads to a variable availability in power generated from these sources. The focus of this thesis research is on issues faced when working with interconnected wind energy. When wind energy is considered, the issues encountered relate to dynamic changes associated with system voltages and other parameters that would make the system stability a challenge. The challenges arise also due to lack of sufficiently dynamic measurement information required to assess the state of the system. Under present day conditions, the only measurements available from the distribution system may include aggregated load demand of the distribution feeder as seen by the substation monitoring system.

Utilities have started to realize that observability of the distribution system is important in order to have a clear understanding of load dynamics and to assess the state of the system. So, many utilities across North America have begun installing smart meters in the form of Advanced Metering Infrastructure (AMI) in their distribution grids [30]. But this only gives a detailed picture in terms of load demand but not in terms of the actual state of the system. Also, these measurements are not time stamped in any way. In this research, the utilization of Phasor Measurement Units (PMU) in order to ensure the proper working of distributed wind generation with storage has been investigated. The smart grid initiative was taken to improve the efficiency and reliability of the overall power system. This research aims to improve efficiency by working at the lowest level of the power system hierarchy. In a smart grid environment, some of the available aspects are renewable energy and advanced measurement infrastructure giving enormous amounts of data. This research aims to make use both of these aspects of the smart grid at the distribution level. The emphasis is on the use of dynamic measurements in order to control the amount and instance of consumption of wind energy or storage. Distributed storage aids this process by working to use stored power from wind energy when it is most required. Even a slight reduction in an individual feeder's load at a given instance of time due to wind and storage can result in aggregated savings of many megawatts of power for the upper generation and transmission system levels, resulting in benefits such as reducing overloads of transmission lines, reduction of required spinning reserve and installed capacity, and improvements in the life expectancy of various equipment including the delaying of buying new equipment.

The penetration of wind energy in the U.S. in the distribution system has been increasing steadily over the last few years partly because of the smart grid initiative. Established practices in the distribution system consist of directly connecting the wind turbines to the distribution grid so that they are always online. But this approach may not yield satisfactory results when the wind generation profile and the load profile in a given distribution feeder are negatively correlated. This research aims to solve this problem with the addition of distributed storage. The batteries directly store the wind energy by taking the turbines offline when the load is below a certain predetermined level. When the load is above this level, the wind turbine energy is directly supplied in order to satisfy load requirements, but the battery is also discharged in order to minimize the part of the load that needs to be satisfied by the bulk power from the source node at the substation. This effectively results in the system trying to keep the substation monitored load as close to a predetermined value as possible. The peak load of the feeder reduces, resulting in various benefits as described earlier when this solution is implemented for multiple feeders.

The other aim of this research is to demonstrate that the usage of dynamic measurements recorded by PMUs will help to reduce the capacity of the storage system required for a certain penetration of wind energy. This is an important problem to investigate as storage is one of the most expensive technologies to implement in a distribution system. The fact remains that presently, PMUs are also expensive to implement, but the benefits that PMUs provide to any part of the power system can outweigh economic costs as the use of the technology becomes more widespread.

1.2 Summary of Results

The change in the profile of the substation monitored feeder load due to direct connection of the wind farm to the distribution feeder is presented initially. We consider the initial wind generation penetration as 30% of the peak feeder load. This number can be increased in future studies. The initial capacity of distributed storage is considered as equal to the installed wind generation capacity. The improvements in the load profile of the distribution feeder are presented for co-ordination between wind generation and distributed storage. The analysis is done for 15-minute forecasted load and wind generation data for a 24 hour period initially and then later for a one second basis load and wind generation profile. Four different combinations of charging and discharging methods of the batteries are investigated in this research. They are given below and will be explained in more detail in the thesis

i. Wind charging and Free-run discharging
ii. Wind charging and Conservative discharging
iii. Sustained average load charging and Free-run discharging
iv. Sustained average load charging and Conservative discharging

All the four combinations described above are investigated and the results presented for both 15-minute basis data as well one-second basis data. The use of wind energy and storage in a distribution system with three-phase unbalanced backward and forward sweep power flow algorithm has been undocumented so far in literature and has been newly implemented in this research. Additionally, conservative discharging of the battery based on instantaneous stored energy level or state of charge, wind generation availability and load requirement is an approach that has been newly investigated in this research. Two methods have been implemented to do this process, one without the direct use PMU measurements and one with the use of direct historic PMU measurements. In all cases, the results presented pertain to the following.

- Load profile of the distribution feeder as seen by the substation monitoring system
- Voltage profile of the node where the wind farm and the storage have been installed
- Charging and discharging of the battery for each time instant
- Energy level curve of the battery based on charging and discharging
- Line losses of the distribution feeder due to installation of the wind farm and battery storage.

All of these results give a detailed picture of the dynamics of load, wind generation and storage, and also provide the results required in order to reduce required battery capacity as dynamic measurements become more available.

1.3 Outline

The first chapter provides an introduction into the problem that the research will try to address and also an explanation of the results that are obtained. Chapter 2 will explain some background about various concepts and methods used in this research and also present literature review about various methods and solutions that have been implemented before in order to solve the problem addressed here. There will also be an explanation of new contributions including techniques and methods developed. Chapter 3 will explain in greater detail the objectives of this research, and the approach and steps in the process of achieving this objective. Chapter 4 will present the creation of test cases and the data that was used in the analysis part of the research. Chapter 5 will explain the tools, such as algorithms for backward forward sweep power flow and battery charging and discharging. Chapter 6 will discuss in detail the results that were obtained in the analysis and research and give the explanation of these results. Chapter 7 will provide conclusions and suggest possibilities for future work.

Chapter 2 - Background and Literature Review

2.1 Background

This section will explain some background about various concepts and methods used in this research. Some fundamentals about various components of this research such as distribution systems, wind generation and storage techniques and parameters, and PMUs, have been explained.

2.1.1 Distribution System Structure

In North America, distribution systems are usually constructed in a radial structure as they are very easy to implement and also are the least expensive and easy to operate and maintain [26]. The other important attribute of the North American distribution systems is that the three phase loads are predominantly unbalanced. So, a single phase equivalent analysis using methods such as the Newton Raphson power flow algorithm would yield inaccurate or unsatisfactory results. So, in distribution system analysis of unbalanced radial feeders, backward forward sweep power flow algorithm is often used [31]. This method follows a three phase equivalent programming structure for voltage, current and impedance and is based on the iterative solution of the basic ladder network from circuit theory. It also considers factors such as mutual impedance between phase conductors. A detailed explanation of this algorithm will be given in chapter 4.

2.1.2 Distribution System Load Profile

In a typical distribution system, the loads vary according to the time of day, day of the week, weather, and season. The load profiles are different for different nature of loads. The profile or shape of the load curve varies based on the type of load and they are classified into the following types:

i. Residential load

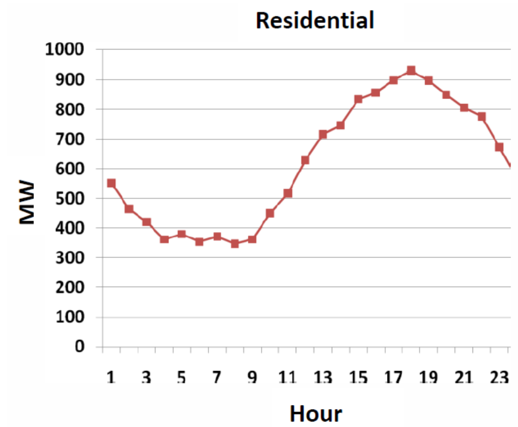

Figure 2.1 Aggregated Residential load curve [26]

ii. Commercial load

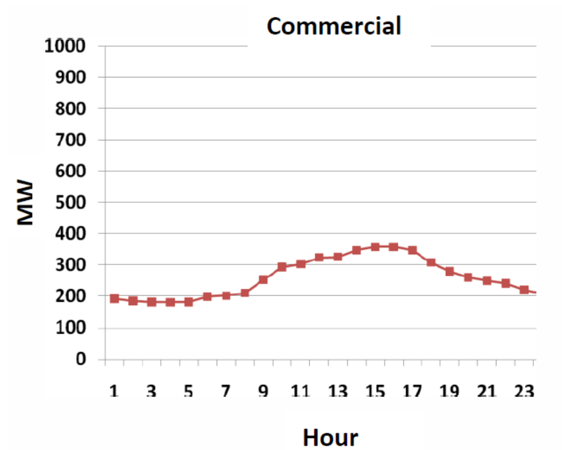

Figure 2.2 Aggregated Commercial load curve [26]

iii. Industrial load

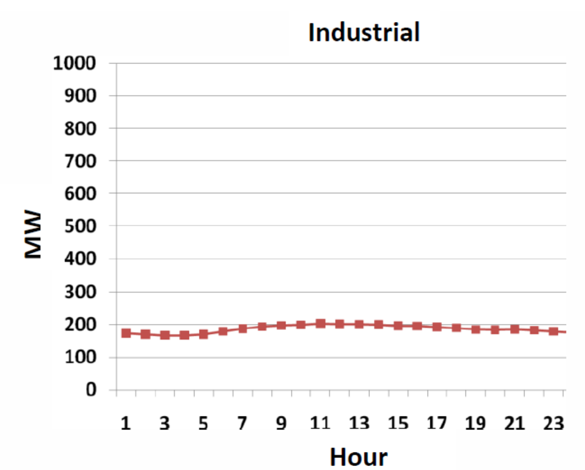

Figure 2.3 Aggregated Industrial load curve [26]

As it can be seen from the figures given above, the residential load is the maximum contributing factor to the dynamics of the distribution feeder load curve. So, the 15-minute average normalized load profile of a group of houses has been used in order to create the test cases for this research. A detailed explanation will be provided in chapter 4.

2.1.3 Wind Energy Generation

Wind energy generation is usually modeled using a Rayleigh or Weibull probability distribution [9]. But in order to clearly observe the effects of different levels of wind generation on the storage system of the distribution feeder, actual data from a wind turbine has been used in this research. Data was recorded for a low wind day, medium wind day, and high wind day on a 15-minute basis for a 24 hour period. There is also a one-second basis wind data file for a 24 hour period [27]. For a wind turbine, the reactive power generated is not a function of rotor dynamics and is produced by the converter that helps connect the wind turbine to the power system. This converter's reactive power output can be controlled between set minimum and maximum values independent of wind power generation. So, for the study of behavior of distributed storage, reactive power generation at constant power factor is considered, i.e., it is always a given fraction of the real power generation. Also, due to this assumption, in the power flow study, wind generation node is considered as negative load node instead of voltage controlled node. If the wind node were to be considered as a voltage controlled node, the reactive power generation of the turbine would have to be a variable for every time instant, as the objective of reactive power generated would be to maintain the positive sequence voltage of the node as close to the nominal value as possible [2].

2.1.4 Distributed Storage

In order to operate a battery as distributed storage, the specifications required are rated power, energy capacity, charging and discharging efficiency, and time delay. The rated power limits the charging and discharging rate of the battery. The energy capacity is a measure of the state of charge and determines the efficient operation of battery for the given load requirement. The efficiency of the battery determines the fraction of wind power that actually charges the battery and the losses through the power converter when the battery is online or connected to wind farm. The time delay is of importance in this study as PMU measurements are involved. PMUs can sample data at 30 samples per second, but the delay of the battery is a few milliseconds to one second [21]. So, the apparent average of 30 measurements from one PMU has been simulated in this study and used in the analysis as one second measurements.

2.1.5 Phasor Measurement Units

Phasor measurement units measure the voltage and phase angle of a node using a time-synchronized GPS (Global Positioning System) signal.

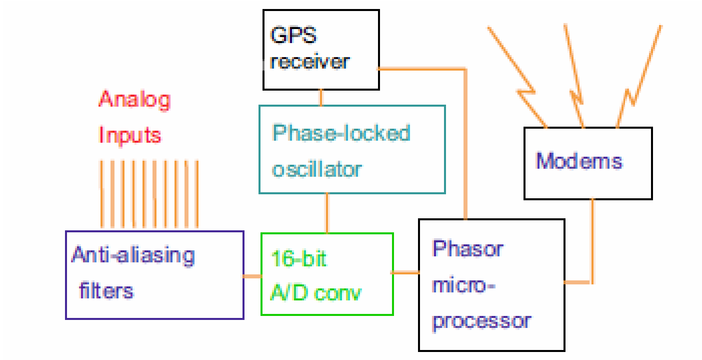

Figure 2.4 Functional block diagram of PMU [6]

The device uses digital signal processors and measures voltage signals at 30 samples per second [12]. This is a huge improvement over earlier systems such as SCADA (Supervisory Control and Data Acquisition) which used to provide a measurement every four seconds. So, a very clear and informative picture about the state of the system can be obtained because direct information about the system state is available. In earlier methods, phase angle would have to be estimated using iterative methods. The values of voltage and phase angle can now be directly plugged into power flow programs as they are readily available. Thus, power flow solutions are greatly accelerated. Instantaneous dynamic information about load and wind generation can be extracted by processing these measurements, which also aids in the progress of this research.

2.2 Literature Review

Some of the major elements of power systems handled in this research work are distribution systems and their unbalanced power flow, wind generation, battery storage technologies, and Phasor Measurement Units (PMU). The work done relies heavily on the usage of the unbalanced backward forward sweep power flow method which was first introduced in [1]. The abilities of the algorithm to handle different types of distributed resources was investigated in [2] and [17] using actual system information from a Shipboard Power System

(SPS). Although the abilities of backward forward sweep power flow to handle distributed generation as both PQ as well as PV have been demonstrated, the negative PQ load version has been used in this research taking into account the wind generation dynamics that have been used here. The IEEE 37 node test feeder has been selected as the case for study in this research work. The information regarding IEEE test feeders is available on the website of the IEEE Power and Energy Society [32]. A clear understanding of the data required for analysis of these feeders can be obtained in [3]. Wind generation and its interconnection with the distribution systems provide some exciting challenges. The impact of different kinds of wind generators and increasing penetration into a distribution system has been discussed in [8]. A detailed probabilistic analysis of changes in voltage profile of a distribution system with increasing wind generation penetration has been done in [7]. The optimal allocation of wind generation at multiple locations in a distribution system based on probabilistic approaches applied to the loss minimization function has been discussed in [9]. However, for the scope of this research which deals with a case study of a small distribution feeder, we consider the centralized location of all the wind generation and storage at a single weakest node in the system. This node has the lowest voltage profile among all the nodes in the system when a base case of power flow is run on it. In distribution systems, the load modeling used to handle various types of loads plays a major role as they affect the system voltage dynamics. This has been investigated in [11] and the various load models have already been incorporated into the backward forward sweep power flow. The relationship between wind generation penetration levels and the effect that they have on distribution system have been discussed in [13]. With the right amount of penetration of wind generation, it has been shown that incorporating wind generation into the distribution system can have beneficial effects.

The Phasor Measurement Units have many benefits for the distribution system as a clear view of system dynamics can be obtained using this technology. Phadke and Thorp first pioneered this technology and the benefits of usage of PMU have been discussed in [6]. The placement of PMUs for maximum observability in a distribution system has been discussed in [4], but the utility standard is to place PMUs at the point of interconnection of wind farms to the system in order to clearly observe wind farm dynamics. Since the test system used in this research work is a small distribution system, we consider a centralized wind farm location and so we have PMUs installed there. We also have a PMU installed at a node closest to the source node in order to have a clear picture about dynamic bulk amounts of power delivered to the distribution system even in the presence of support from energy storage. A stochastic analysis of PMU placement for maximum observability has also been done in [5] along with consideration to state estimation functions. The overall benefits that can be obtained by the usage of PMUs in power distribution networks have been discussed in detail in [12]. A major interest in present day power systems, namely the usage of PMUs in a distribution system for interconnection of islanded systems has been discussed in detail in [10]. This is one of the reasons that PMU could become beneficial in future installations when high penetration of renewable energy is expected.

The utility standard NAS battery has been considered as the energy storage system in this research. The NAS (Sodium Sulfur) battery has been used widely across the world in utility operations. The basic specifications and properties of NAS battery have been explained in [14]. The effective utilization of a NAS battery at a large installation in a university in Japan has been demonstrated in [15], proving the operational efficiency and advantages of the NAS battery. The methods used in the basic charging and discharging operations of NAS battery, on which the methods used in this research are loosely based, have been discussed in [22]. A comparison of different storage technologies suitable for storage of wind power has been discussed in [20], and the NAS battery has more benefits among other battery technologies. The benefits of using storage technologies in order to support wind generation operations has been discussed in [16] and [23]. The potential for battery technologies for combined usage with wind generation, including the special benefits of using the NAS battery have been discussed in [19]. The actual simulation of NAS battery with wind generation based on forecasted load operation has been discussed for a balanced system in [18], and the unbalanced mode of operation of NAS battery with wind generation in order to achieve the same functions discussed in this research work have been based on this work. The operation of a wind farm with the specific case of an NAS battery has been investigated in [21]. The applications of combining wind power generation with energy storage in a smart grid environment have been discussed in [24]. The actual simulation of a wind farm with battery storage has been done in detail in [25].

As it can be seen, all of the individual components of the processes being analyzed in this research work have been discussed in literature, but investigations of the combination of these technologies for effective control of the problem addressed here have been undocumented. The usage of PMUs in order to integrate wind energy and storage into the distribution system has been undocumented. Also, there is no published literature on the combined operation of wind generationand storage instantaneously in order to achieve load reduction and dispatch of distributed renewable resources. All of these issues have been investigated in this research.

Chapter 3 - Research Objectives and Proposed Solution

This section will explain the problem that this research tries to address and the steps that are proposed to solve this problem.

3.1 Research Objectives

Typically, in a distribution system, the wind turbines are directly connected to the distribution feeder and always stay interconnected except in case of contingencies, during which they are required to disconnect from the main system. There is no correlation between distribution feeder load and wind generation profiles. With increasing penetration of wind energy into the distribution grid, there are worst cases of load to wind profile relationship where there is negative correlation. If the load profile is close to base load and there is high wind generation, the part of the load to be supported by the conventional generation from source node may become alarmingly low, and if there is heavy loading while there is very little wind generation, there is maximum possible need for the generation from the centralized energy source node to satisfy. This problem has been addressed in this research. The approach of using storage to help balance this situation requires results to reduce the size of the battery in order to support wind energy storage and peak power reduction effectively. The criteria that are used to charge and discharge the battery play a major role in the capacity utilization of the storage system. This research also provides insight into strategies used to utilize the energy storage system effectively. The availability of dynamic load information also decides the capacity utilization of the battery. This has also been tested using instantaneous measurement information from PMUs.

3.2 Proposed Solutions

The solution to the problem explained above is studied by using the forecasted load data for a given distribution feeder. The assumption is 30% wind generation penetration in the system. This amount of wind generation penetration has been assumed so as to be significant enough to suit modern day smart grid standards, but also to not dominate the energy consumed from the centralized energy source node. The initial assumption is to start with a battery capacity equal to the installed wind generation. The strategy uses the average load of the feeder as the deciding criterion for charging or discharging the battery. Two different charging schemes have been studied.

i. In one approach, when the value of feeder load at any given instant is below the average load, the wind energy generation for that instant of time is used completely to charge up the battery. The load is satisfied completely using the conventional generation only.

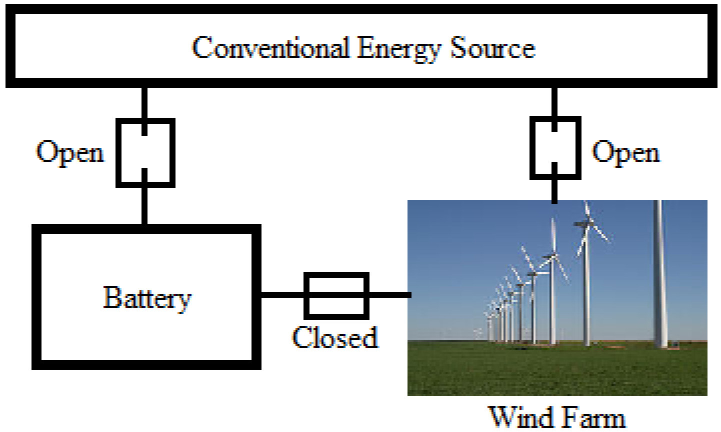

Figure 3.1 Wind charging only

ii. In the other approach, as long as the load is below the average value, the wind energy is fully used to charge up the battery, but the difference between the average load and the instantaneous load value is also extracted from conventional generation to charge the battery such that the feeder load is always at the average value. This method could be suitable for low wind generation days in particular, but assumes a more advanced charge controller that can determine the instances when battery charging using conventional generation is necessary.

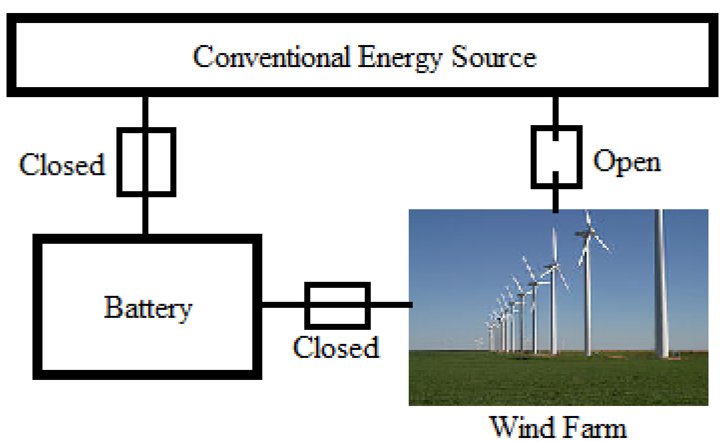

Figure 3.2 Sustained average load charging

In both of these charging methods, the battery can only be charged up to its maximum energy capacity, and if battery has been completely charged up, the wind energy is directly supplied to the system to satisfy the load irrespective of whether load at that instant is above or below the average value.

Similarly, the discharging of the battery can be done in two ways, the Free-running discharge method, or the Conservative discharging method.

i. In the Free-running method, during the discharging of the battery under instantaneous load being higher than average, the wind energy is directly provided to the feeder to satisfy load requirements, and the battery is discharged such that the substation monitored feeder load is as close to the average value as possible. This ensures peak reduction when battery capacity is available for discharge, but under low wind conditions, the risk of the battery being in idle state for longer periods of time than preferred is possible. This may result in unsatisfactory peak reduction when there is low wind generation and the battery capacity has hit minimum.

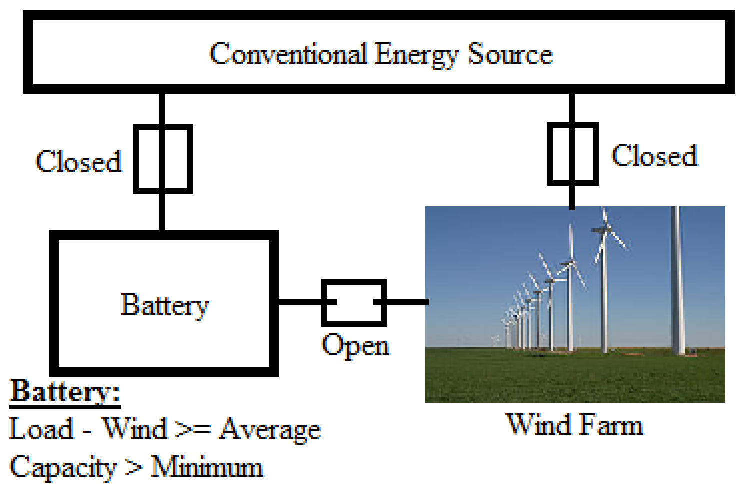

Figure 3.3 Free running discharge

ii. The problem that arises from the above method can be solved using the Conservative discharging method. The amount of discharge for a given feeder load instance beyond the wind generation is determined considering the average load requirement starting from that time instant up to the final time instant, the energy capacity left in the battery for that instant of time, and the maximum possible power rating of the battery. This ensures that there is at least a minimum possible reduction in the peak load of the feeder, and also ensures that the battery capacity is fully utilized, irrespective of size of the battery.

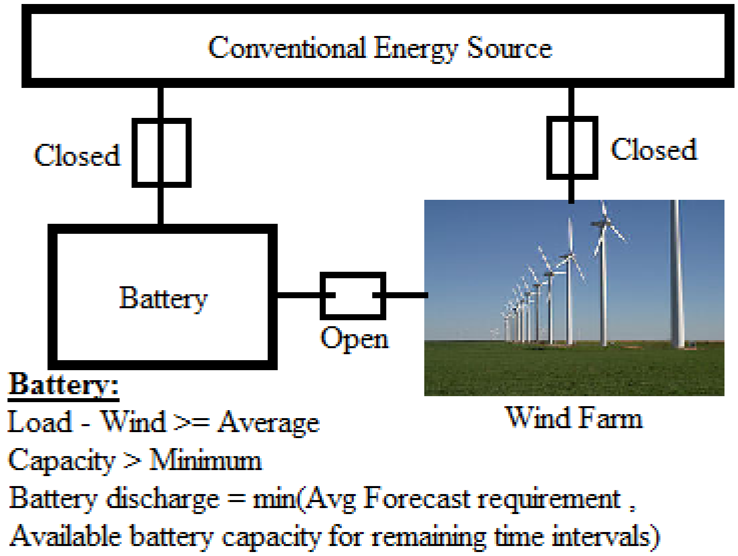

Figure 3.4 Conservative Discharging

In both of these discharging methods, the battery can only be discharged up to the minimum level fixed, and if the battery has hit the minimum level, the wind generation is connected directly to the feeder if the load is above the average value.

The charging and discharging techniques discussed above are implemented for the 15-minute average forecasted 24 hour load profile of the IEEE 37-node test feeder initially while considering low wind, medium wind and high wind generation data taken from a real Northwind 100 kW wind turbine [27]. The data is multiplied by a factor of 8 in order to account for 30% wind generation penetration given that the capacity of the feeder under test is 2500 kVA. So, the installed wind generation capacity is 800 kW. The reactive power is generated by the converter under constant power factor, i.e., the reactive power is always a constant fraction of the real power of the wind turbine. Here, 45 kVAR of reactive power for 100 kW of real power is considered as per the specifications of the wind turbine. This gives a power factor of 0.912 uniformly used throughout this research. The peak reduction performance of the feeder, voltage profile, battery power charging and discharging values, and energy capacity utilization of the battery are investigated for all the cases.

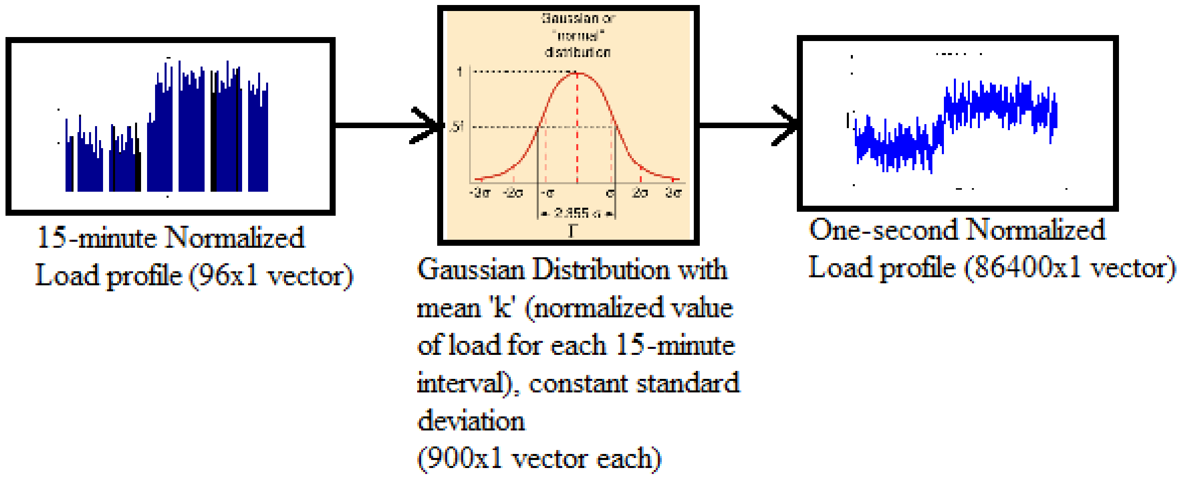

Figure 3.5 Conversion of 15-minute load profile into One-second load profile

The one-second data is created for the feeder by using the 15-minute data and using a Gaussian distribution to create one second load fractions for every 15-minute period. The mean of the Gaussian distribution for a given 15-minute period is the value of the 15-minute average load fraction for that period. The value of standard deviation is chosen such that the values of load fraction are always positive. For this, the minimum value of the 15-minute load fractions is selected and this is divided by a factor of 3. The resulting value is the maximum value of standard deviation that can be used. The decided value is usually a little lesser than this maximum value in order to have all of the probabilistic values positive. The calculation described is based on the fact that most of the values fall within the six-sigma interval of the Gaussian distribution. Using the one second data, it is possible to demonstrate that as instantaneous values are available due to use of PMUs, the battery capacity initially assumed is never used completely as many instances of intermittent charging and discharging of the battery are observed as we have more measurements within a given time period.

The final part of the research is an attempt to predict the required dispatch from the battery using previous time instances' recorded load information from PMUs for real time operation as opposed to earlier attempts which use forecasted load information. It is possible to set different values for the window of time for which historical load information obtained by processing PMU measurements can be calculated. For the sake of uniformity, the time window used in the study described in this research has been set at five minutes. The maximum value of load above the average value for a period of five minutes prior to a current time instant is calculated using PMU measurements. From this value, the wind generation of the current time instant is subtracted in order to yield the battery discharge value for the current time instant. So, the need for forecasted load information is completely eliminated.

Chapter 4 - Test Cases, Data and Tools

4.1 Test Cases and Data

This section will explain about the test cases that were used to analyze the problem including the creation of the normalized distribution system load profile, IEEE distribution system test feeders and their specifications, standard NAS (Sodium Sulfide) battery specifications and so on.

4.1.1 Average Normalized Load Profile for a group of houses

The 15-minute averaged load data for a day for each house in a group of houses present in a real distribution feeder is available in a test case file [26]. A Matlab program is used to extract this information for each house in the feeder. The load information is extracted for each house from a group of ten selected houses that have legitimate realistic load information and then aggregated. The final aggregated 15-minute averaged demand histogram for a group of ten houses is given below.

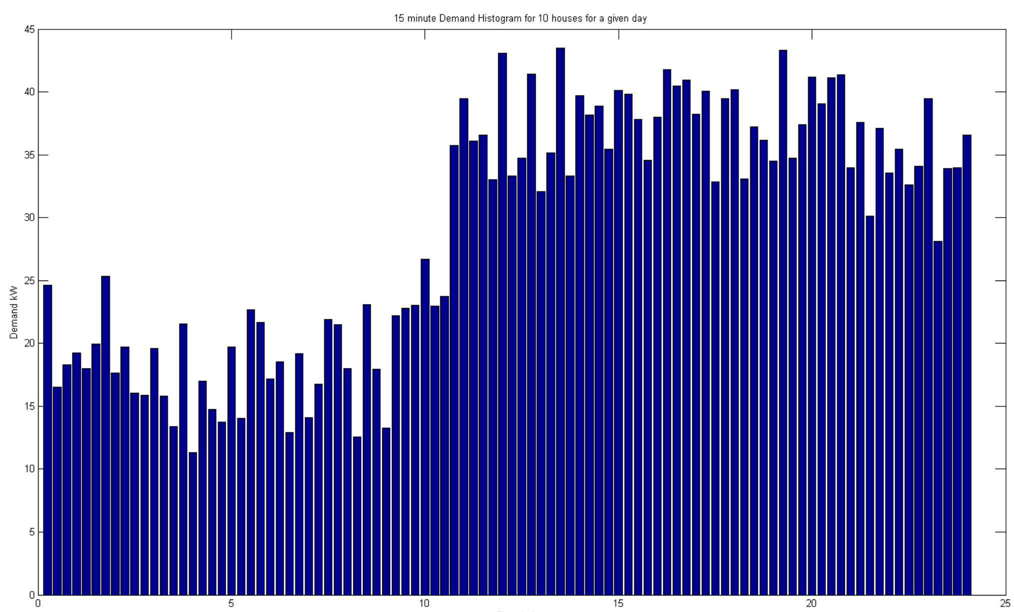

Figure 4.1 Aggregated 15-minute demand histogram for ten houses for a day [26]

But for a distribution feeder, beyond a certain value of load, the coincidence factor becomes a constant value as shown in the figure below.

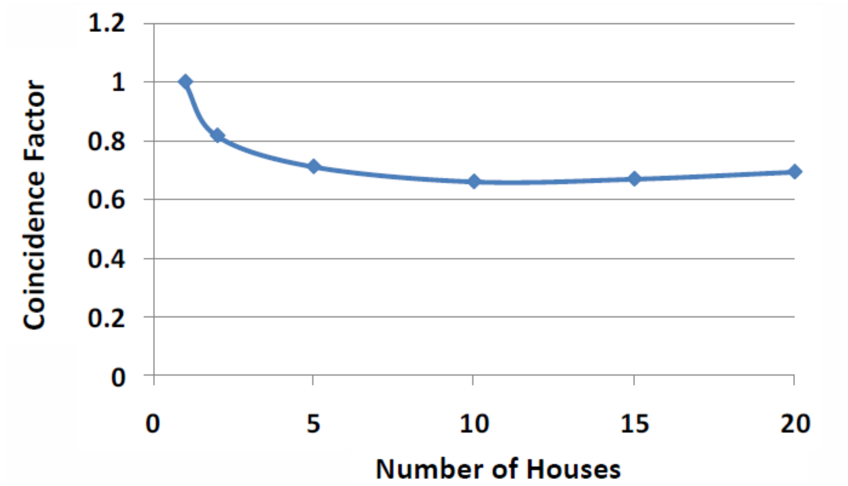

Figure 4.2 Coincidence factor as a function of number of houses [26]

So, it is possible to normalize the load profile of the group of houses shown before to a factor of one or 100% and use it for any distribution feeder as a whole as the demand follows a similar profile on a given day for all feeders. After normalization, the 15-minute averaged and normalized demand histogram for a distribution feeder may be obtained as given below.

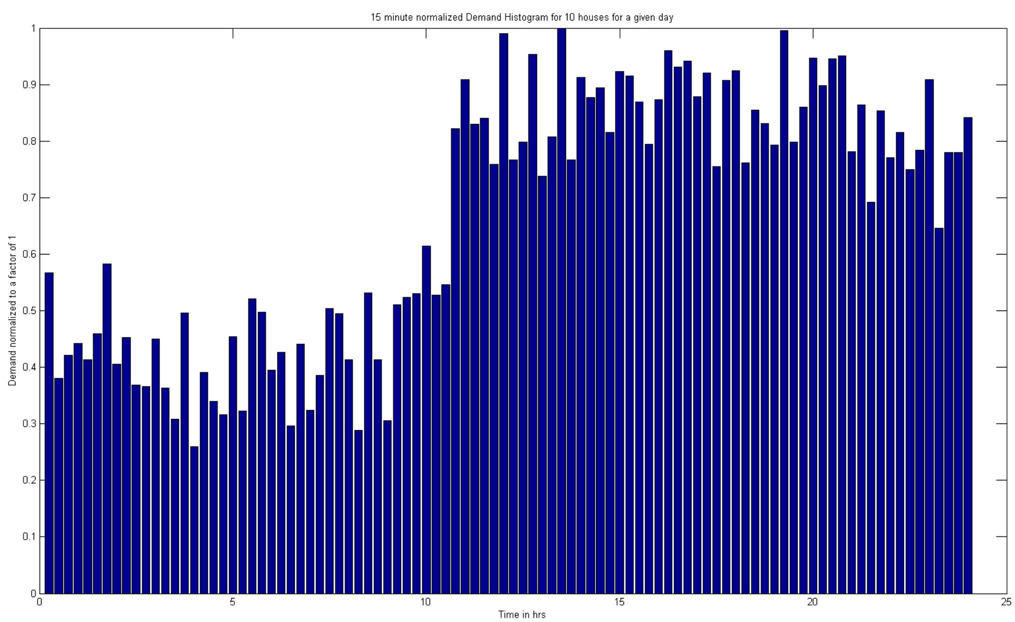

Figure 4.3 15-minute average normalized demand histogram for a day

When the one second calculation of dispatch operations of storage is considered, the 15-minute normalized load profile is converted into an equivalent one second load curve by using the normalized demand factor for each fifteen minute interval as the mean of the Gaussian distribution and using a value of constant standard deviation in such a way that the demand factor does not become a negative value. For the above fifteen minute normalized demand histogram, the lowest value of recorded load factor was 0.2598. In a Gaussian distribution, 97% of the values tend to fall between the six-sigma interval [-3σ 3σ]. So, an ideal value for the standard deviation can be calculated as follows

$$\text{Standard Deviation } \sigma < 0.2598/3 = 0.866$$

On repeatedly plugging in values of σ less than this value and then reducing to get the load factor to always be greater than 1, the value of σ is fixed to be 0.065 for this test case. The one second normalized load curve that was obtained is given below.

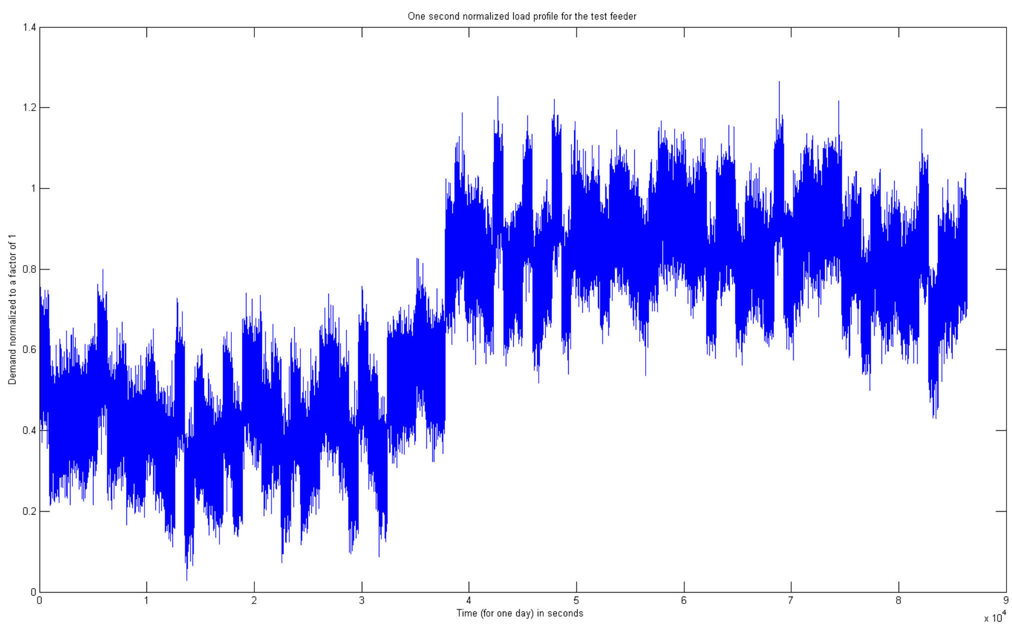

Figure 4.4 One-second normalized demand curve for a day

It is observed that load factor exceeds one in some intervals for this curve, but this is realistic as this load dynamic is not captured in a typical distribution feeder when fifteen minute average load is calculated.

4.1.2 IEEE 37 node test feeder

The IEEE 37 node test feeder is selected as a standard case in order to study the dispatch operation of battery storage with distributed wind generation. It is an actual test feeder in use in

Australia. It is completely underground and has been selected for this research as it is the simplest to analyze because of the following reasons:

i. The limited number of nodes makes it easy to renumber the nodes for backward forward sweep power flow analysis

ii. It is completely composed only of Delta configuration lines and transformers, making the study easier.

iii. It has no additional circuit components such as capacitors, switches and uniformly distributed loads, and it also has only four types of line configurations, making the analysis very simple and straightforward.

The information for the feeder is given in appendix A. The figure 4.5 shows the feeder. It may be noted that regulator information for the feeder is also available, but has not been used in this analysis as there is a need to clearly observe the effects of distributed wind generation and storage on the voltage profile of certain nodes in the feeder. The regulator would tend to improve the voltage profile and prevent the observation of actual effects.

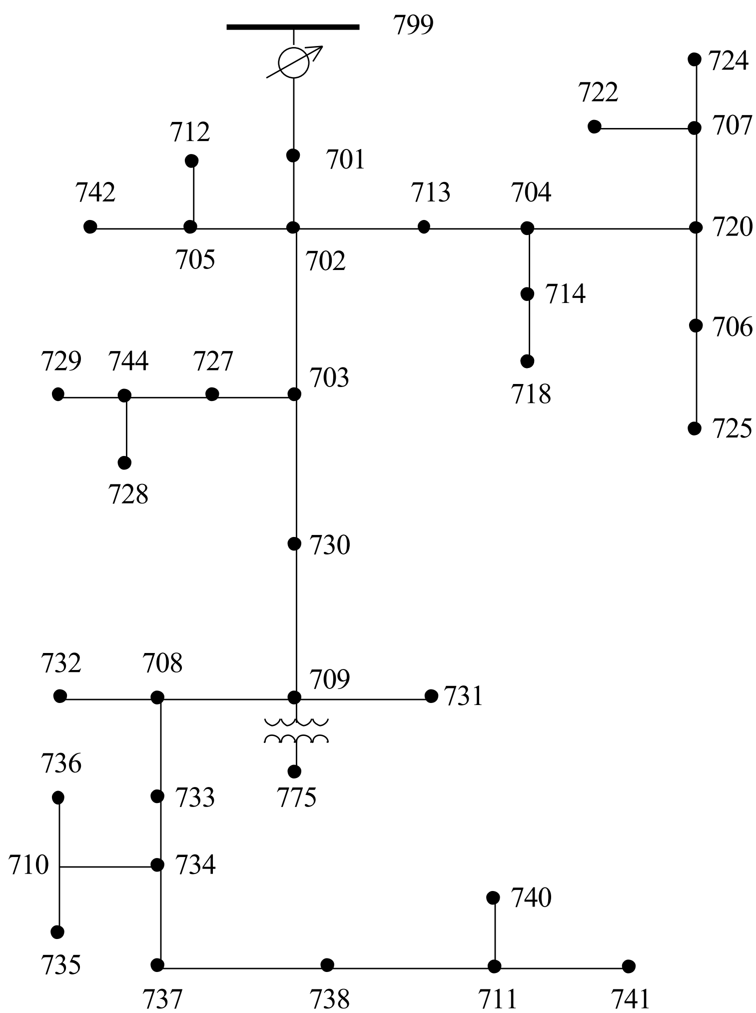

Figure 4.5 IEEE 37 node test feeder

The spot load data given with the test feeder specifications is considered as the 15-minute peak load corresponding to a load factor of 1. All the other cases are considered as the load fractions of this peak load. For the purpose of analysis, this puts forward the assumption that all the loads present in the feeder have the same load factor at any given instant.

4.1.3 Distributed Wind Generation

The real power generation data of an actual wind turbine manufactured by Northwind has been used in this research. This is a wind turbine present in Riley County, Kansas and the data is available online publicly for research purposes [27]. The real power rating of the turbine is 100 kW although the generation can go up to 120 kW when wind is abundant. The reactive power of the turbine is independent of wind dynamics and is generated by the converter used to connect the turbine online. The converter can produce any value between +/- 45 kVAR based on user settings. In order to simplify the analysis, generation at constant power factor is considered. A value of +45 kVAR of reactive power generation for 100 kW of wind generation is considered. So, this constant fraction of active power is maintained throughout the operation of the wind turbine. For this analysis, a wind power penetration of 30% of feeder peak load has been considered. Given that the peak load of the feeder is about 2500 kVA, 800 kW of installed wind generation capacity is assumed by multiplying the generation of one wind turbine by a factor of eight. Although the combined wind power generation of eight wind turbines in reality would be a lot smoother function of time, the criticality of this case would prove as a test of the abilities of the control strategies being tested in this research. This wind generation information for one day on a fifteen minute averaged basis is obtained for three different wind scenarios: low wind, medium wind and high wind. This is because, fifteen minute analysis is less time consuming and so, it is possible to observe the effect of wind generation on the operation of battery very easily. The information obtained has been attached in appendix B.

In order to perform the one second analysis for the test system, one single case of wind generation data from the Northwind turbine on a one second basis has been taken. This is because; the wind generation information for a day on a one second basis is memory intensive and requires about 6 to 7 megabytes of space for an Excel file, containing 86400 rows and 6 columns. This information cannot be attached to this thesis as the file could consume a large amount of space exceeding the allowed length of this document.

4.1.4 Standard NAS (Sodium Sulfide) battery specifications

The battery used to investigate dispatch operations of wind generation in this research is the utility standard NAS battery [14]. This is a tried and tested battery popularly used in utility load support operations and more recently, islanding. It is widely used in Japan and has some very useful advantages making it an attractive option for large scale battery energy storage system operations [15]. The battery has almost no self-discharge characteristics. It operates at a very high temperature of 285-300 ºC, and the resistance goes down with the increase in temperature. It has a high efficiency of more than 81% which is greater than most other battery technologies (Table 4.1). It also has a very long life-cycle of about 15 years. The specifications of the NAS battery for one unit have been given below.

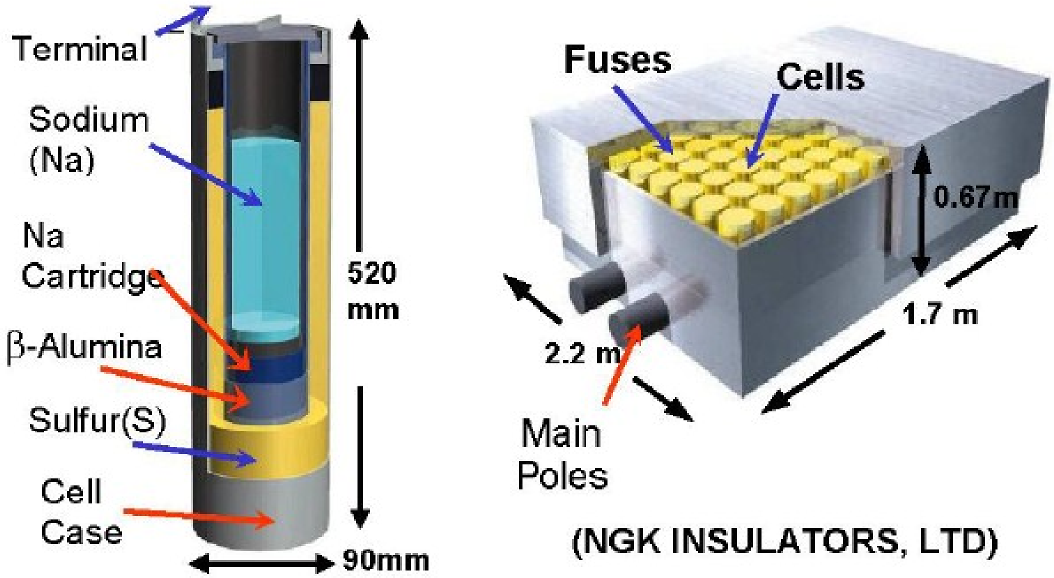

Figure 4.6 NAS Battery Cell module and Cell structure [15]

Output	52.1 kW
Voltage	58V / 116V
Current	726A / 363A
Capacity	375 kWh
Efficiency	~ 83%
Weight	3.5 ton
Energy Density	160 kWh/cu-m
Number of Cells	320

Table 4.1 50 kW NAS Battery module specifications [14]

Although the specified output rating is 52.1 kW, in actual practice, 50 kW is the observed output power. Initially, the installed battery capacity for the test studies is assumed to be equal to the installed wind generation capacity of 800 kW. So, the initial value of total installed battery capacity is also 800 kW. Sixteen units of the specified battery module are assumed, making the energy capacity 6000 kWh which is considered the measure of the state of charge of the battery. Initially a realistic value of battery efficiency of 81% is assumed which is close to the actual value, so that the charging and discharging efficiencies are 90% each, respectively. In order to ensure effective operation, the limits of the battery are set such that the battery can only be discharged up to a minimum charge of 20% of maximum value. Beyond this state, the battery is switched off. Also, if the battery is charged up to the maximum value, it is switched off in case the load is low and charging operations are still possible.

4.2 Tools

All of the simulations required for this research are carried out using a standard Dell Desktop Personal Computer with the following specifications

Processor	Intel® Core™2 Duo @ 3.00 GHz
Installed Memory	4.00 GB (3.50 GB usable)
System Type	32 Bit
Operating System	Microsoft Windows 7 Enterprise Service Pack 1

Table 4.2 Computer Specifications

The software tool used to create the code and run the simulations is Matlab R2011b. Matlab is uniquely suited to analyze the problems described in this research as it is effective at handling matrices and some of the major components of this research including Backward forward sweep power flow and battery storage utilization require large amounts of calculation and logic intensive matrix analysis.

4.2.1 Backward Forward Sweep Power Flow Algorithm

The backward forward sweep power flow algorithm is the best method to analyze unbalanced radial distribution systems as it is a detailed three phase analysis method that takes into consideration even factors such as mutual impedance between phase conductors. It is based on the iterative solution of the simple ladder network from circuit theory and provides a high level of accuracy in the power flow solution. It is essential in this research as it is a constant part of all the analysis approaches used in the solution to the problems addressed here. It also provides the PMU measurements that will be used in the final stages of this research. In actual practice, PMU measurements would be measured in the field and then plugged into the power flow solution. But here, as the historical PMU measurements of previous time instants are primarily utilized to dispatch the battery, the voltage measurements of certain nodes solved by using the power flow problem are recorded as PMU measurements.

4.2.1.1 Node Renumbering

In the backward forward sweep power flow analysis, the speed of the solution can be greatly enhanced by using proper node renumbering as the number of laterals branching off from the main feeder determines the number of equations and unknowns in this algorithm. So, a breadth first order is followed in the renumbering of the nodes. Whenever a lateral branches off from a given feeder, the lateral is numbered first before returning to the main feeder. An illustrative example is given below.

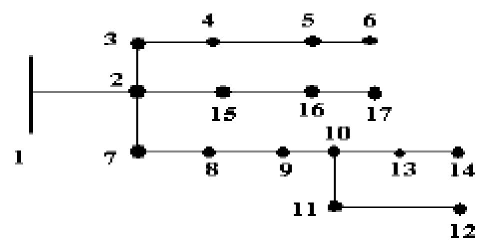

Figure 4.7 Node Renumbering [2]

In this way, the IEEE 37 node test feeder is renumbered for analysis in this research and the renumbered feeder has been given below in figure 4.8.

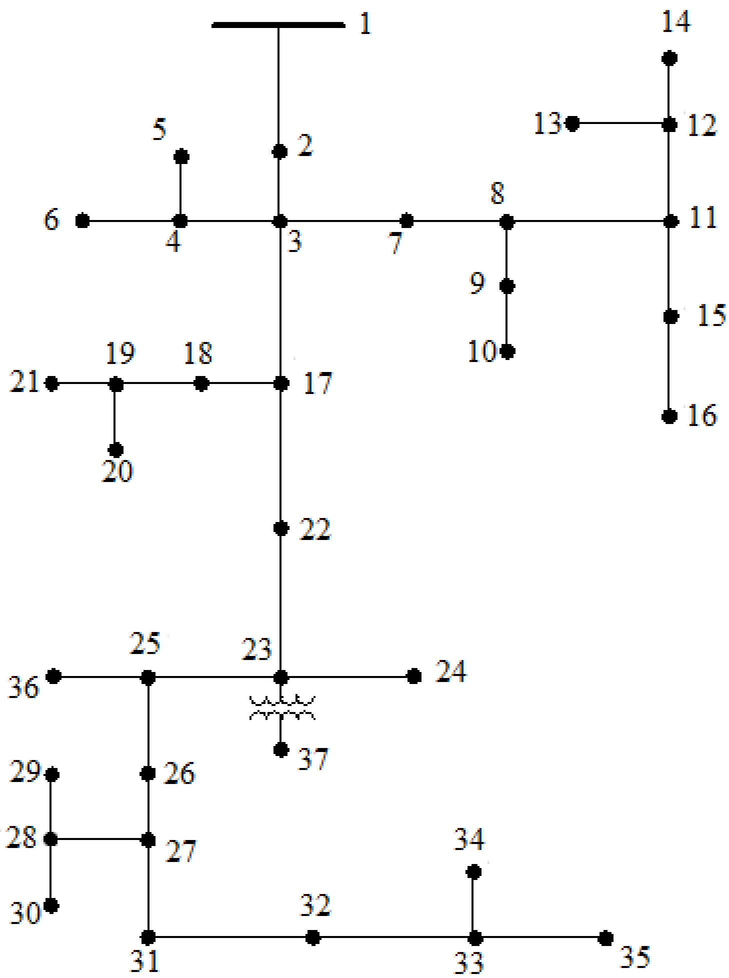

Figure 4.8 Renumbered IEEE 37 node Test Feeder

4.2.1.2 Method

The backward forward sweep power flow algorithm has been explained in great detail in [2], but some of its features used in this research have been described in this section. In the backward forward sweep power flow analysis, the first step involves the calculation of voltages and currents of the feeder starting from the terminal nodes and progressing towards the source node. This is called as the forward sweep. In the first iteration, the terminal voltages are assumed to be at the three phase nominal voltage of the given feeder. Then, the currents and voltages of each node and the line currents between nodes are progressively calculated using the following equations.

$$V_i = V_{i+1} + ZI_{i+1} \quad \textbf{(4.1)}$$

$$I_i = I_{i+1} \qquad \textbf{(4.2)}$$

Where $I_{i+1}$is the line current from the given node **i** to the succeeding node **i+1**. The line current calculations are performed by the summation of node currents and line currents of succeeding nodes. The node currents are calculated based on the type of load as given below

i. Constant Power loads: The real and reactive power injections are kept constant. These are similar to the traditional PQ loads in single phase equivalent power flow problems.

ii. Constant Impedance loads: Using the given real and reactive power values, the node impedance at nominal voltage is calculated and kept constant for all the iterations. The node current is calculated from this impedance value and the node voltage for that iteration.

iii. Constant Current loads: The magnitude of node current at nominal voltage is calculated from the given real and reactive power values and kept constant. The phase angle value is calculated for each iteration and attached to this current magnitude value.

The node current calculation equations for various load models are given in the table below.

Load Type	Wye	Delta
Constant PQ	$IL_i^{ph} = \left(\frac{S_i^{ph-n}}{V_i^{ph-n}}\right)^*$	$IL_i^{ph} = \left(\frac{S_i^{ph-ph}}{V_i^{ph-ph}}\right)^*$
Constant Z	$Z_i^{ph-n} = \frac{\lvert V_i^{ph-n}\rvert^2}{S_i^{ph-n^*}}$, $IL_i^{ph-n} = \frac{V_i^{ph-n}}{Z_i^{ph-n}}$	$Z_i^{ph-ph} = \frac{\lvert V_i^{ph-ph}\rvert^2}{S_i^{ph-ph^*}}$, $IL_i^{ph-ph} = \frac{V_i^{ph-ph}}{Z_i^{ph-ph}}$
Constant I	$IL_i^{ph-n} = \lvert IL_i^{ph-n}\rvert * /\_\delta_i{}^{ph-n} - \theta_i{}^{ph-n}$	$IL_i^{ph-ph} = \lvert IL_i^{ph-ph}\rvert * /\_\delta_i{}^{ph-ph} - \theta_i{}^{ph-ph}$

Table 4.3 Load Model Equations [2]

The second step of every iteration is the backward sweep which assumes the sources node 1 to be at nominal voltage and then uses the line currents calculated in the forward sweep process to calculate the voltages of all nodes starting from source and progressing towards the terminal nodes. The equations used are given below.

$$V_i^{new} = V_{nominal} - ZI_i \qquad \textbf{(4.3)}$$

The above equation applies only for node 1.

$$V_{i+1} = V_i^{new} - ZI_{i+1} \quad \textbf{(4.4)}$$

There is a possibility of the feeder containing other circuit components such as capacitors, line transformers and switches as well. These are modeled in the following ways.

i. Line transformers are modeled as in [ ] and the update equations from the various transformer matrices may be given as follows. These equations can be applied irrespective of transformer type.

   Forward Sweep

$$V_i = a_t V_{i+1} + b_t I_{i+1} \quad \textbf{(4.5)}$$

$$I_i = d_t I_{i+1} \quad \textbf{(4.6)}$$

   Backward Sweep

$$V_{i+1} = A_t V_{i+1}^{new} - B_t I_{i+1} \quad \textbf{(4.7)}$$

ii. Switches are modeled as zero impedance branches.

   Forward Sweep

$$V_i = K * V_{i+1} \quad \textbf{(4.8)}$$

$$I_i = K * I_{i+1} \quad \textbf{(4.9)}$$

   Backward Sweep

$$V_i^{new} = K * V_{nominal} \quad \textbf{(4.10)}$$

$$V_{i+1} = K * V_i^{new} \quad \textbf{(4.11)}$$

   where K could be 0 or 1 depending on the state of the switch.

iii. Capacitors are modeled as constant impedance matrices similar to constant impedance loads.

   For Wye connected capacitor bank

$$Z_i^{ph-n} = \frac{\left|V_i^{ph-n}\right|^2}{S_i^{ph-n^*}}, \ IC_i^{ph-n} = \frac{V_i^{ph-n}}{Z_i^{ph-n}} \quad \textbf{(4.12)}$$

   For Delta connected capacitor bank

$$Z_i^{ph-ph} = \frac{\left|V_i^{ph-ph}\right|^2}{S_i^{ph-ph^*}}, \ IC_i^{ph-ph} = \frac{V_i^{ph-ph}}{Z_i^{ph-ph}} \quad \textbf{(4.13)}$$

The load flow involves the comparison the source node voltage with the nominal voltage at the end of every forward sweep. If the difference is beyond a certain set value of tolerance, the next iteration is calculated. The flowchart for the backward forward sweep power flow algorithm follows.

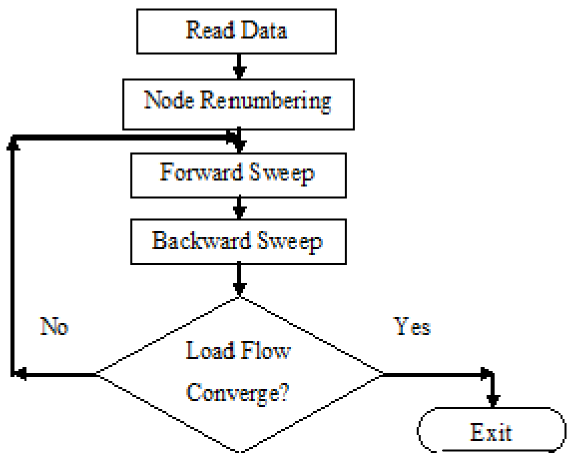

Figure 4.9 Flowchart of the backward forward sweep power flow algorithm

4.2.1.3 Distributed Generation

The backward forward sweep power flow algorithm can be used to handle distributed generation in the form of voltage controlled or PV nodes where they are installed by slightly modifying the calculation process. But in this research, wind energy has been handled as a constant power factor input and so, for any given time instant, the value of P and Q are constants. So, distributed wind generation has been considered as negative PQ load in the power flow process. Wind turbines can be installed at multiple nodes, but for the sake of simplicity, for the IEEE 37 node test feeder, centralized location of all the generation has been considered at a single node. The wind generation is included into the power flow process by subtracting the given values of real and reactive power generation from wind from the actual load of the node where it is connected in the feeder.

The battery dispatch, which is also a constant three phase value for any given time instant is handled in a similar fashion. The difference lies in the fact that battery charging and discharging is always a real value. In the case of charging of the battery, the real power generation from wind is directly added to the energy level of the battery and not treated as negative PQ load. In the case of discharging, the battery dispatch is subtracted from the feeder node where the wind farm and battery have been connected as negative P similar to the way wind generation was handled as explained earlier. The power flow is calculated after these values have been plugged in to the input data.

This chapter has discussed the base cases on which some of the studies were done in order to investigate the addition of wind generation and battery storage along with the measurements of PMUs. There was also a discussion about the IEEE 37-node test feeder on which all the studies were done in this research. The backward forward sweep power flow algorithm that was used throughout this research in order to provide measurements required in the calculation of dispatch for wind generation and battery storage has also been discussed in some detail. The final section also discussed the methods used to include wind generation and batteries in the power flow process as negative PQ load.

Chapter 5 - Algorithm and Analysis

5.1 Storage Dispatch Operation Algorithms

In this section, various approaches that were used in this research in the dispatch operation of battery storage with wind generation are discussed. The first method describes the use of forecast data in order to perform the ideal operation of battery storage with wind generation. This method is tested for both the fifteen minute basis data as well as the one second data in order to observe the effects of battery storage operation with wind generation on the overall load of the feeder, individual phase loads, three phase voltage profile of the node where wind farm and battery have been installed, battery power charging and discharging profile, battery energy level profile, losses of the feeder, and the fifteen minute averaged normalized demand profile.

The second method, which is more realistic and suited to real time utility operations, is based on calculations done using historical PMU measurements and is tested only for one second data. The effects on various system parameters is also observed as discussed above.

5.1.1 Test Setup of Feeder Components and Measurements

The Backward forward sweep power flow algorithm which was described earlier is used for the IEEE 37 node test feeder at peak load conditions without any wind generation initially. The purpose of this power flow solution is to determine the weakest node, i.e., the node with the lowest voltage profile. This node will become the site of installation of the wind farm as traditionally followed in real world applications. As the battery storage takes power from the wind farm when in charging mode, this node will also be the site of the battery installation. The Phasor Measurement Units (PMU) are installed at two locations for this test feeder while larger feeders with more number of feeders can have more installations. The PMUs are installed for this system at node 738 (renumbered to 32) and node 701 (renumbered to 2) as they are the most critical nodes in the system. Node 701 is the node that is present right after the source node. The voltage difference between the source node and this node is a direct measure of the net load on the feeder at any time instant and so can be very advantageous for monitoring and operations purposes. This property has been taken advantage of in this research when real time operation is considered. The wind farm and battery node is given a PMU because voltages at this node are a direct measure of the wind generation and battery charging or discharging for the system. The test system setup has been given below. It may be mentioned that the PMUs being used are distribution level PMUs that have reduced functionalities as opposed to transmission level PMUs that have multiple functions.

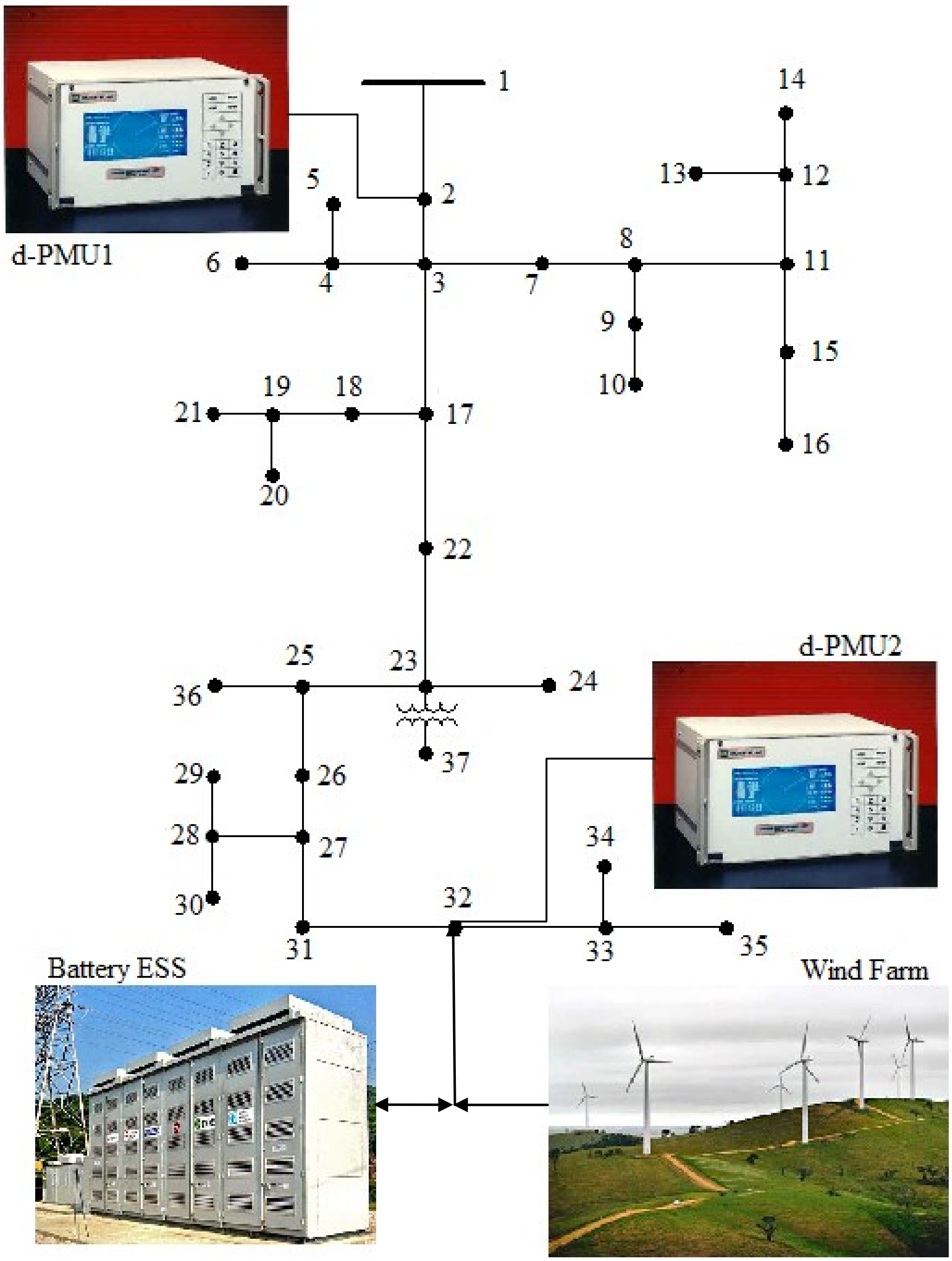

Figure 5.1 Dispatch Operations Simulation Test Setup*

*Pictures courtesy of www.macrodyneusa.com, www.zmescience.com, www.wastedenergy.net

5.1.2 Testing for conventional base cases

The initial testing involves running the power flow algorithm without any wind generation and then with wind generation considered in the system. The fifteen minute data is analyzed with low, medium and high wind generation data and the one second data is tested for one single case of wind generation. The results obtained from these test runs will act as comparison data for results that will be obtained later using wind generation and battery combined in the system. The flowcharts for algorithms used for instantaneous power flow in conventional cases have been given below.

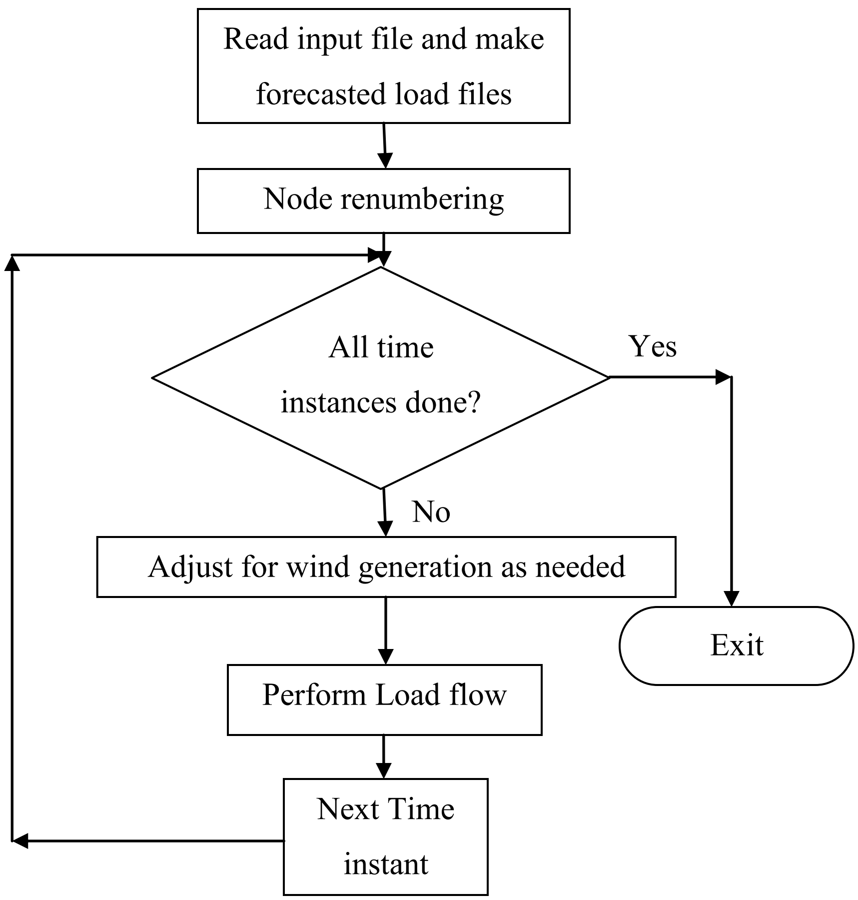

Figure 5.2 Flowchart for base case testing with or without wind generation

The only difference in the above method when wind energy is considered is that the given value of wind generation for that time instant is treated as negative PQ load and subtracted from the actual load of the node where wind generation has been installed. In the case of the IEEE 37 node test feeder, node 738 (renumbered to 32) has been considered as the wind generation node.

5.1.3 Dispatch operations for forecasted load information

The dispatch operation of the battery with distributed wind generation using forecasted load information can be used to determine the ideal characteristics of battery charging and discharging in order to perform load support operations purely using wind generation, as described earlier. Two different approaches have been tried in order to discharge the battery and additionally, two methods of charging the battery have also been investigated. So, a total of four different combinations are possible. These methods have been tested for both the fifteen minute forecasted load as well as the one second forecasted load information. The four methods have been described below and their respective flowcharts have been presented.

i. **Wind charging with free running discharging mode:** In this method (Figure 5.3), for all the time instances, if the load for a given time instant is less than the daily average load of the feeder, the wind farm is directly connected to the battery for charging. If the forecasted load is above the average, the wind farm is connected to the feeder and the battery is also discharged in such a way that the overall feeder load seen by the substation is equal to the average forecasted load of the feeder. If the battery has hit any of its limits, i.e., if maximum level has been reached during charging, or if minimum level has been reached during discharging, the battery is switched off and wind generation is directly connected to the feeder. This method is subject to the available capacity in the battery as beyond a certain time instant, apart from the battery capacity, if wind generation becomes reduced as well, peak reduction in feeder load may not be possible if battery is shut off too soon.

ii. **Wind charging with conservative discharging mode:** In this method (Figure 5.4), for all the time instances, if the load for a given time instant is less than the daily average load of the feeder, the wind farm is directly connected to the battery for charging. If the forecasted load is above the average, the wind farm is connected to the feeder and the battery is also discharged, but the availability of battery capacity for all the remaining time instances of the day is calculated for every time instant such that the full available capacity of the battery is utilized over the entire length of the day. This value is compared with the average load requirement of the remaining time intervals and the minimum of these values is selected. This method may not succeed in maintaining the feeder load close to the average load all the time, but ensures that there is at least a certain minimum value of load reduction at every time instant. There is also full battery capacity utilization irrespective of battery size.

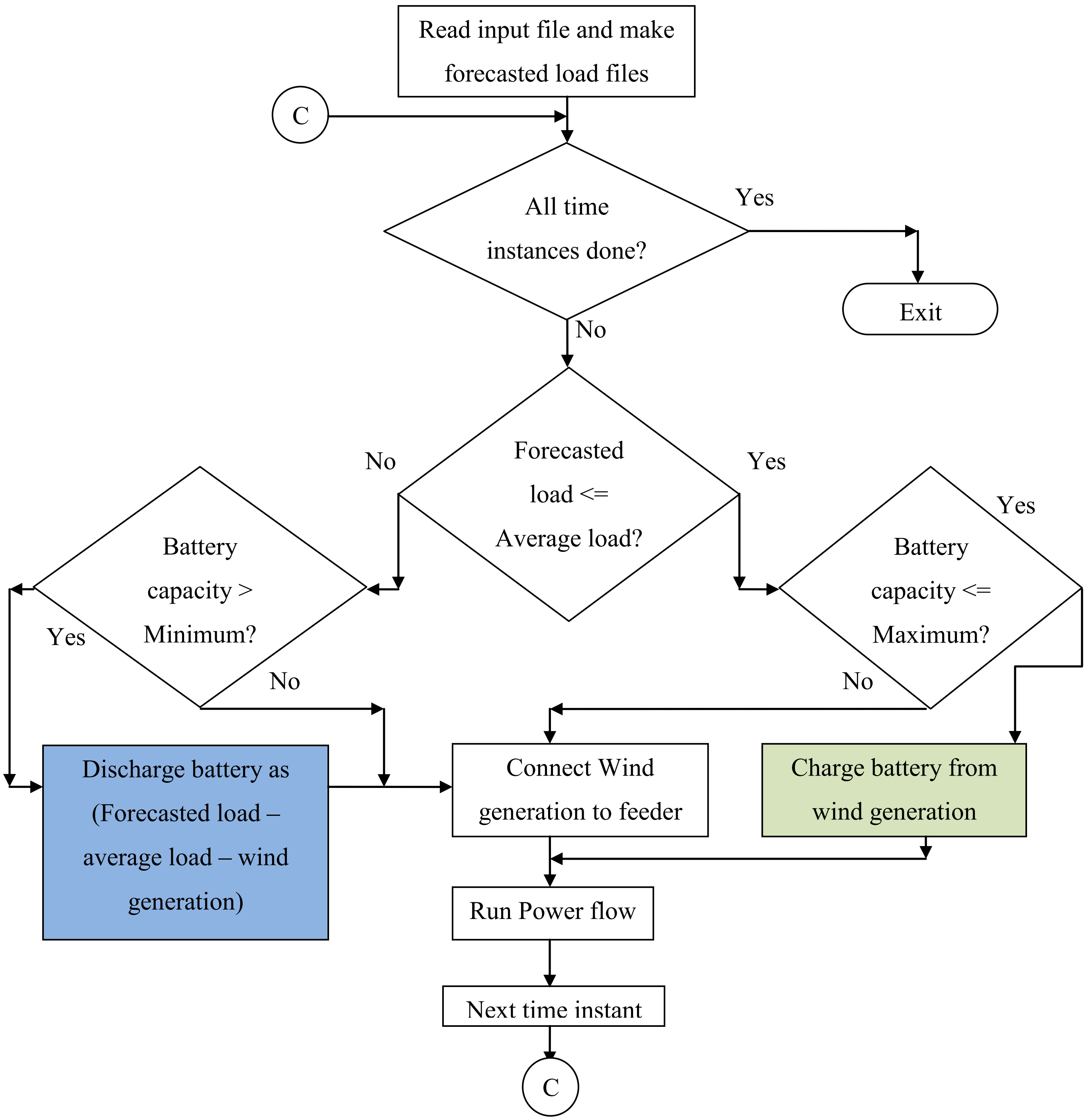

Figure 5.3 Flowchart for battery dispatch operation for wind charging with free running discharge

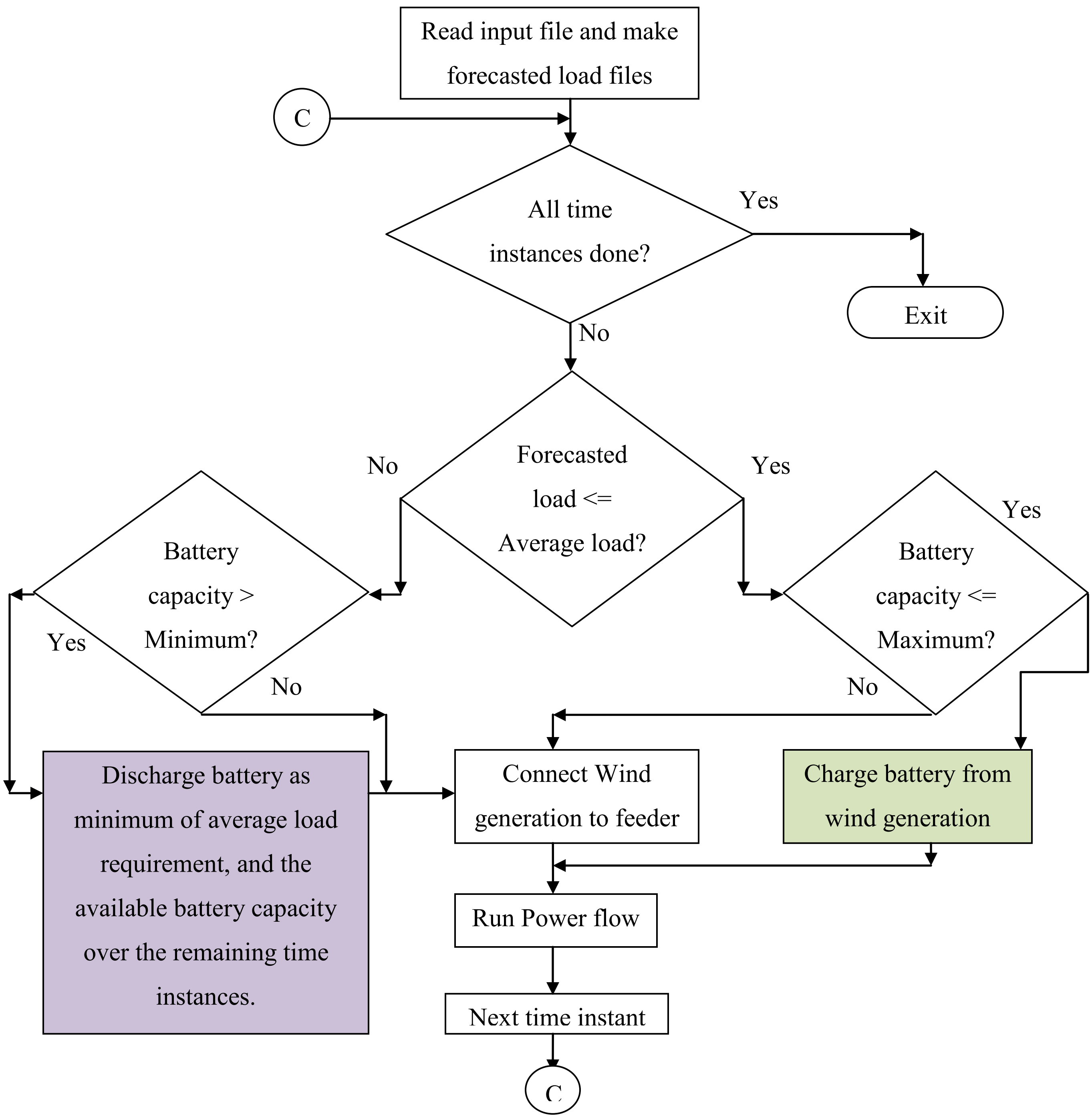

Figure 5.4 Flowchart for battery dispatch operation for wind charging with conservative discharge

iii. **Sustained average load charging with free running discharge:** In this method (Figure 5.5), if the forecasted load is below the average load of the feeder, the battery is charged from the wind generation and also the difference between average and forecasted load is taken from the main supply in order to charge up the battery. The resulting feeder load during times of battery charging is equal to the average load. If forecasted load is above average load, the wind farm is directly connected to the feeder, and also load component above the average load apart from wind generation is supplied by the battery irrespective of available capacity. This method ensures that there is always sufficient battery capacity in order to perform efficient peak reduction during heavy load conditions. The catch lies in the fact that this method requires a highly advanced charge controller for the battery that is currently not available but, this method may become possible in the future. Under current conditions, however, this method cannot be implemented in real time.

iv. **Sustained average load charging with conservative discharge:** This method (Figure 5.6) uses the same charging strategy as described above, but if the forecasted load becomes greater than the average load, the average load requirement over the remaining time instances is calculated along with the available battery capacity over the remaining time instances. The minimum of these two calculations is taken as the battery discharge. Again, this method also ensures full capacity utilization of the battery irrespective of size.

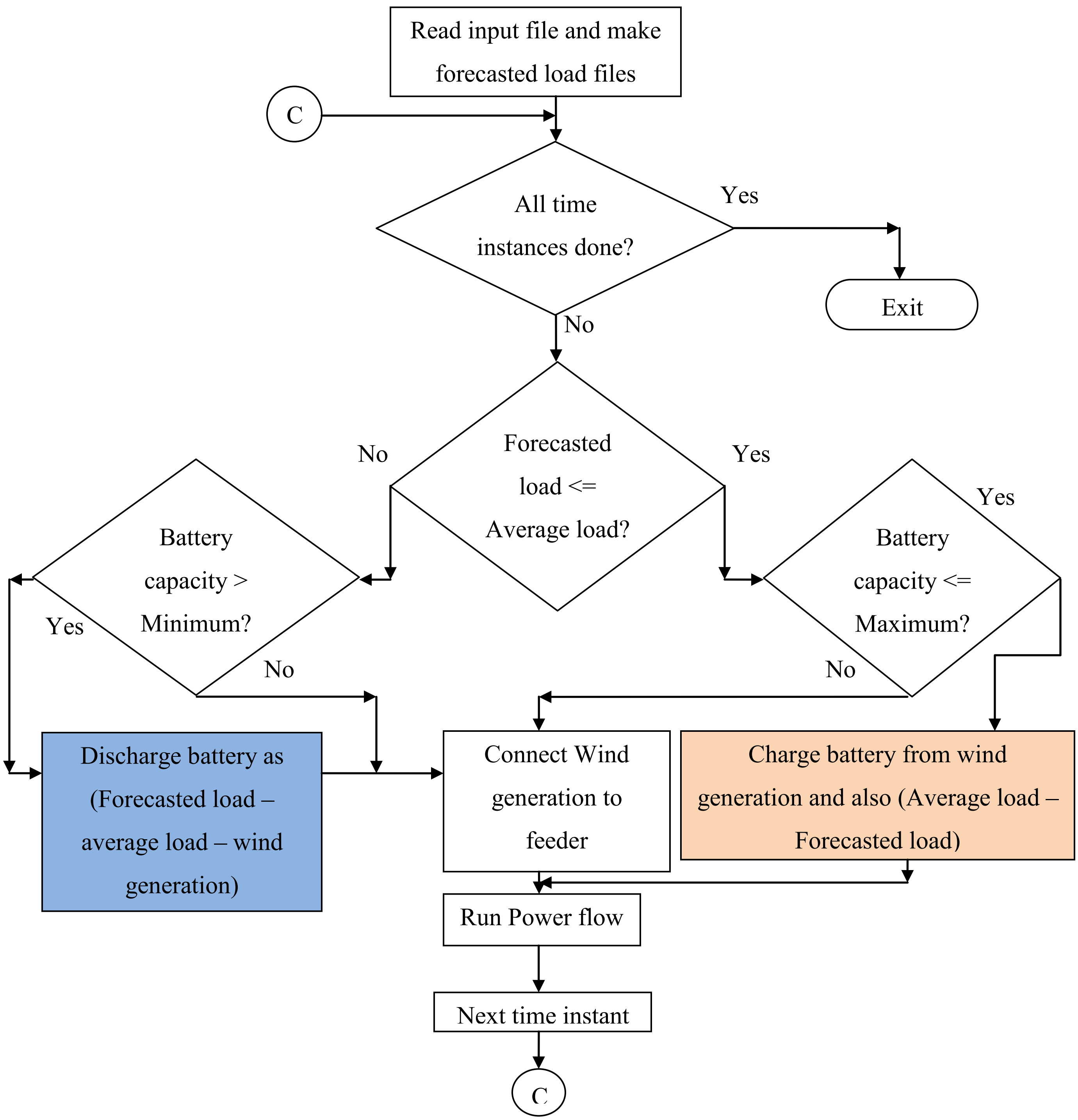

Figure 5.5 Flowchart for battery dispatch operation for sustained average load charging with free running discharge

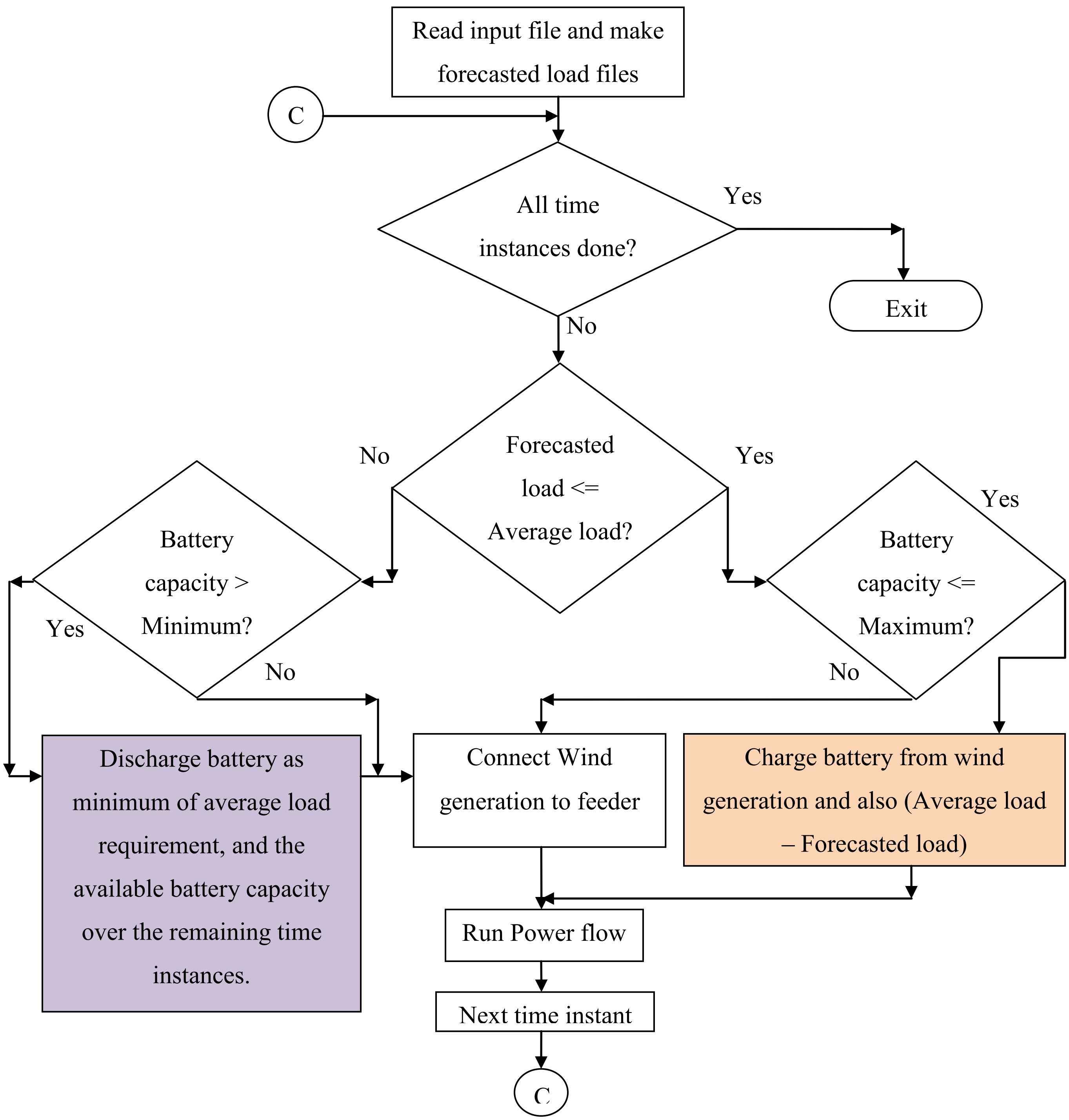

Figure 5.6 Flowchart for battery dispatch operation for sustained average load charging with conservative discharge

5.1.4 Dispatch operations for historical load information from PMUs

The actual real time operation of battery storage with wind energy using historical PMU measurements can be achieved using this method (Figure 5.7). The only information that this method requires during operation is an approximate value of the average load of the distribution feeder. This method is applied only for the one second data as the required results cannot be obtained with fifteen minute data. The decision of charging or discharging the battery is based on the maximum value of the load in a given group of previous load instances. This value of load is calculated by taking into account the PMU measurements of the node that is close to the source node.

For the test system, as described earlier, the PMU is at node 701 (renumbered to 2). This method also ensures that there is always some measure of reduction in the load of the feeder during heavy load conditions. This is ensured by changing the discharging of the battery to the conservative discharging mode described earlier when the battery capacity falls below a certain set value that is still above the minimum level of the battery. The mixed approach is adopted for the discharging of the battery as it is observed in the forecasted load studies that free running mode seems to perform relatively well for one second data except during the last time instances of the day.

The charging of the battery is done using only the wind generation in this case as it is intended for real time purposes and the sustained average load approach is currently not suitable for real time operation. The simulation of this method does not utilize the full capabilities of the PMU however. PMUs can sample data at up to thirty samples a second, while the scope of this study is limited to a much lower rate of one sample per second. This is because actual wind generation information obtained is available for research on a minimum basis of one second, and also, the operational dynamics of distribution system load do not require the resolution offered by the full potential of PMU sampling information. This is evidenced by the fact that conventional utility standards rely on a minimum averaged load sampling of one sample every fifteen minutes, which is much higher than the sample periods being investigated in this research.

The initial condition followed in the implementation of this algorithm is that for the first sample period, the wind generation is used to charge up the battery irrespective of load. This is in order to ensure that PMU measurements are available for any given sampling interval as soon as the initial sampling interval has been crossed. The flowchart for this method has been given below

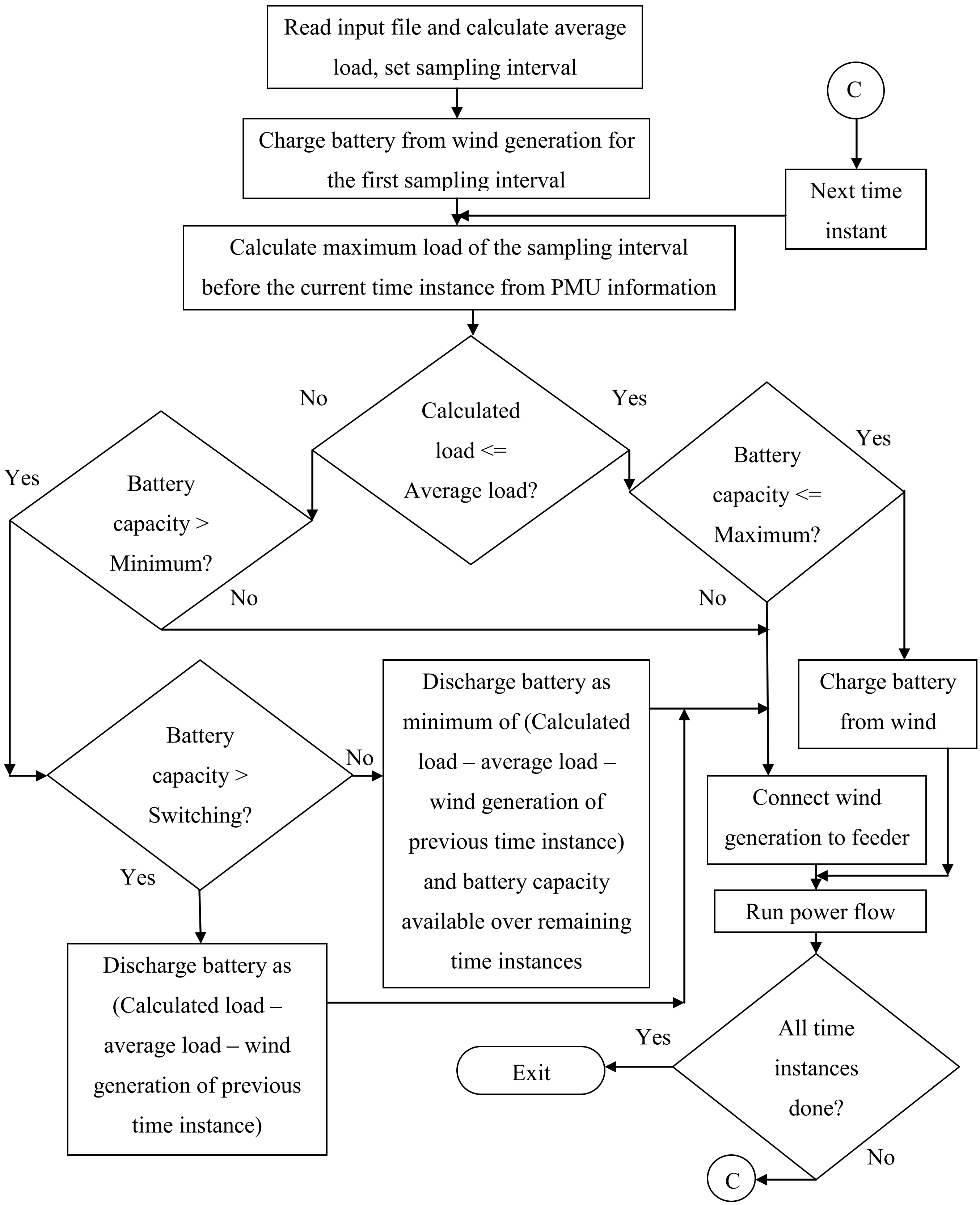

Figure 5.7 Flowchart for real time battery operation with wind generation using PMUs

Chapter 6 - Results and Discussion

6.1 Results obtained for base cases of load flow

The base cases of load flow for both the 15 minute as well as one second data serve as a measure of comparison of the benefits of using battery storage with wind generation. The most basic load flow without any wind generation or battery gives the peak load of the feeder and also the heavy power losses that are encountered because of the usage of source power alone. In the next sub-sections, the base cases of load flow with and without wind generation have been shown for the fifteen minute basis demand as well as the one second basis demand data.

6.1.1 Results obtained for base cases of load flow without wind generation

The following results were obtained for the 15-minute basis forecasted load data for the IEEE 37 node test feeder. The analysis was carried out for all the load instances over a period of 24 hours. The results obtained here will serve as a comparison to the peak reduction achieved using direct wind connection as well as the dispatch operation of the battery storage as it is a case of maximum source power usage from the conventional generation. In order to clearly observe the effects of using PMU information in the battery dispatch process, the results need to be presented in such a way that they can be compared to the simplified fifteen minute normalized demand histogram. The final comparison of all the methods tested in this research work is with the normalized histogram of the base case. The other comparison factor is the power loss in the feeder without any wind generation or battery storage. All the other results are obtained in order to check for normal operation without any unstable or irregular conditions. The voltage profile plot shown for all cases is that of the node where the wind generation and battery storage have been installed. This node is selected as it is subjected to maximum irregularity at every time instant as both the wind generation and the battery storage keep changing. If this voltage is within allowable limits, it can be said with confidence that the other nodes in the feeder are also within normal operating voltages. The plots obtained for base case of feeder load without any form of distributed generation are given below.

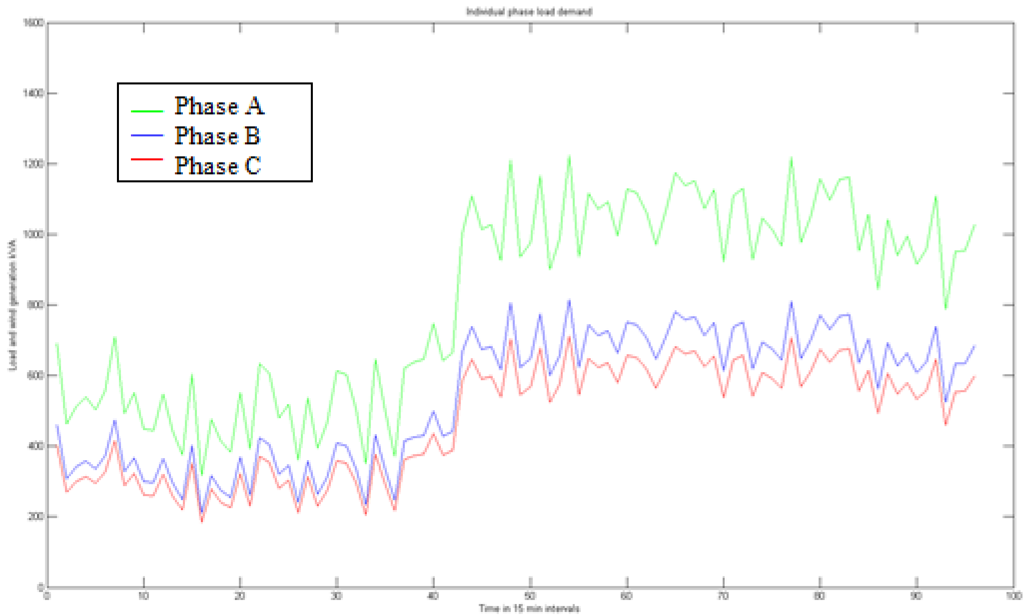

Figure 6.1 Individual demand of phases a, b and c of the feeder for 15 minute data

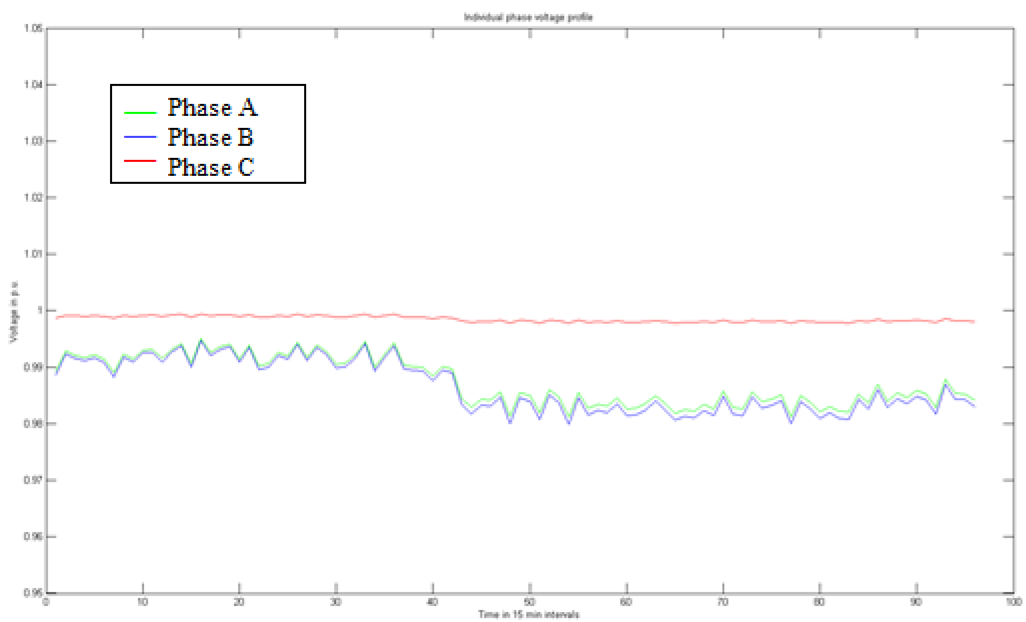

Figure 6.2 Individual voltages of phases a, b and c for node 32 for 15 minute data

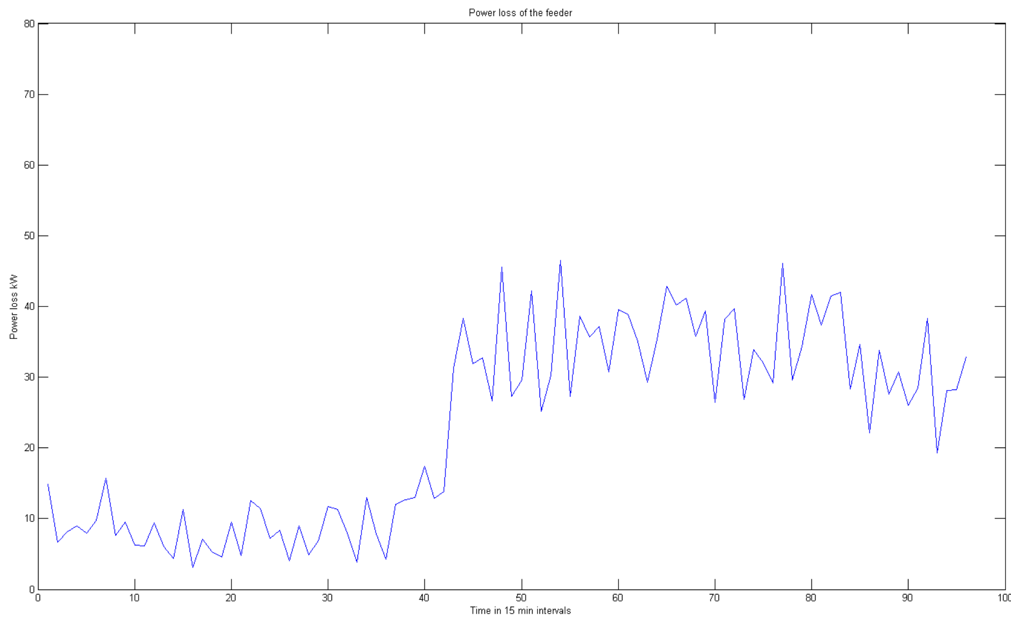

Figure 6.3 Power losses for the entire feeder for 15 minute data

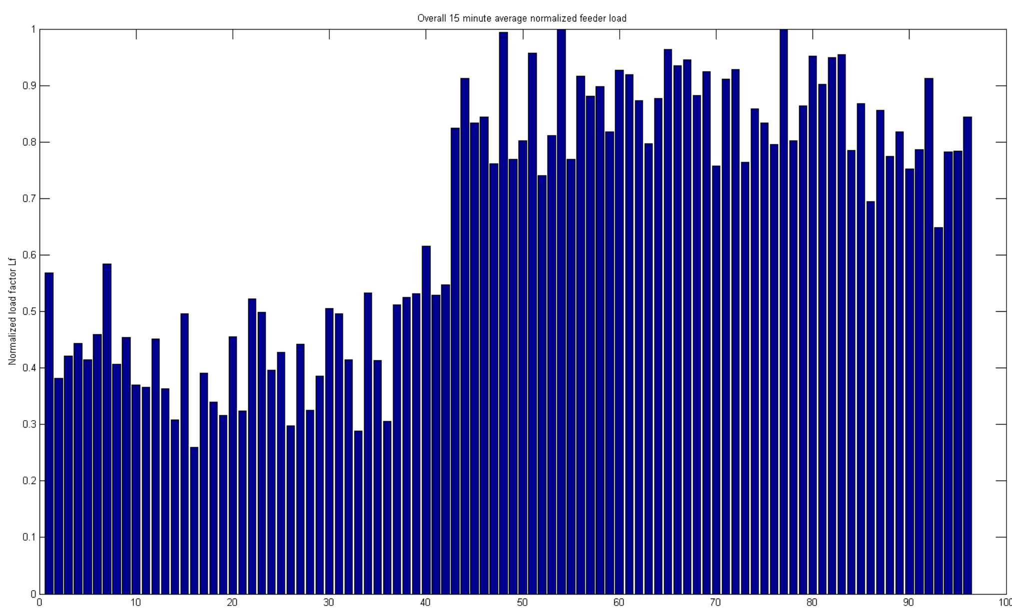

Figure 6.4 Average normalized 15-minute load profile of the feeder without wind generation

As it can be seen from the above plots, the load on the feeder follows a standard pattern which results in base load as well as peak load conditions. The above results are for a standard three phase backward forward sweep power flow for all the 96 fifteen minute time intervals of the day. It is also seen that the losses of the feeder are directly related to the amount of power drawn from the conventional generation. The objectives to be achieved are to reduce the peak load conditions that are seen in the 15-minute demand histogram, and also the minimization of losses that arise from more power consumption from conventional generation. It will be observed later that when the first objective is met, the second objective is also met as a result.

The 15-minute load data is multiplied with a Gaussian distribution in order to get one second forecasted data for the purpose of analysis as explained in chapter 4 on test cases. The base case without any distributed wind generation or battery is also run for the one second data. The results obtained are used to show the actual operational dynamics of the load of the feeder and the increase in actual peak load of the feeder when one second data is used. The fifteen minute averaged demand histogram is also created from the one second demand data in order to provide a direct comparison to 15-minute data. The results obtained are given below in figures 6.5 through 6.9.

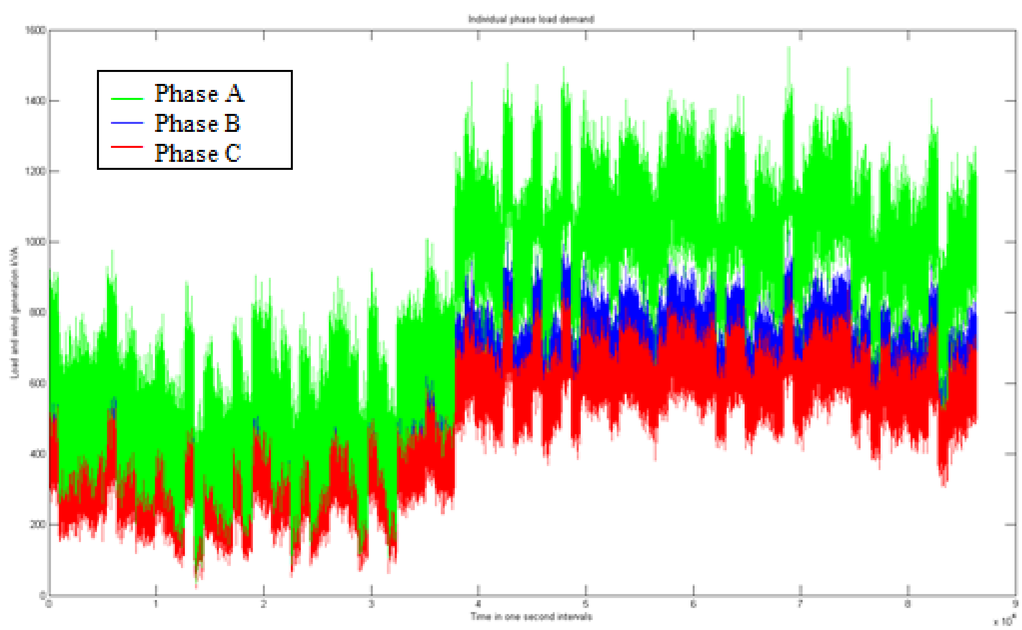

Figure 6.5 Individual demand of phases a, b and c of the feeder for one second data

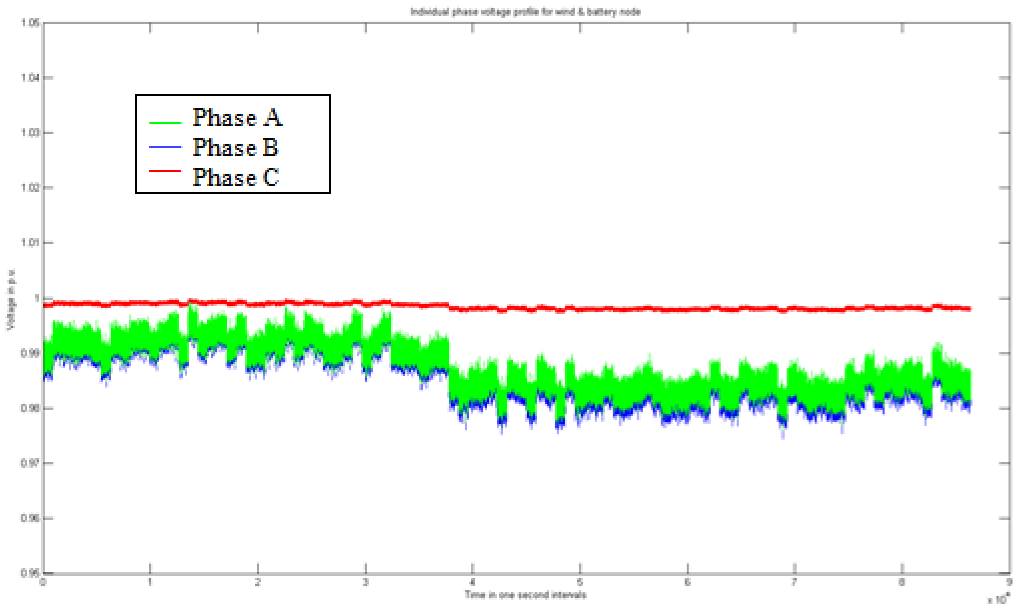

Figure 6.6 Individual voltages of phases a, b and c for node 32 for one second data

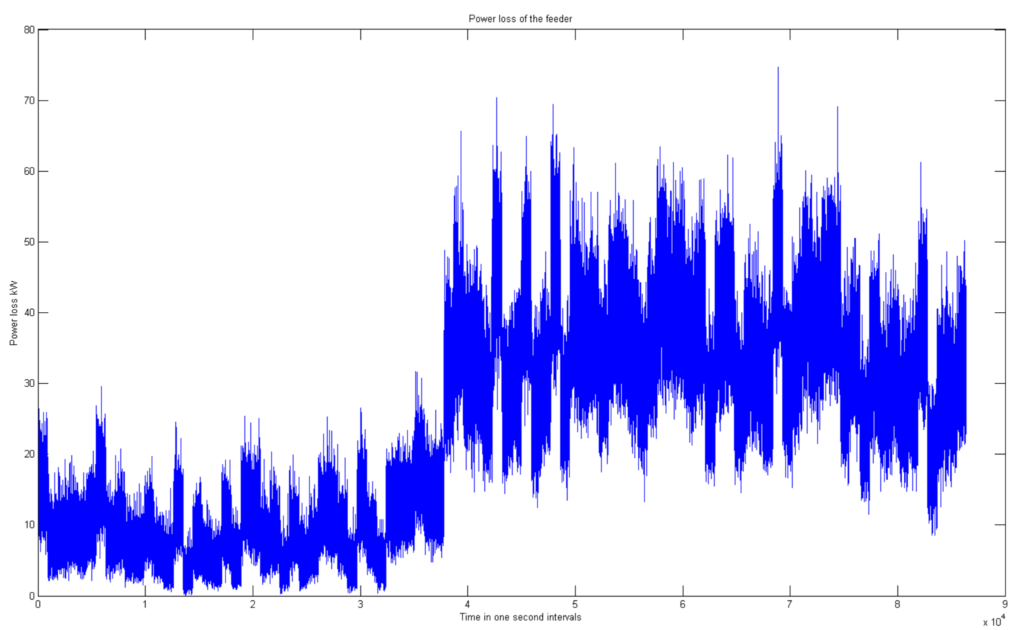

Figure 6.7 Power losses of the entire feeder for one second data

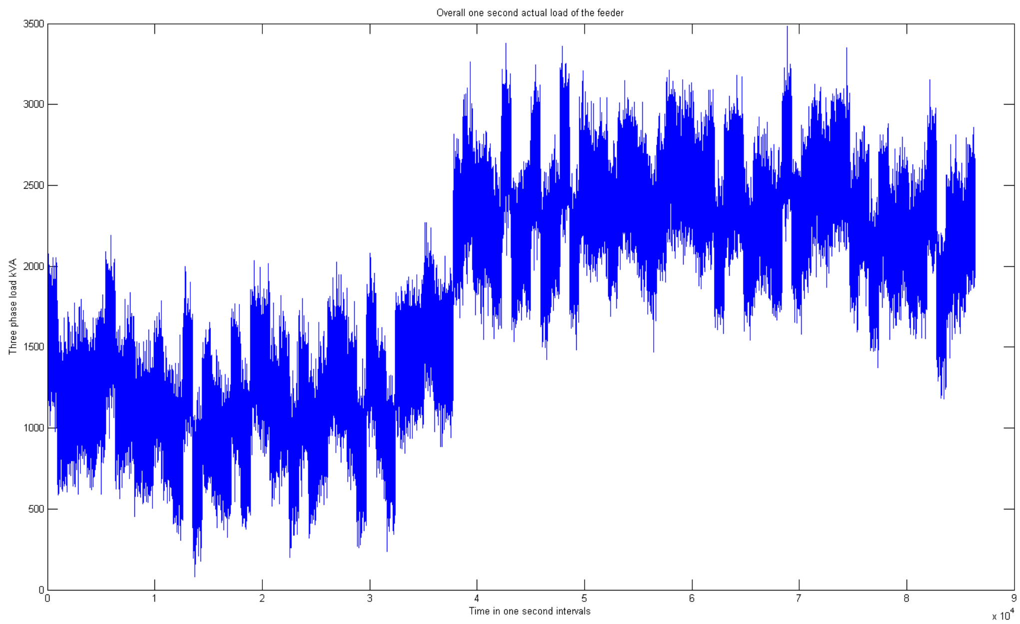

Figure 6.8 Total three phase demand of the feeder for one second data

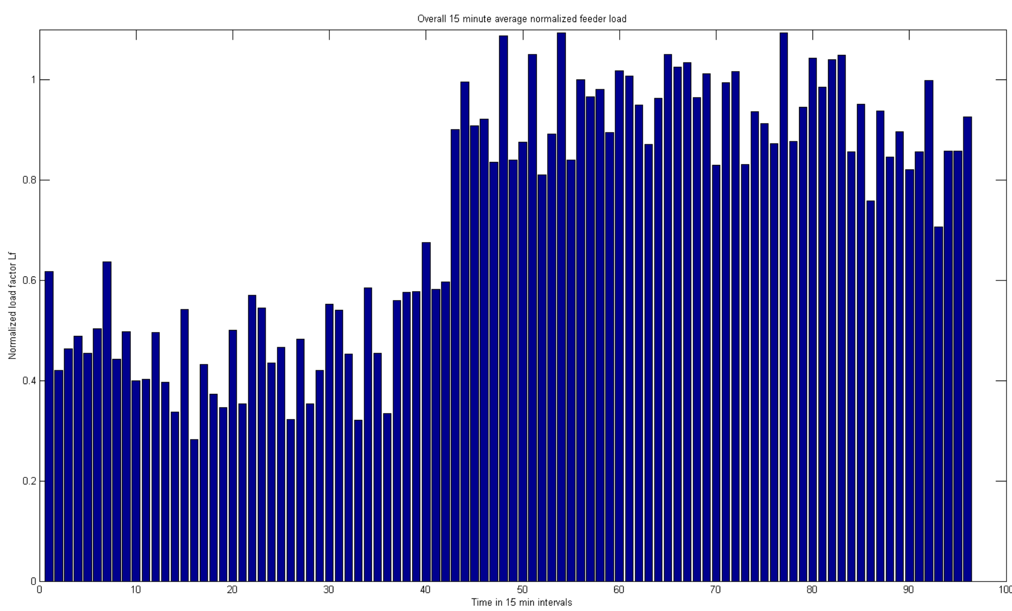

Figure 6.9 Average normalized 15-minute demand histogram for the feeder obtained from one second demand

It is observed from the one second approximation of the 15-minute load profile that actual values of load seen by the distribution feeder are much higher than the planned average 15-minute load capacity of the feeder. Although load differences in actual cases may not be as high as the probabilistic case tested here, there is a need to address the problem of increasing load levels with time. This is one of the reasons why peak reduction algorithms are of great importance in modern power system studies. The criticality of the one second basis test case being analyzed in this research will help in the design of robust and foolproof algorithms in the future when actual utility implementation of the algorithms using PMU become possible.

6.1.2 Results obtained for base cases of load flow with wind generation

Current approaches used in utility operation of wind turbines mostly involve the direct online connection of wind farm generation. The load is partially satisfied all the time by the available value of wind power. There is no control strategy involved except in the case of contingencies such as excessive wind during which the turbines are offline. Wind energy in this case can be used up when its requirement is not of great importance and alternatively, there might be no support when there are heavy load conditions. It is also rare to observe an idealized characteristic for wind generation for a given day when load and wind are positively correlated, i.e., the wind generation is highest when the load levels are high. This is the only scenario when maximum peak reduction using wind generation alone is possible. The fifteen minute direct wind connected case power flow data have been presented below for low wind, medium wind and high wind conditions. It does not make sense to calculate peak reduction metrics for direct wind connection as the peak reduction in this case is a function of magnitude, and also the time of wind availability which can be different on different days.

The power flow results obtained for a given day with high wind generation are given below. The results obtained are for the individual phase demands after wind connection (Figure 6.10), voltage profile of the feeder where wind farm and battery have been connected (Figure 6.11), the losses of the feeder after wind generation (Figure 6.12), and the normalized fifteen minute demand after wind connection (Figure 6.13).

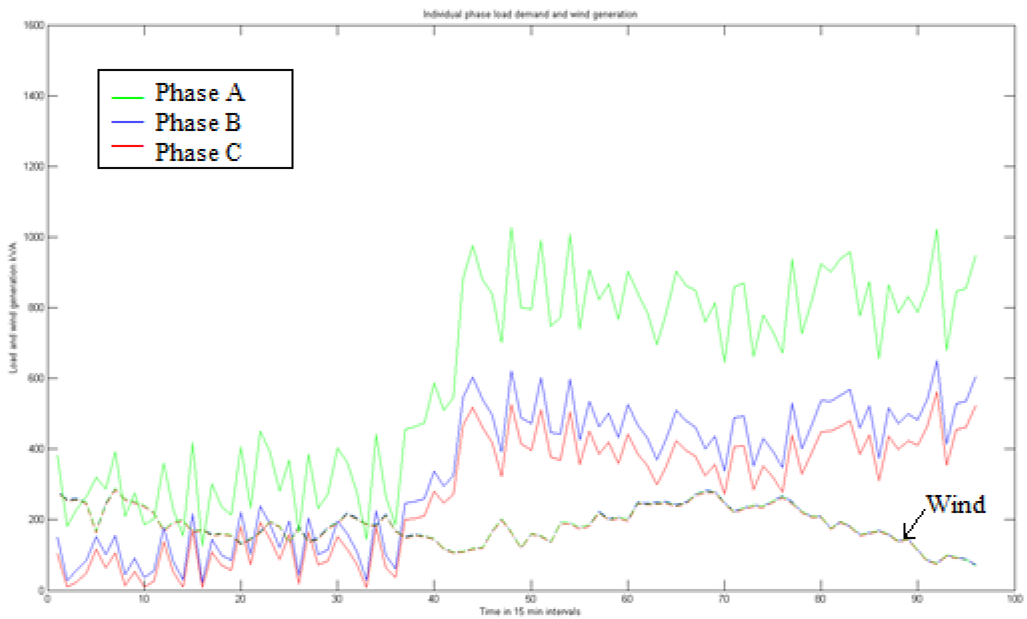

Figure 6.10 Individual phase demands with direct wind generation connection and high wind for fifteen minute data

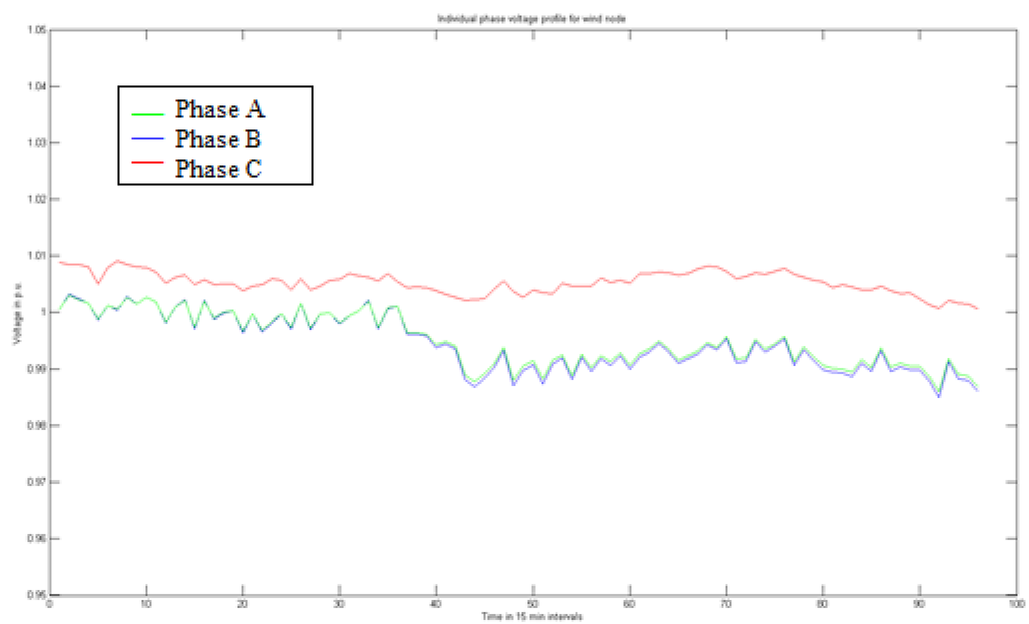

Figure 6.11 Individual phase voltages for node 32 with direct wind connection and high wind for fifteen minute data

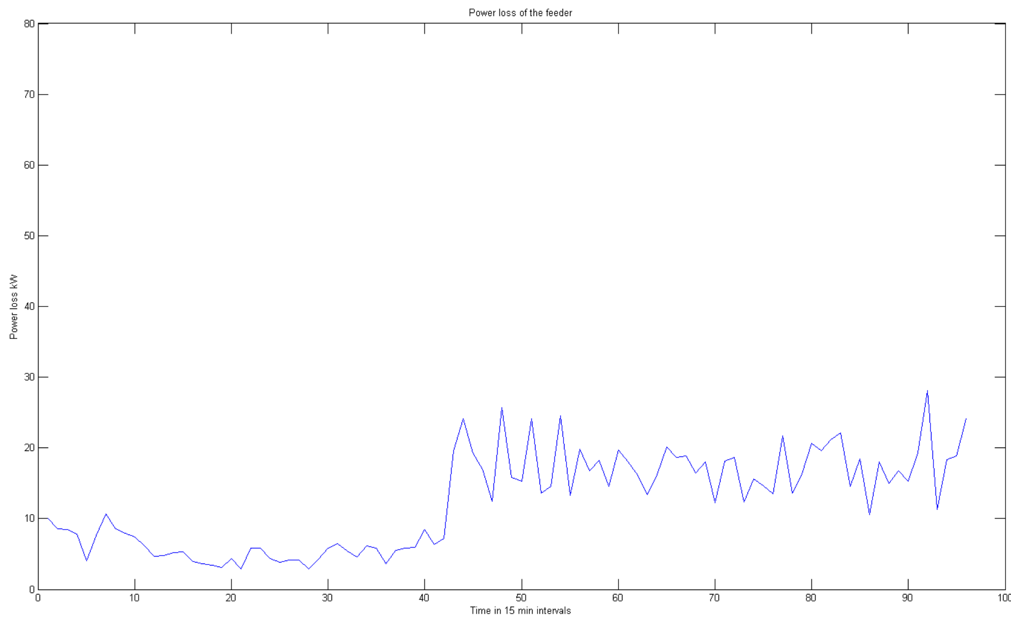

Figure 6.12 Power losses for the feeder with direct wind connection and high wind for fifteen minute data

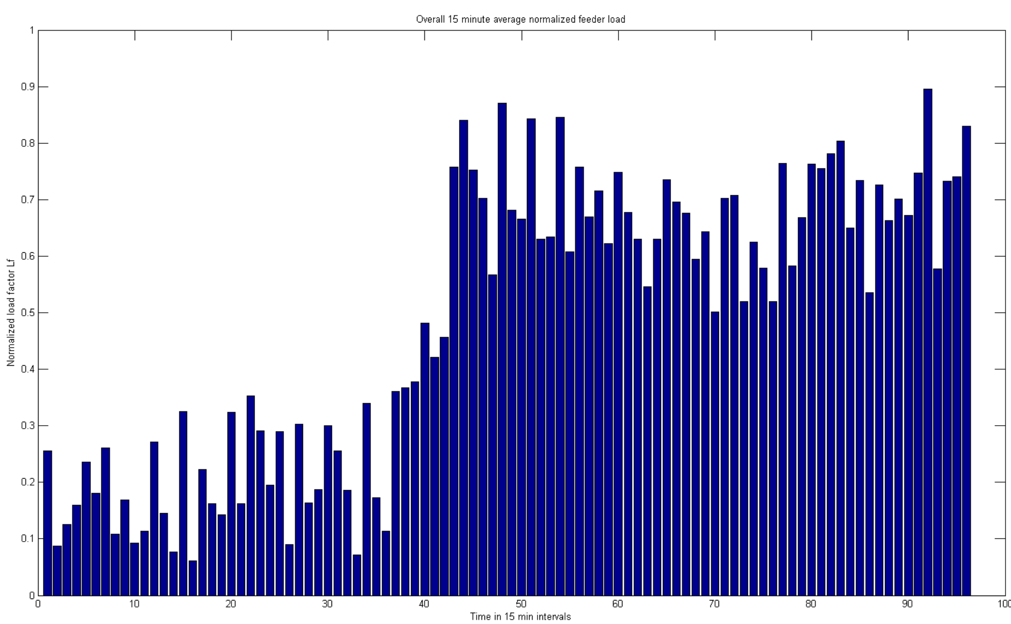

Figure 6.13 Normalized fifteen minutes load histogram as seen by the substation with direct wind connection and high wind

As it can be seen from the results above, direct wind connection yields good results when high wind generation is available, but there is a direct relation between the amount of wind generation and peak reduction achieved in a given instance. During instances when the feeder is lightly loaded, the load can drop to dangerously low levels so as to cause unstable conditions such as the Ferranti effect, although this is a rarity as it has to happen simultaneously in multiple feeders.

The power flow results for medium wind generation for a given day for fifteen minute data have been given below from figure 6.14 through 6.17.

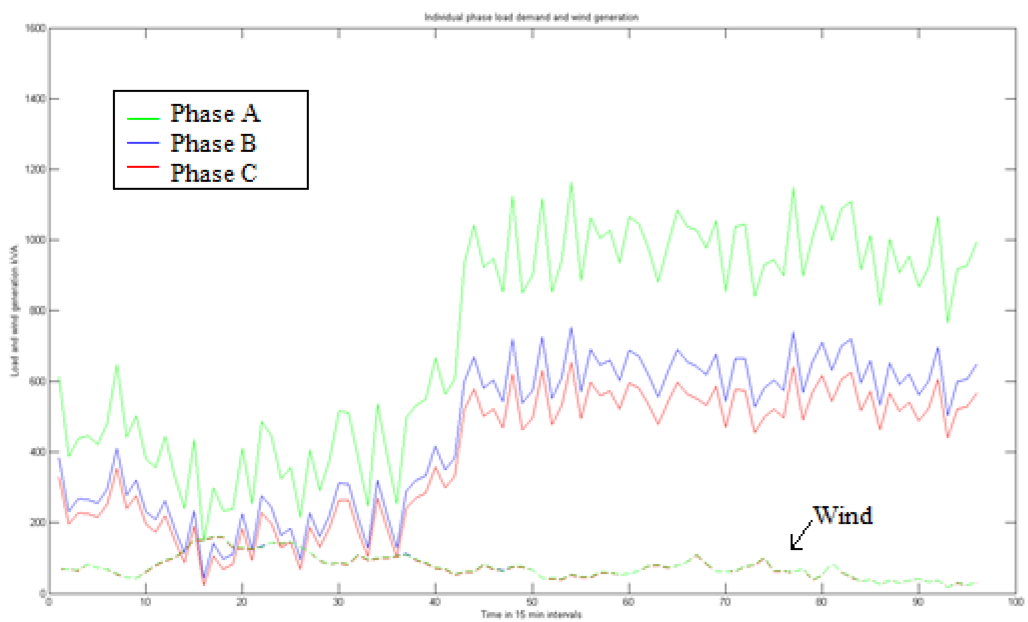

Figure 6.14 Individual phase demands with direct wind generation connection and medium wind for fifteen minute data

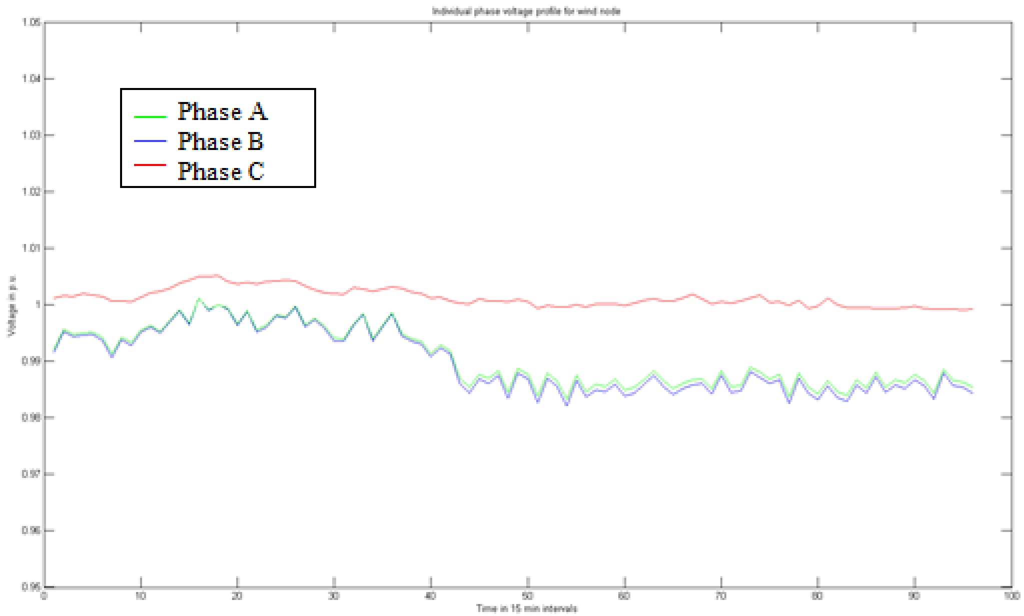

Figure 6.15 Individual phase voltages for node 32 with direct wind connection and medium wind for fifteen minute data

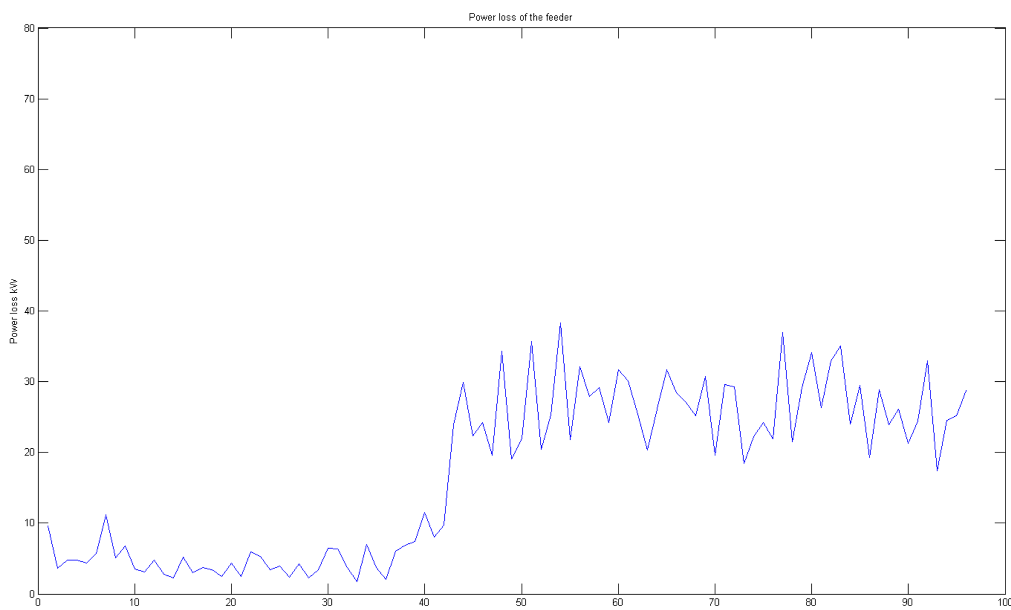

Figure 6.16 Power losses for the feeder with direct wind connection and medium wind for fifteen minute data

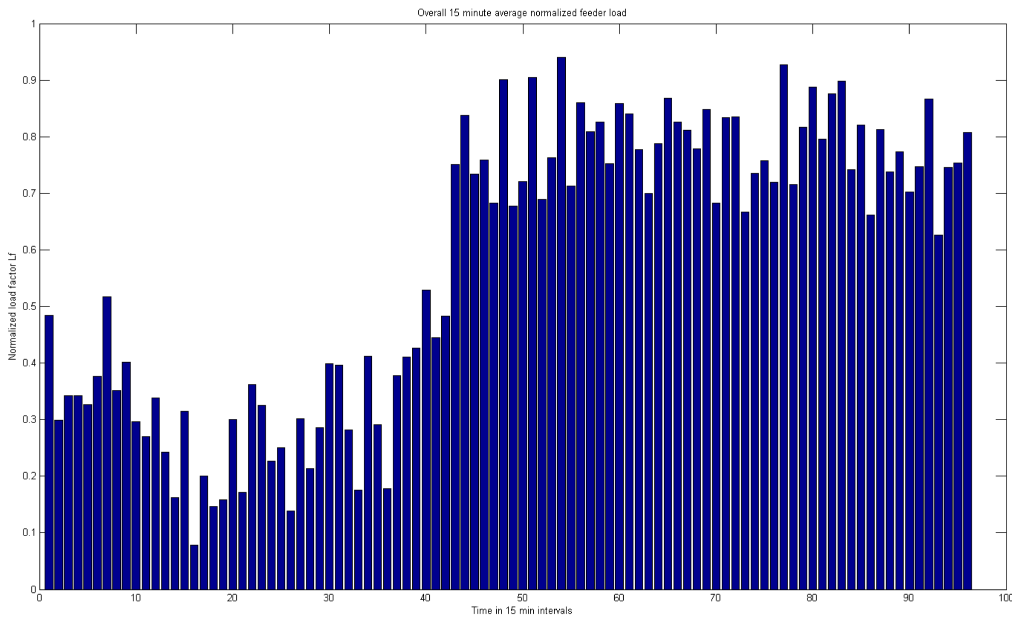

Figure 6.17 Normalized fifteen minutes load histogram with direct wind connection and medium wind

From the results obtained above, we see that the losses encountered in a distribution feeder decrease with the increase of locally generated power. The power flow results for the same data for low wind generation have been given in figures 6.18 through 6.21. The results obtained in the case of low wind generation prove that increase of locally generated power, especially renewables, reduces feeder losses.

Amount of Wind Generation	Average Feeder losses (kW)
High wind	12.4448
Medium wind	17.1213
Low wind	20.9120
No wind	22.9694

Table 6.1 Comparison of feeder losses for different wind generation levels

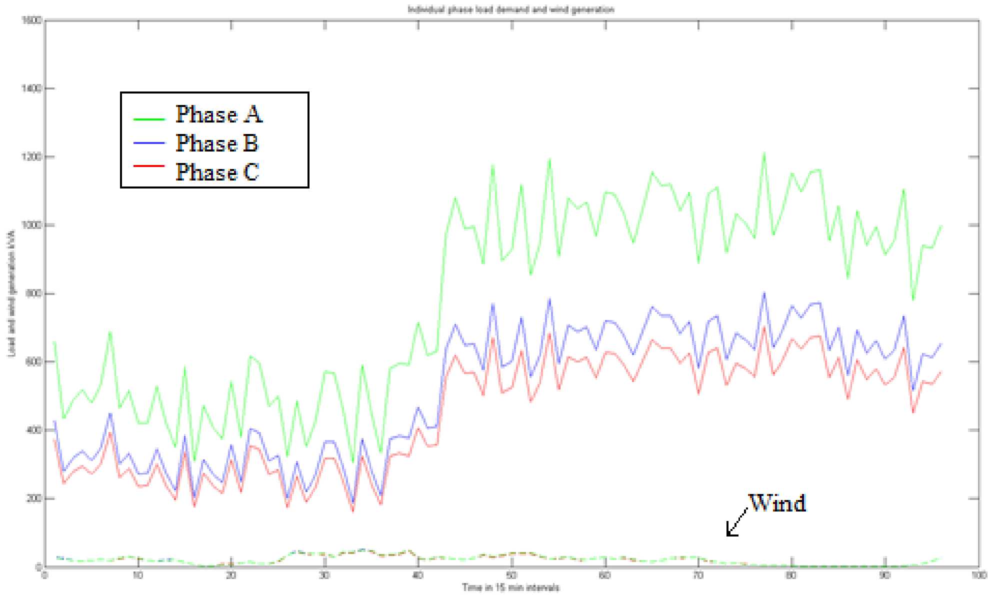

Figure 6.18 Individual phase demands with direct wind generation connection and low wind for fifteen minute data

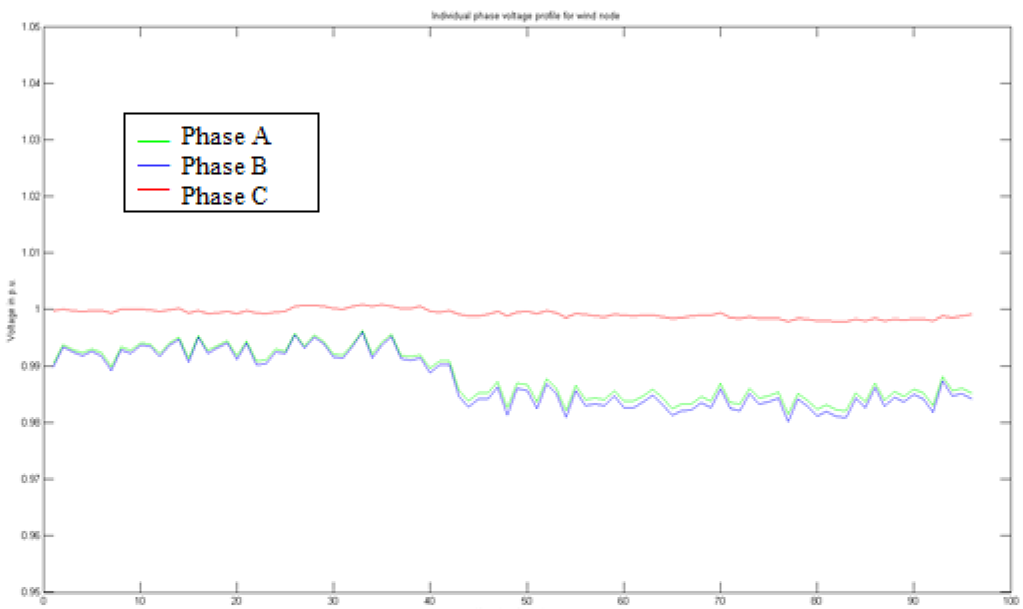

Figure 6.19 Individual phase voltages for node 32 with direct wind connection and low wind for fifteen minute data

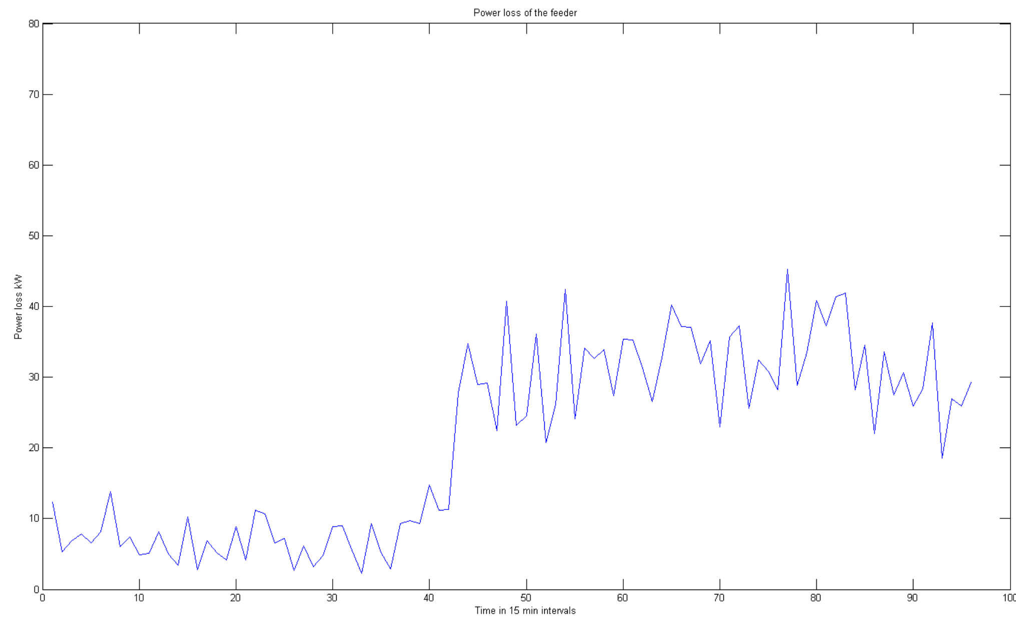

Figure 6.20 Power losses for the feeder with direct wind connection and low wind for fifteen minute data

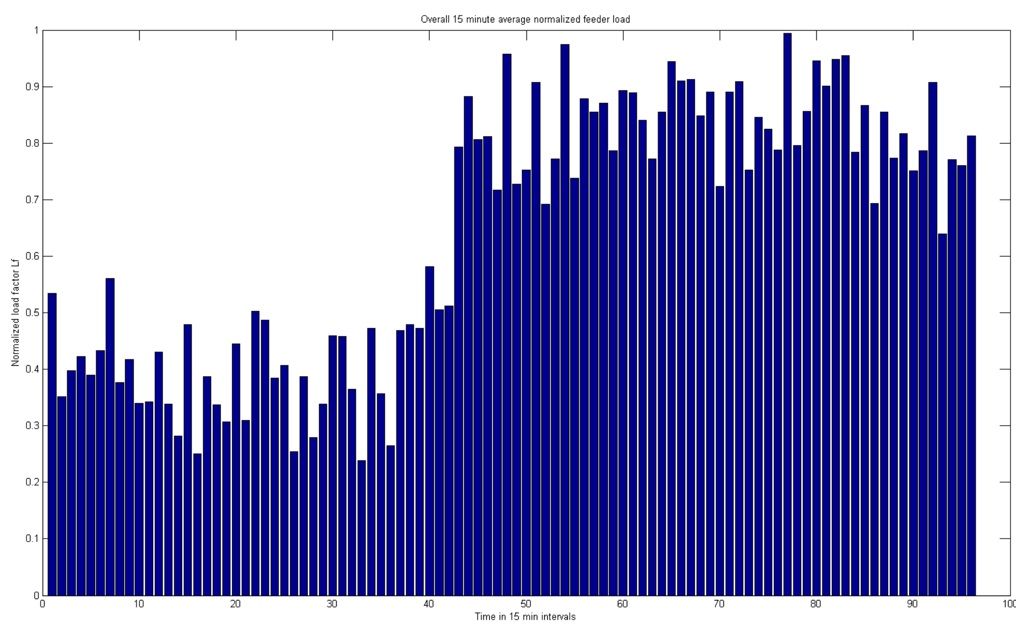

Figure 6.21 Normalized fifteen minutes load histogram with direct wind connection and low wind

The power flow results for one second basis forecasted load information and wind generation data have been given below in figures 6.22 through 6.26. It is seen that as in all the above cases, the peak load reduction is a direct function of wind generation availability, and the actual one second load of the feeder in spite of wind generation can be much higher than the average fifteen minute forecasted load. The peak reduction is also not very effective for one second wind generation as seen in the normalized demand plot. All the problems being observed in this section have been addressed in the next section.

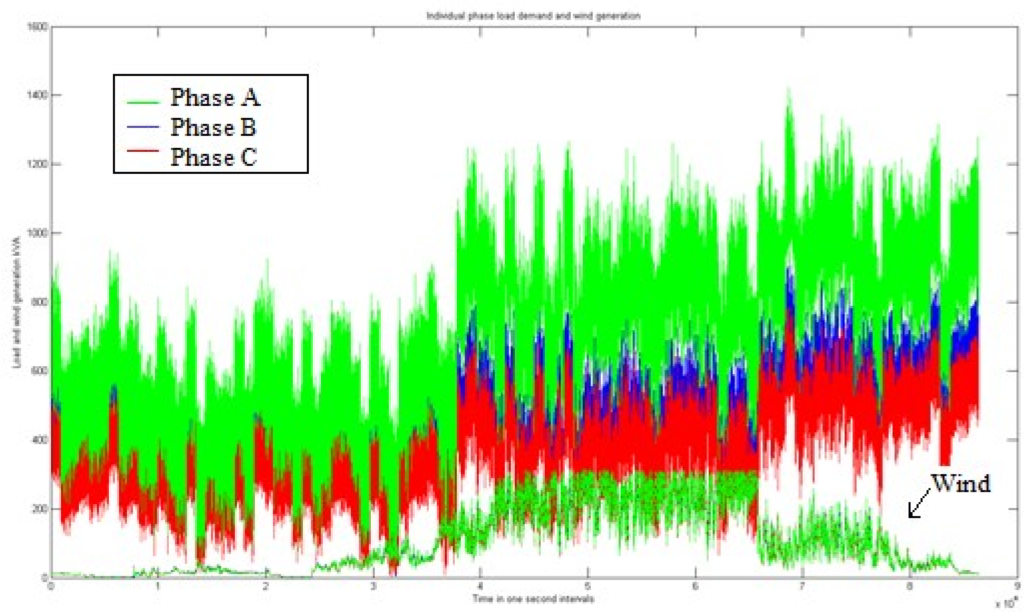

Figure 6.22 Individual phase load demand for one second basis data with direct wind generation connection

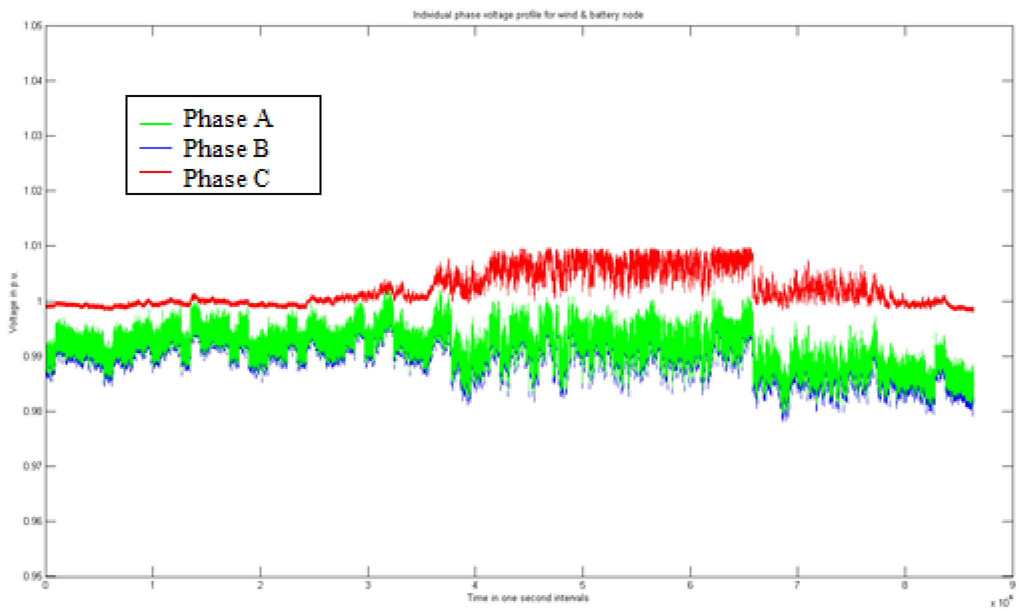

Figure 6.23 Individual phase load voltages for one second basis data with direct wind generation connection

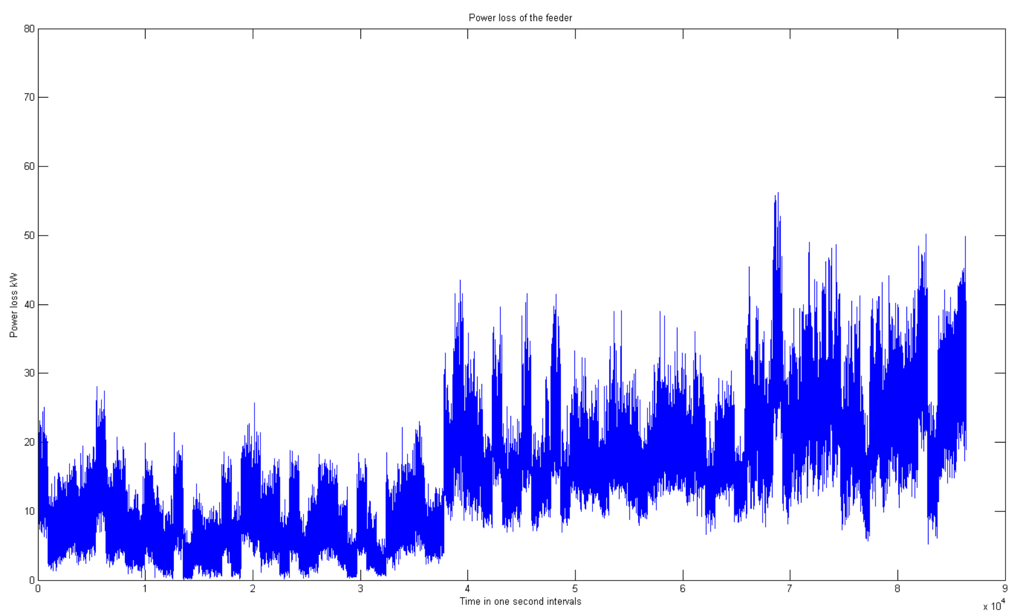

Figure 6.24 Feeder power losses for one second basis data with direct wind generation connection

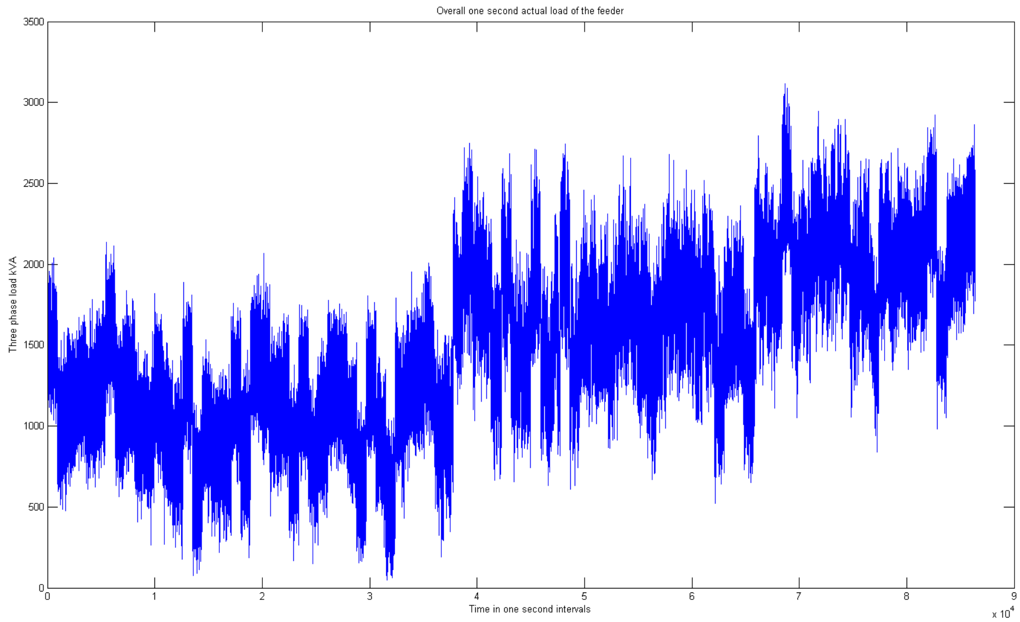

Figure 6.25 Overall demand of the feeder for one second basis data with direct wind generation connection

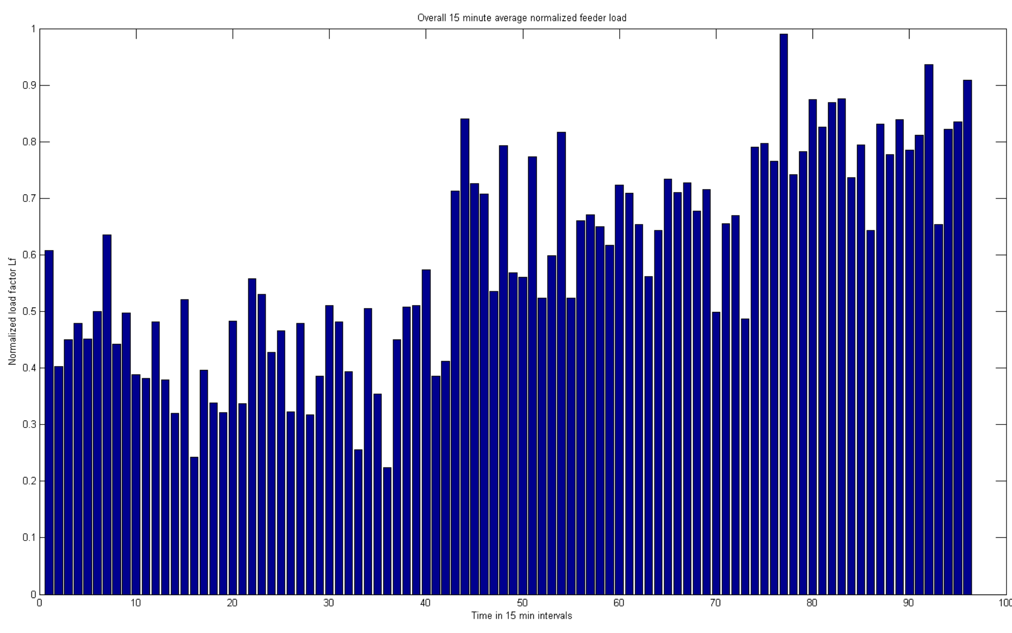

Figure 6.26 Fifteen minute average normalized demand of the feeder for one second basis data with direct wind generation connection

6.2 Results obtained for wind generation and battery storage integration for forecasted load information

In this section, results that were obtained for battery integration along with wind generation into the test feeder have been discussed. The results have been obtained for both fifteen minute data as well as one second data. In the results that follow, the plots obtained for individual phase loads, feeder losses and voltage profile of the critical feeder are not shown due to similarity and redundancy of results when battery storage is integrated into the system. The initial results shown are for wind and battery integration in case of fifteen minute data for low wind, medium wind and high wind conditions. The two methods of charging and discharging the battery that were described earlier, namely wind charging, sustained average load charging, free running discharge and conservative discharge methods and their results have been presented below for the fifteen minute data. The results shown only pertain to battery power of charging and discharging, energy level of the battery, overall one second actual load demand after storage integration, and the 15-minute normalized demand of the feeder. In all the energy plots, the black line indicates the minimum capacity beyond which the battery cannot be discharged any further. The results for high wind generation for fifteen minute data are given in figures 6.27 to 6.29.

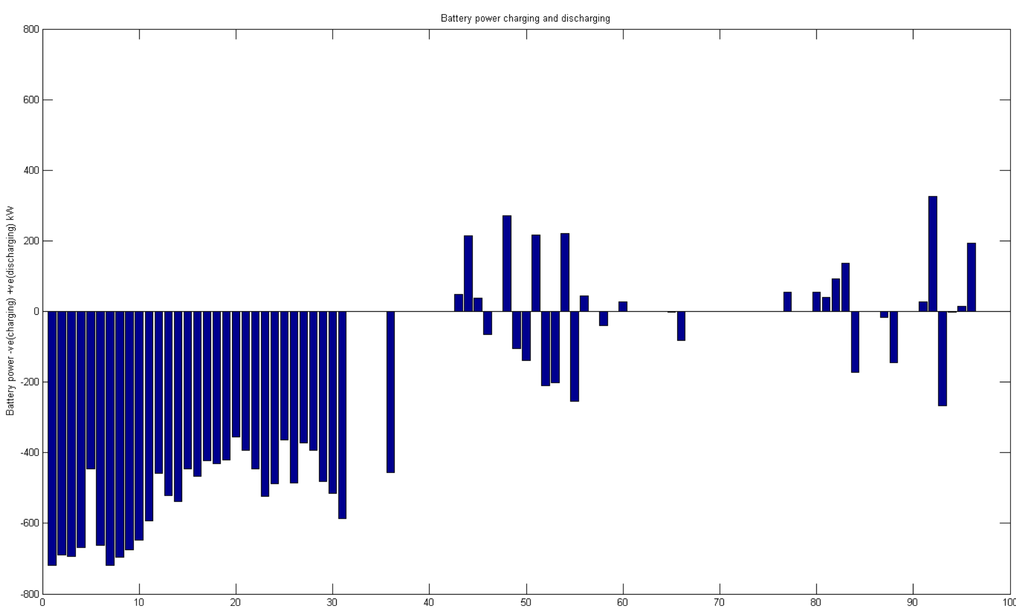

Figure 6.27 Battery charging and discharging for fifteen minute data with high wind generation in free-running discharge and wind charging

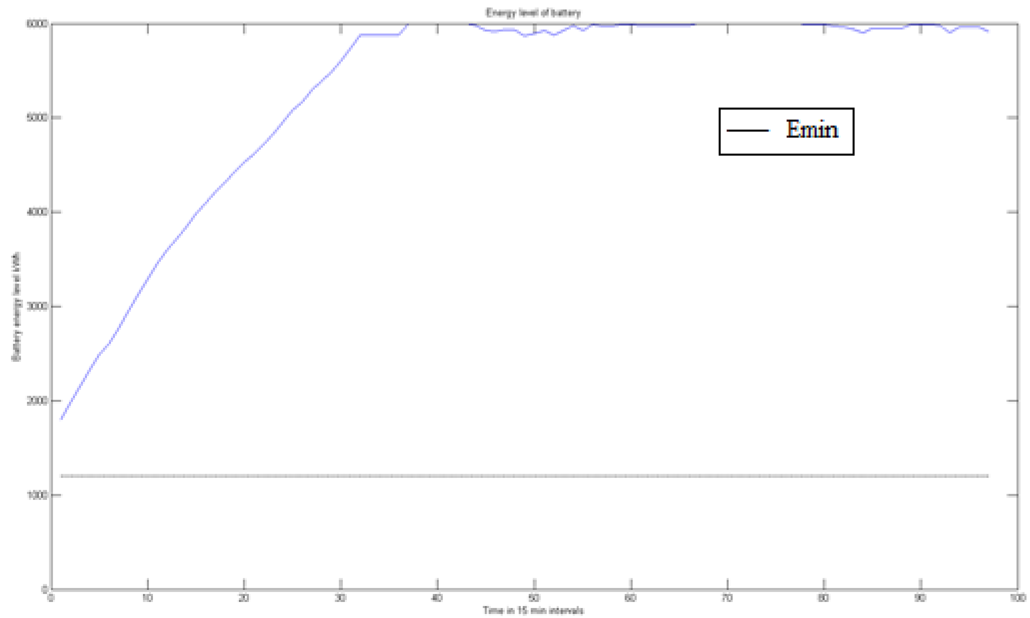

Figure 6.28 Battery state of charge for fifteen minute data with high wind generation in free-running discharge and wind charging

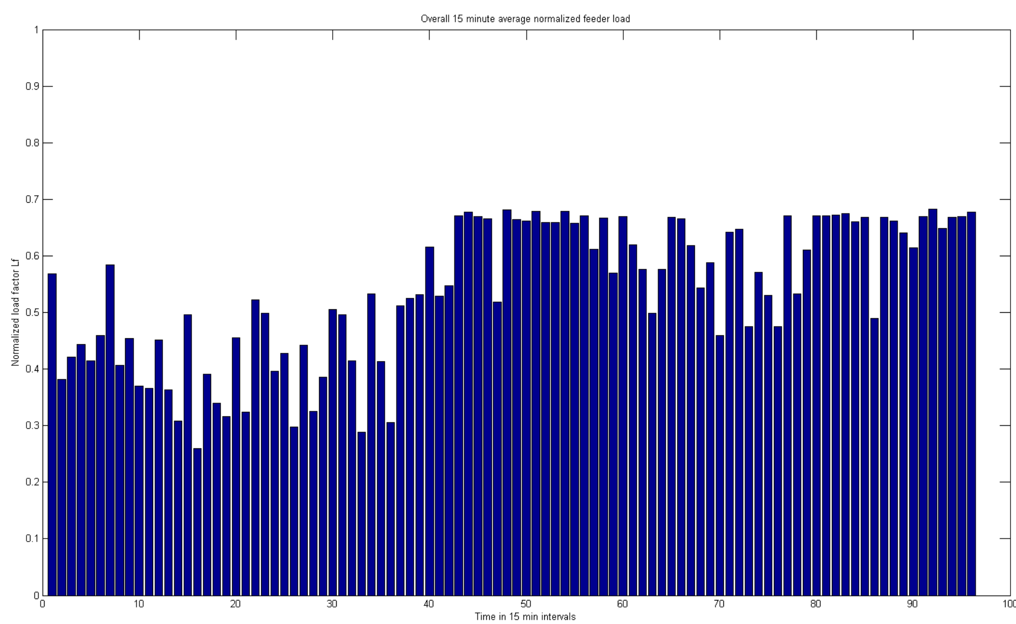

Figure 6.29 Normalized overall feeder load demand for fifteen minute data with high wind generation in free-running discharge and wind charging

The peak reduction achieved in case of even the fifteen minute low resolution data for battery discharging is high in cases of high wind generation. But the battery capacity cannot be effectively utilized as wind generation is available abundantly but cannot be stored effectively due to the non-availability of high resolution information. The results for free running discharge and sustained average load charging are given in figures 6.30 to 6.32.

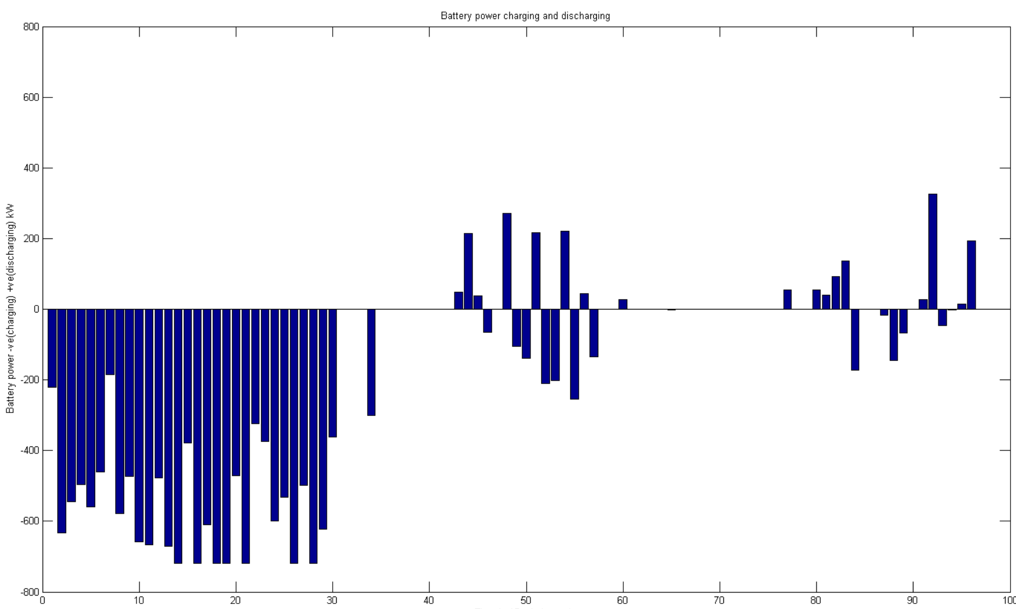

Figure 6.30 Battery charging and discharging for fifteen minute data with high wind generation in free-running discharge and sustained average load charging

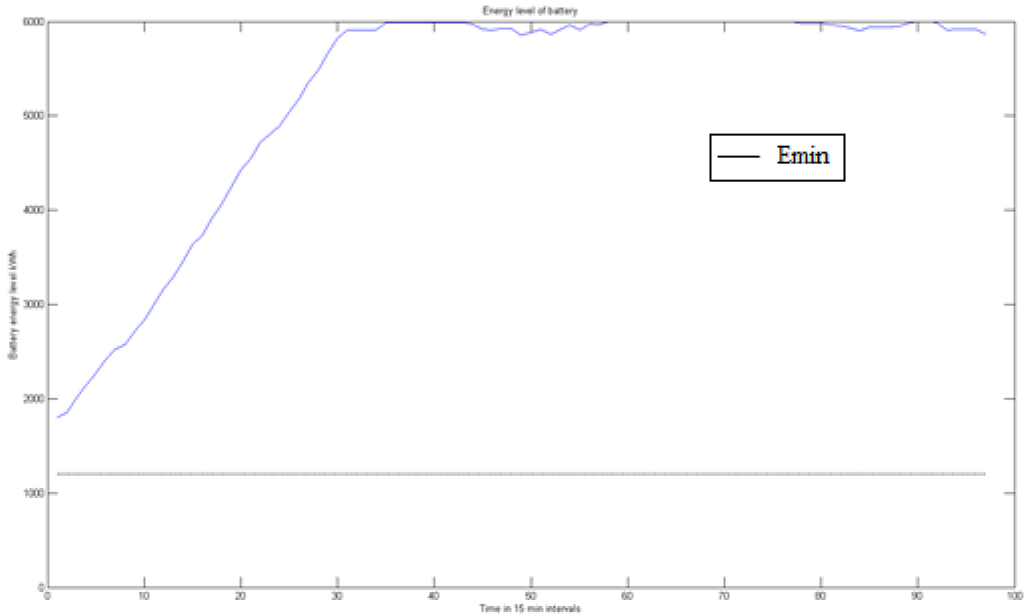

Figure 6.31 Battery state of charge for fifteen minute data with high wind generation in free-running discharge and sustained average load charging

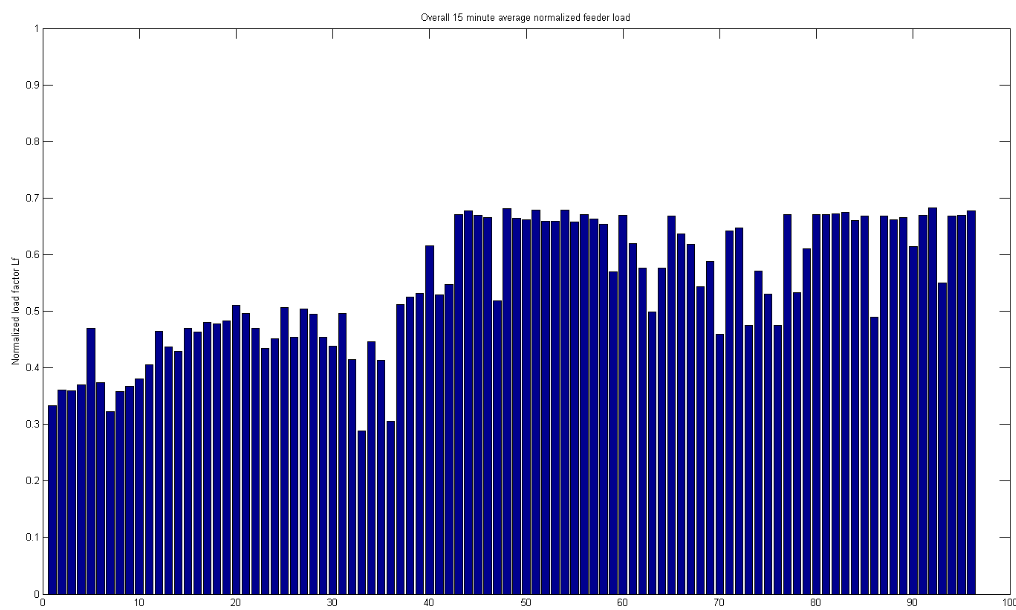

Figure 6.32 Normalized overall fifteen minute demand histogram with high wind generation in free-running discharge and sustained average load charging

The results obtained above are similar to the case without sustained average load charging. There is also no scope for the efficient utilization of wind generation due to lack of data resolution. The results obtained for conservative discharging mode with wind charging have been given in figures 6.33 to 6.35.

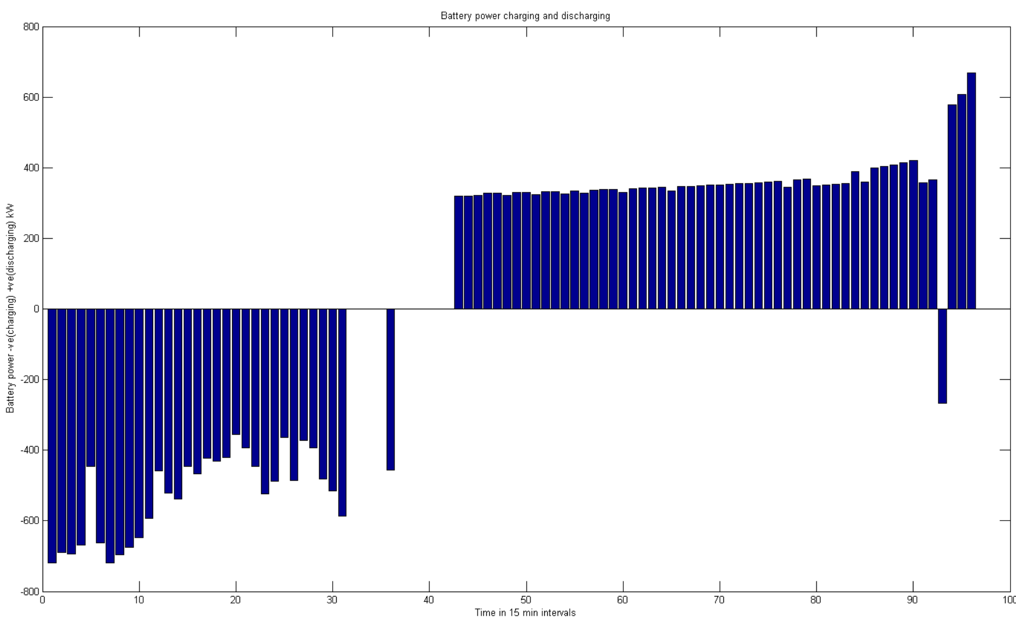

Figure 6.33 Battery charging and discharging for fifteen minute data with high wind generation in conservative discharge and wind charging

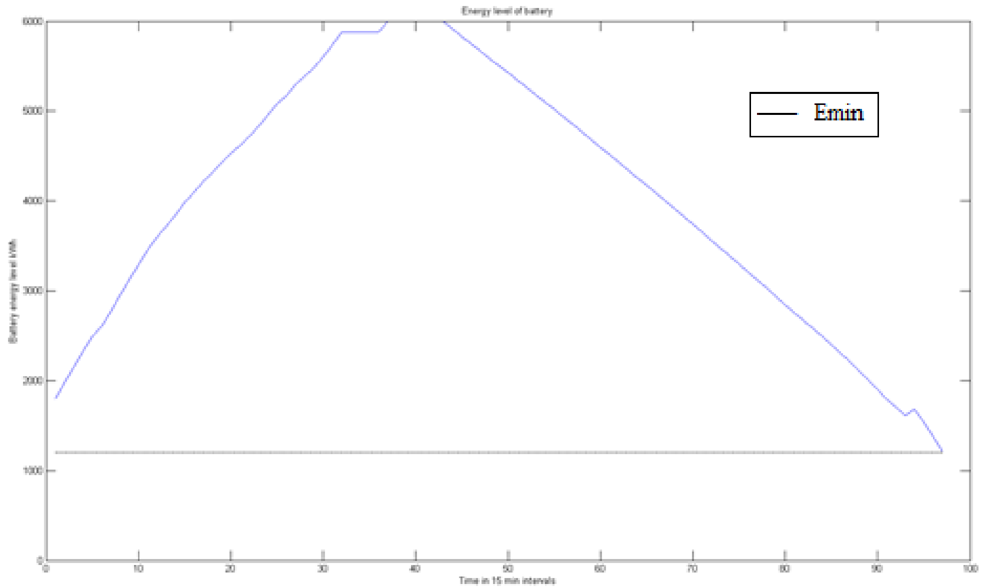

Figure 6.34 Battery state of charge for fifteen minute data with high wind generation in conservative discharge and wind charging

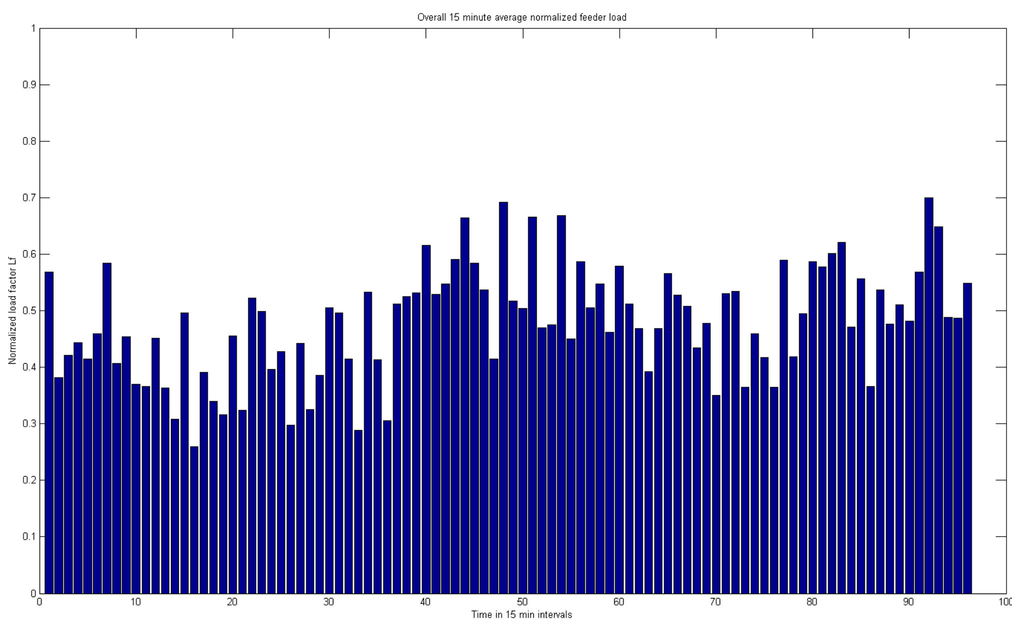

Figure 6.35 Normalized demand histogram for fifteen minute data with high wind generation in conservative discharge and wind charging

The peak reduction achieved in the case of conservative discharging with high wind generation and free running discharge is appreciable, but the battery is charged up to the highest level possible and also discharged to minimum in a single day. So, this method of discharge is only suitable for days during which wind generation is low in order to conserve battery capacity such that it is available for all the load intervals. The results obtained in case of high wind generation with sustained average load charging and conservative discharging are given in figures 6.36 to 6.38.

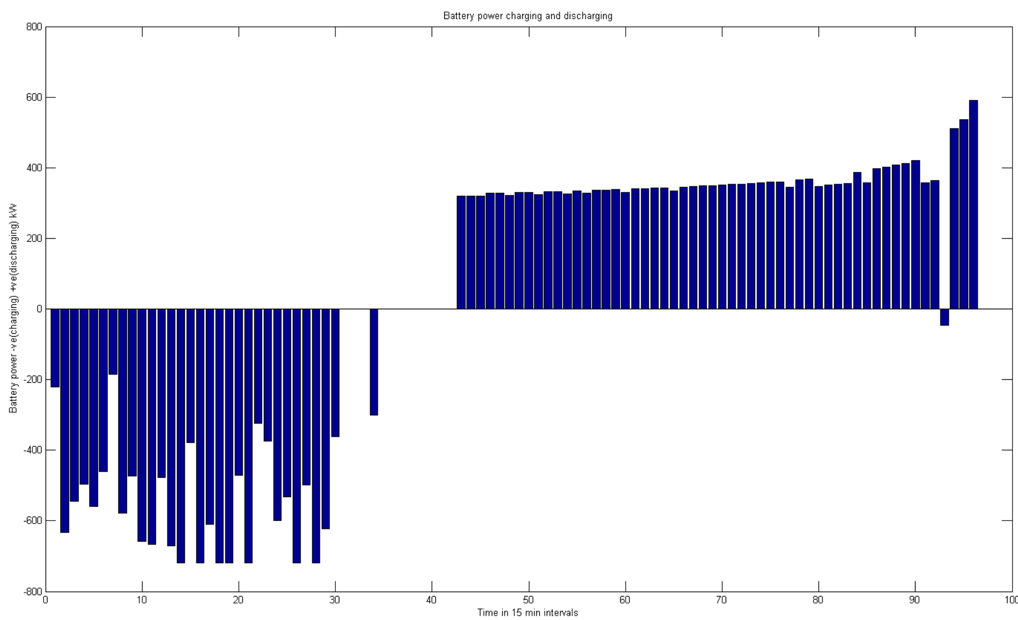

Figure 6.36 Battery charging and discharging with high wind generation in conservative discharge and sustained average load charging

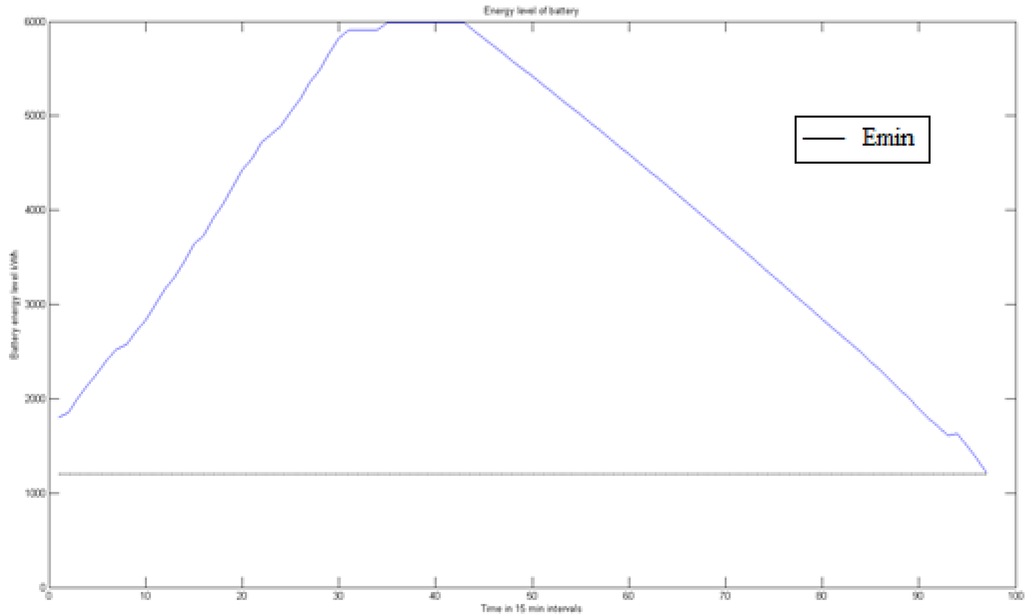

Figure 6.37 Battery state of charge with high wind generation in conservative discharge and sustained average load charging

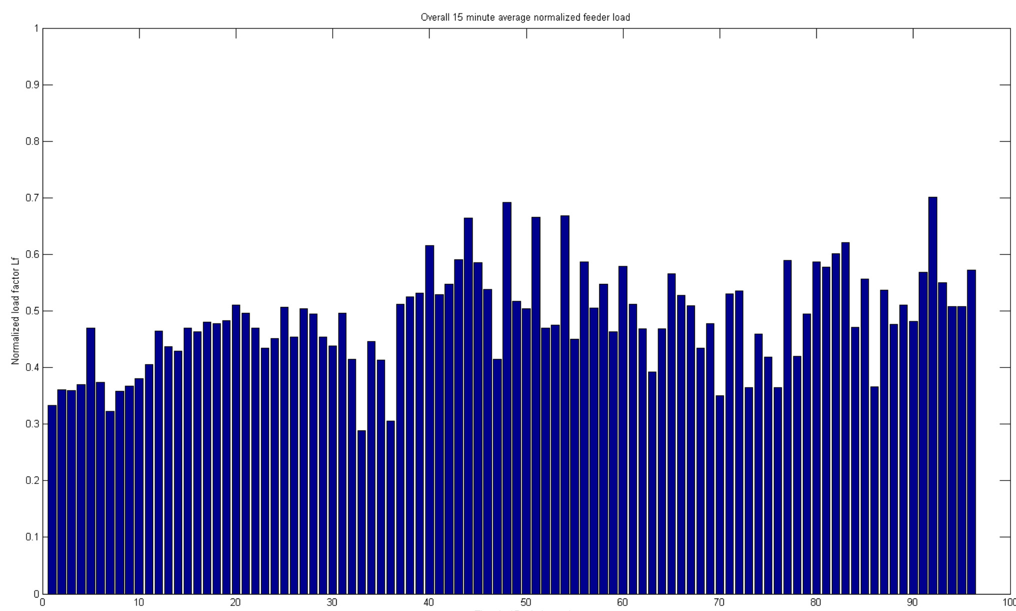

Figure 6.38 Normalized demand histogram with high wind generation in conservative discharge and sustained average load charging

The same results for all the four combinations of charging and discharging methods for the battery have been shown below for medium wind generation and low wind generation in figures 6.39 to 6.44.

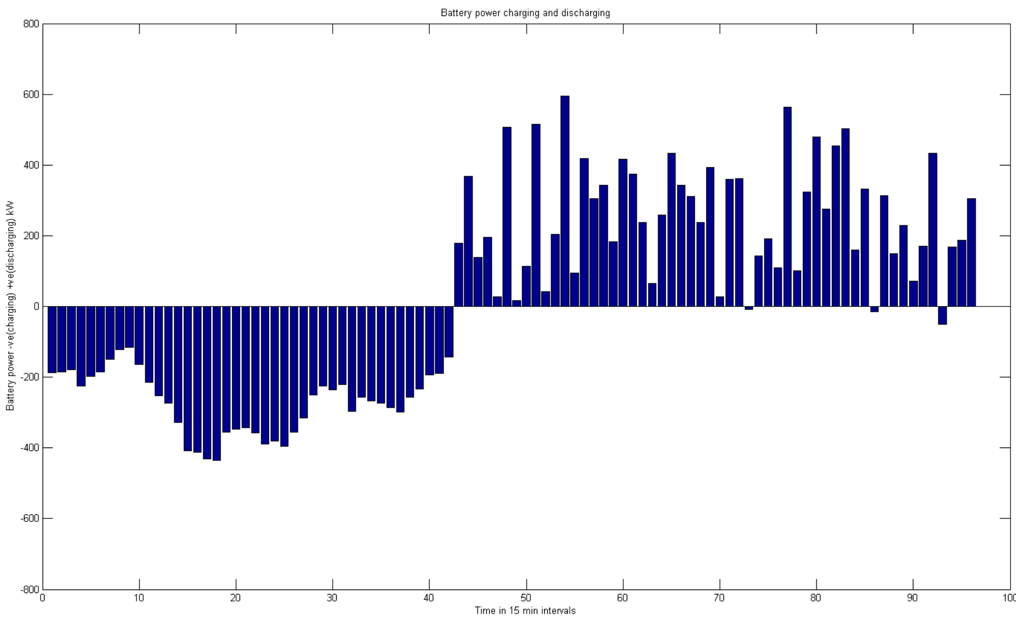

Figure 6.39 Battery charging and discharging for fifteen minute data with medium wind generation in free-running discharge and wind charging

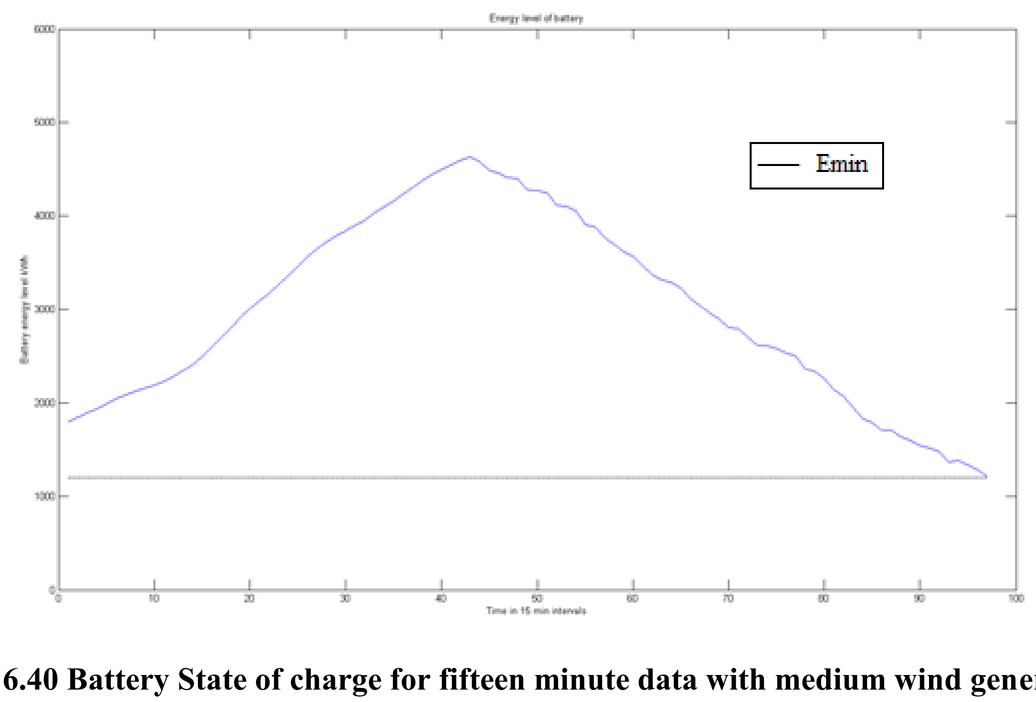

Figure 6.40 Battery State of charge for fifteen minute data with medium wind generation in free-running discharge and wind charging

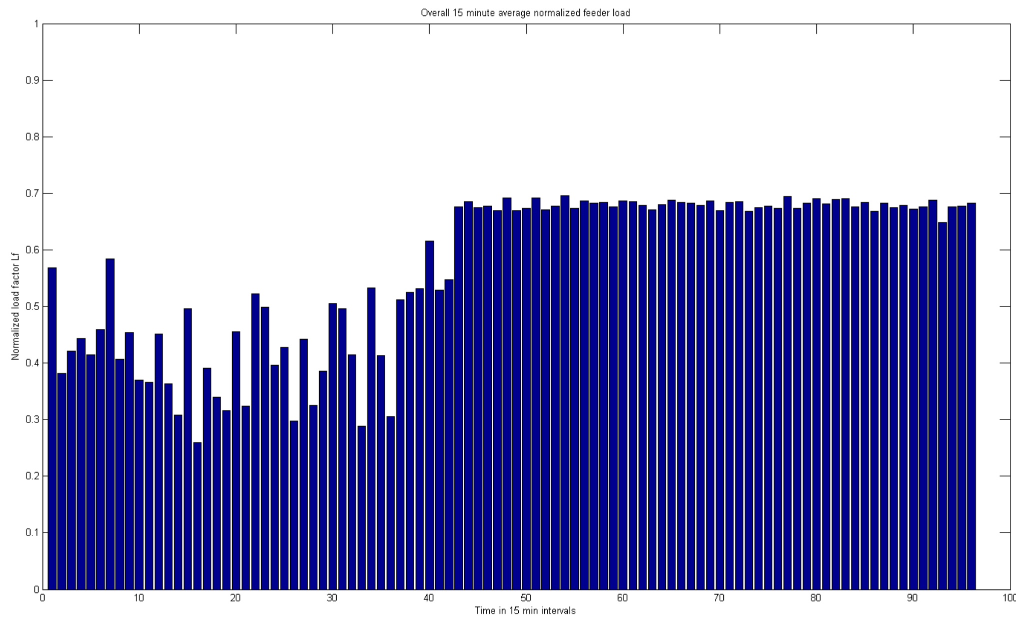

Figure 6.41 Normalized overall feeder load demand for fifteen minute data with medium wind generation in free-running discharge and wind charging

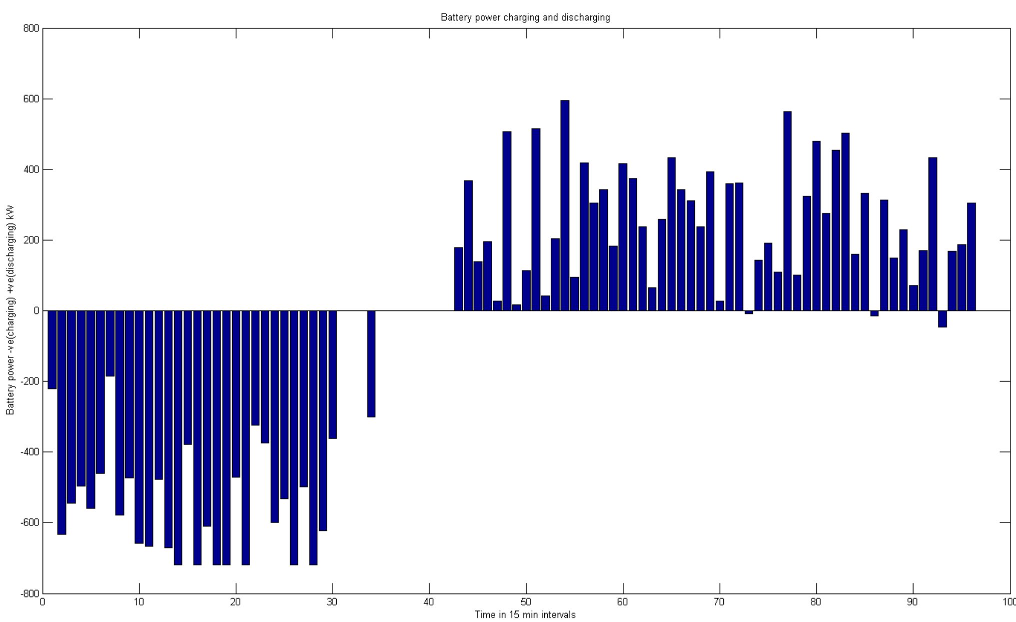

Figure 6.42 Battery charging and discharging for fifteen minute data with medium wind generation in free-running discharge and sustained average load charging

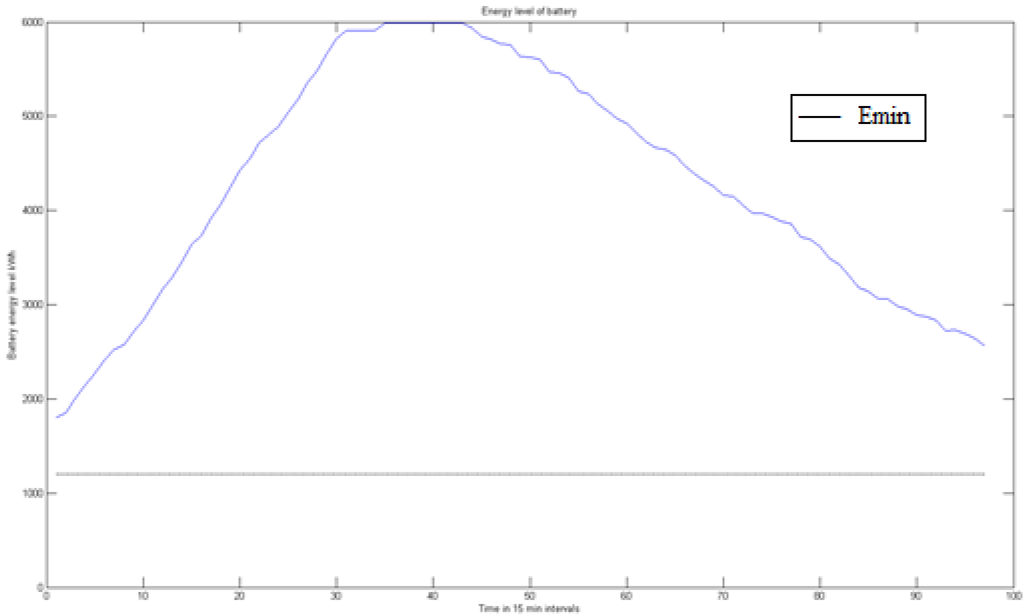

Figure 6.43 Battery state of charge for fifteen minute data with medium wind generation in free-running discharge and sustained average load charging

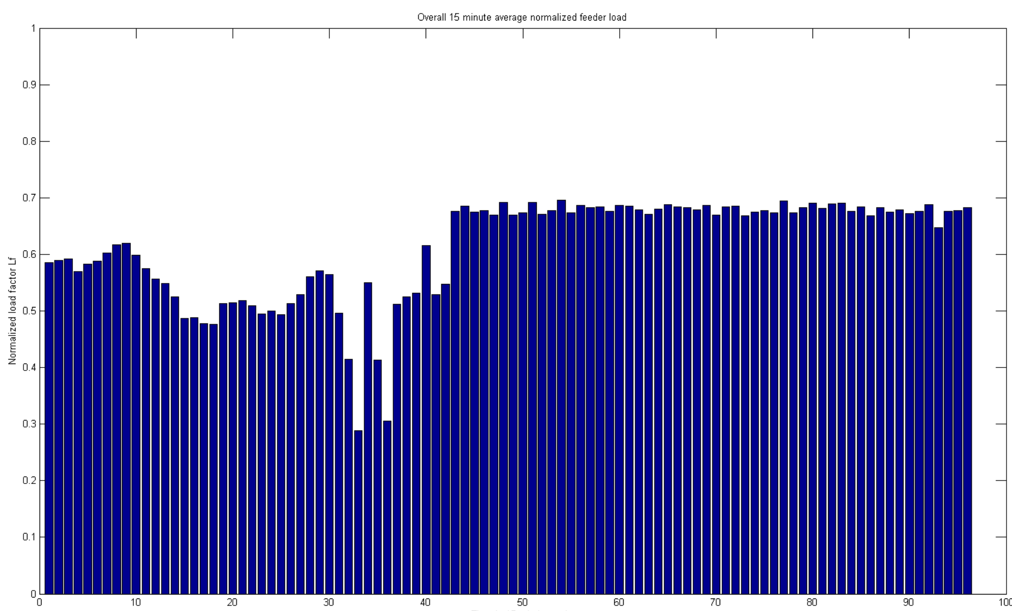

Figure 6.44 Normalized overall fifteen minute demand histogram with medium wind generation in free-running discharge and sustained average load charging

The difference that is clearly observed in this case is that on a given day during which an average amount of wind generation is available, if sustained average load charging is used, the average load tends to be higher than other cases. But the peak reduction is better than in other combinations of charging and discharging. The results for conservative discharging with wind charging as well as sustained average load charging have been given in figures 6.45 through 6.50.

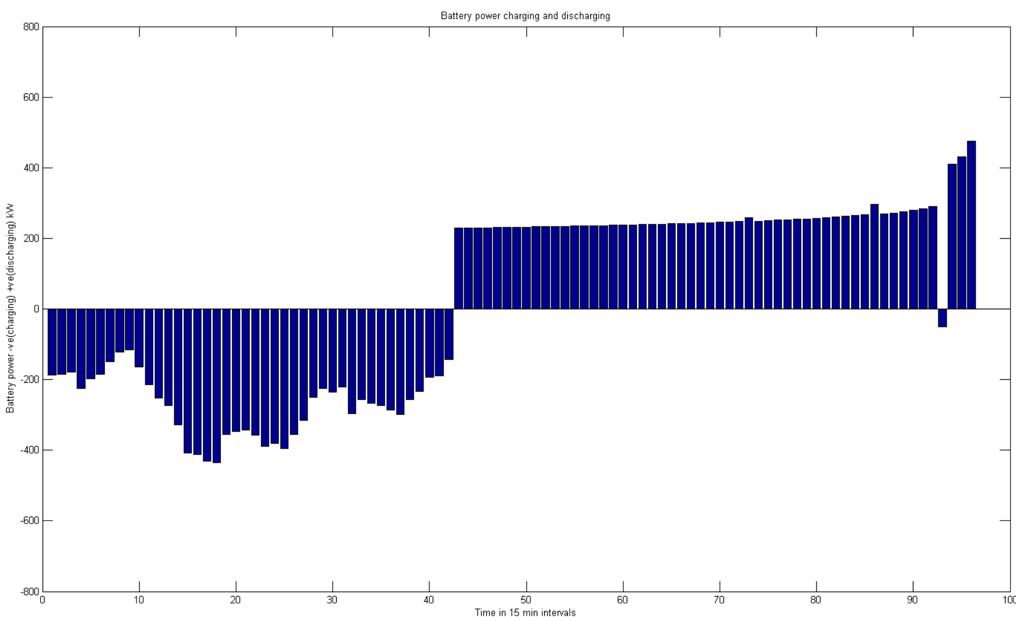

Figure 6.45 Battery charging and discharging for fifteen minute data with medium wind generation in conservative discharge and wind charging

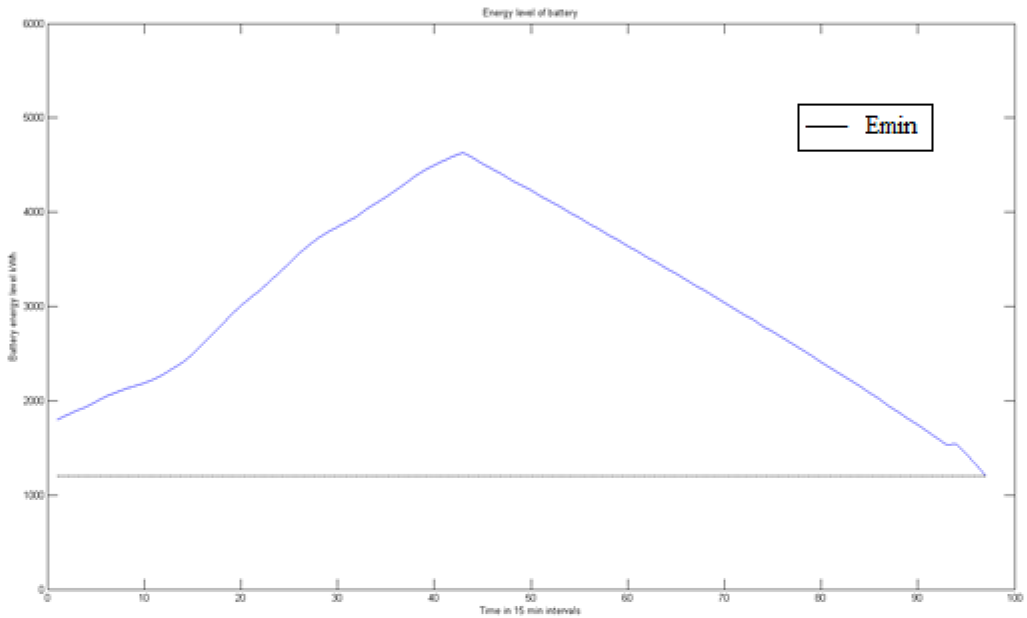

Figure 6.46 Battery state of charge for fifteen minute data with medium wind generation in conservative discharge and wind charging

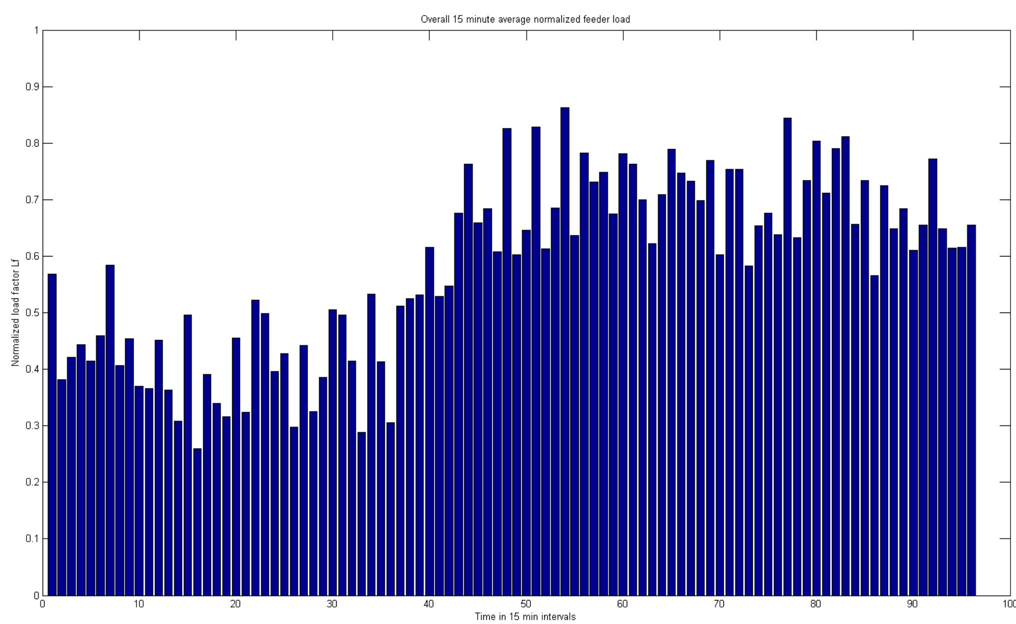

Figure 6.47 Normalized overall fifteen minute demand histogram with medium wind generation in conservative discharge and wind charging

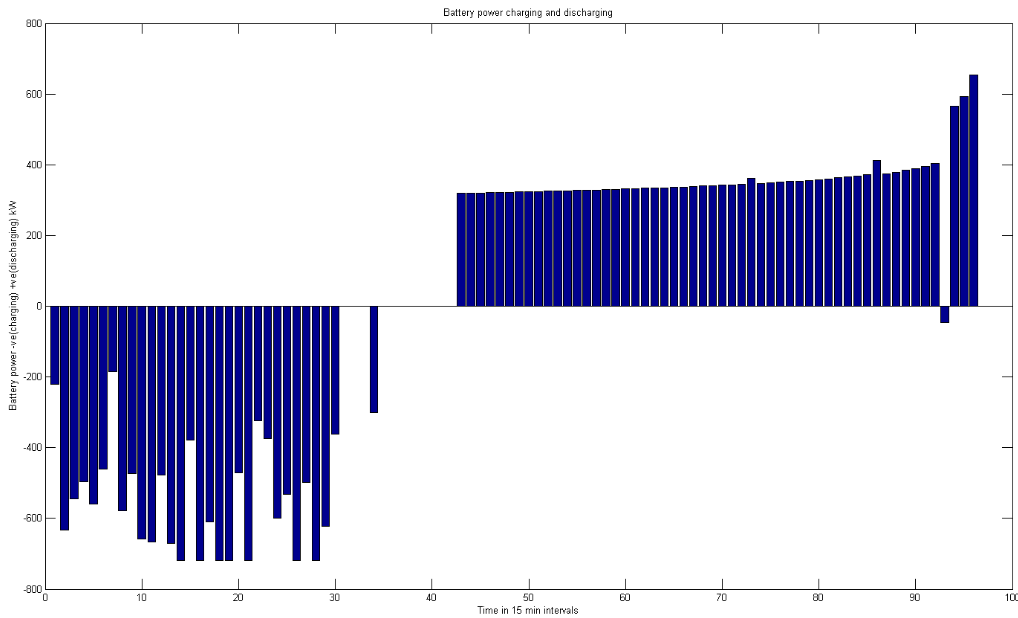

Figure 6.48 Battery charging and discharging for fifteen minute data with medium wind generation in conservative discharge and sustained average load charging

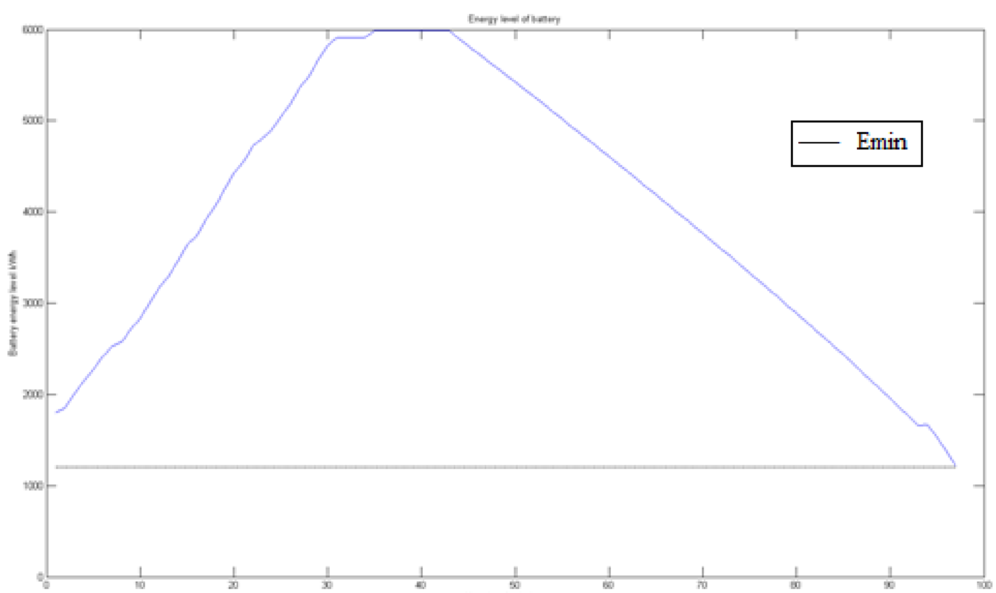

Figure 6.49 Battery state of charge for fifteen minute data with medium wind generation in conservative discharge and sustained average load charging

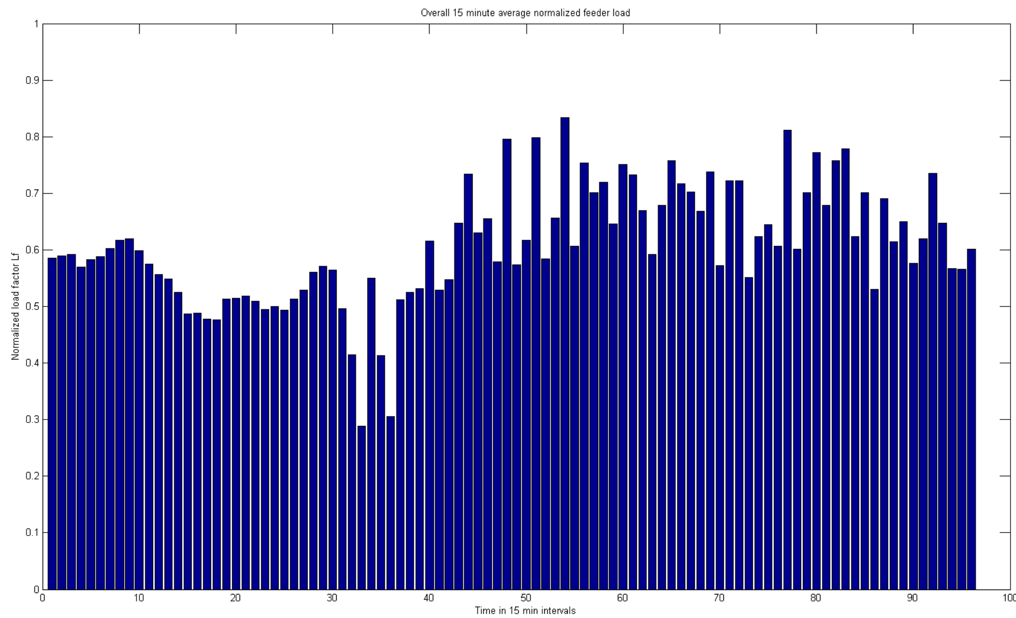

Figure 6.50 Normalized overall fifteen minute demand histogram with medium wind generation in conservative discharge and sustained average load charging

The results given below in figures 6.51 through 6.56 are for low wind generation with all the four combinations of charging and discharging methods for fifteen minute data.

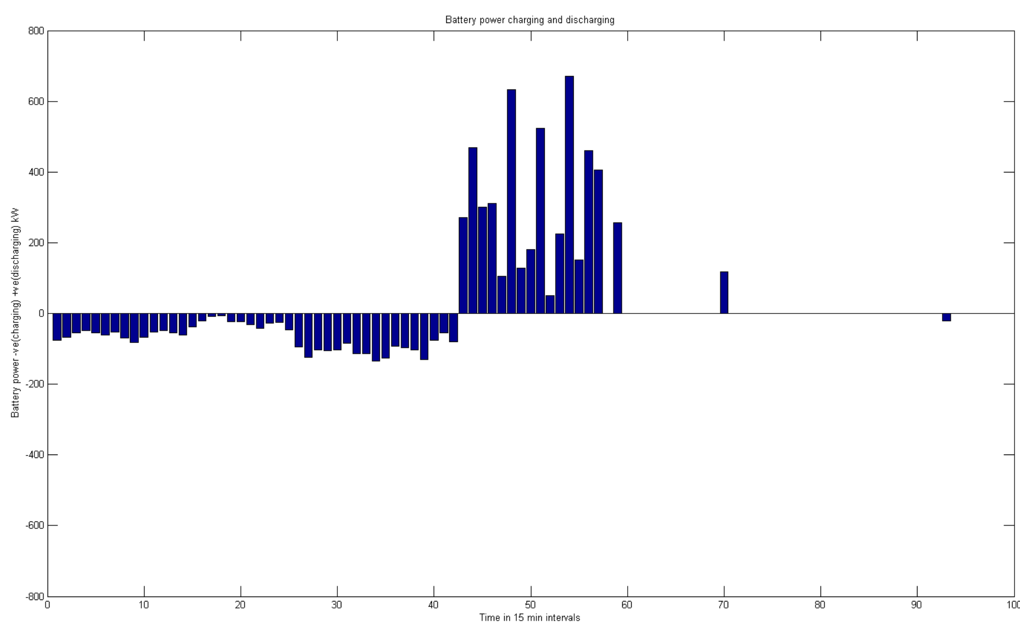

Figure 6.51 Battery charging and discharging for fifteen minute data with low wind generation in free-running discharge and wind charging

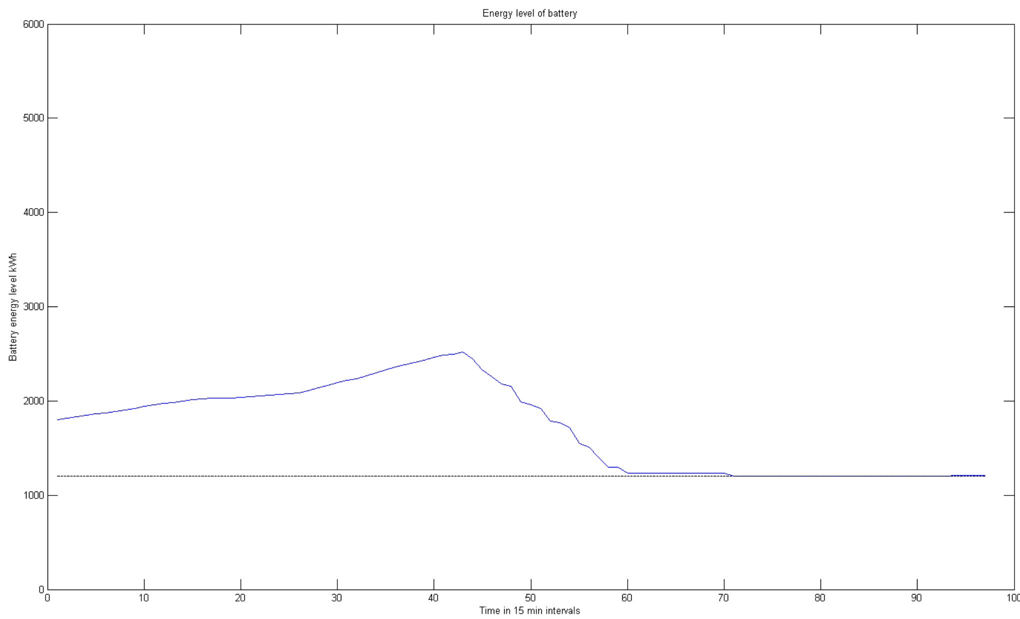

Figure 6.52 Battery state of charge for fifteen minute data with low wind generation in free-running discharge and wind charging

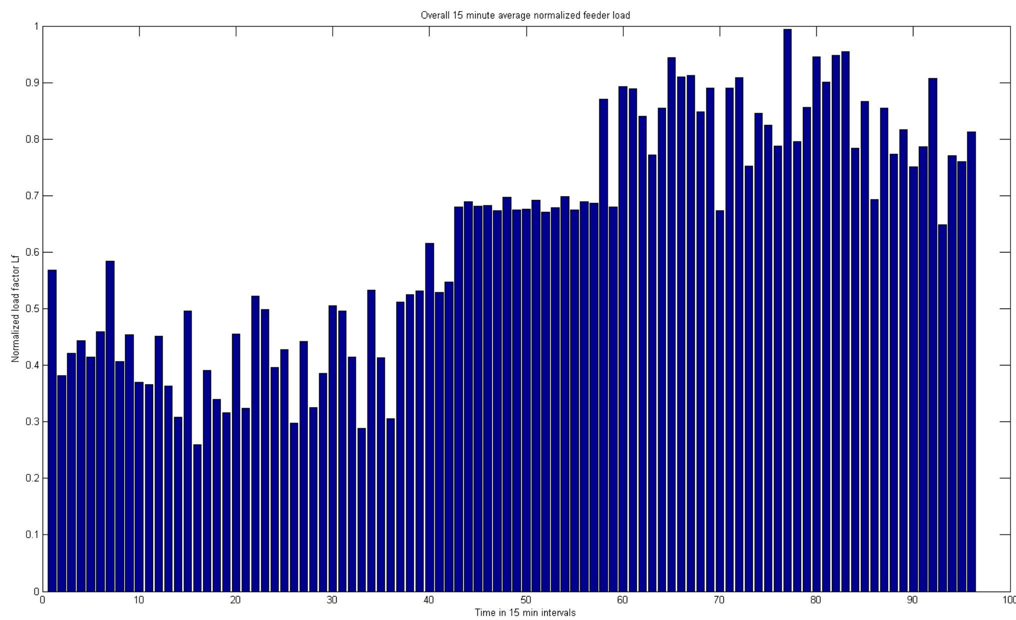

Figure 6.53 Normalized overall feeder load demand for fifteen minute data with low wind generation in free-running discharge and wind charging

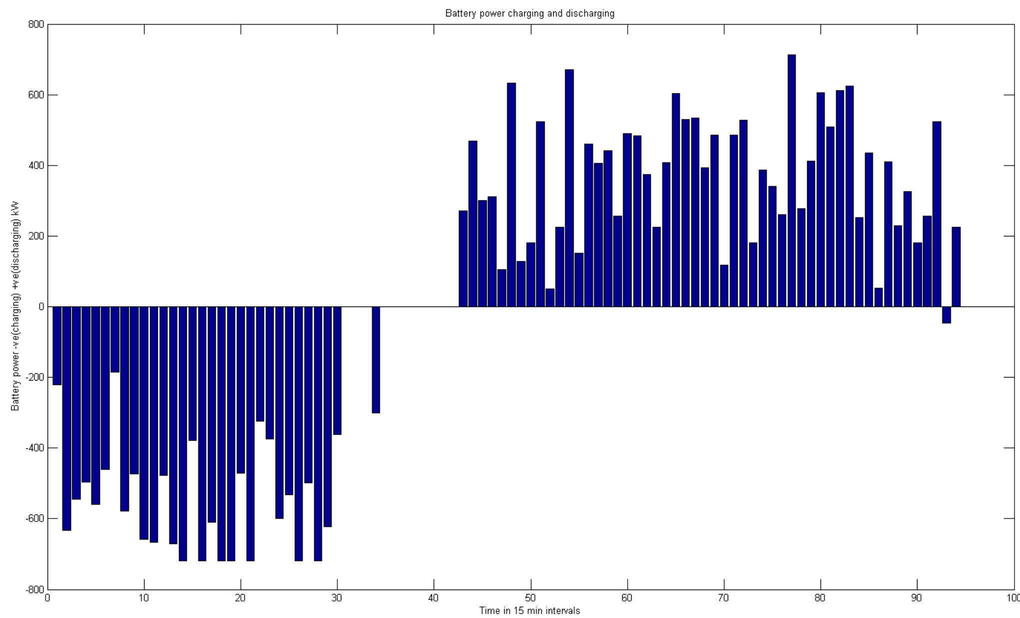

Figure 6.54 Battery charging and discharging for fifteen minute data with low wind generation in free-running discharge and sustained average load charging

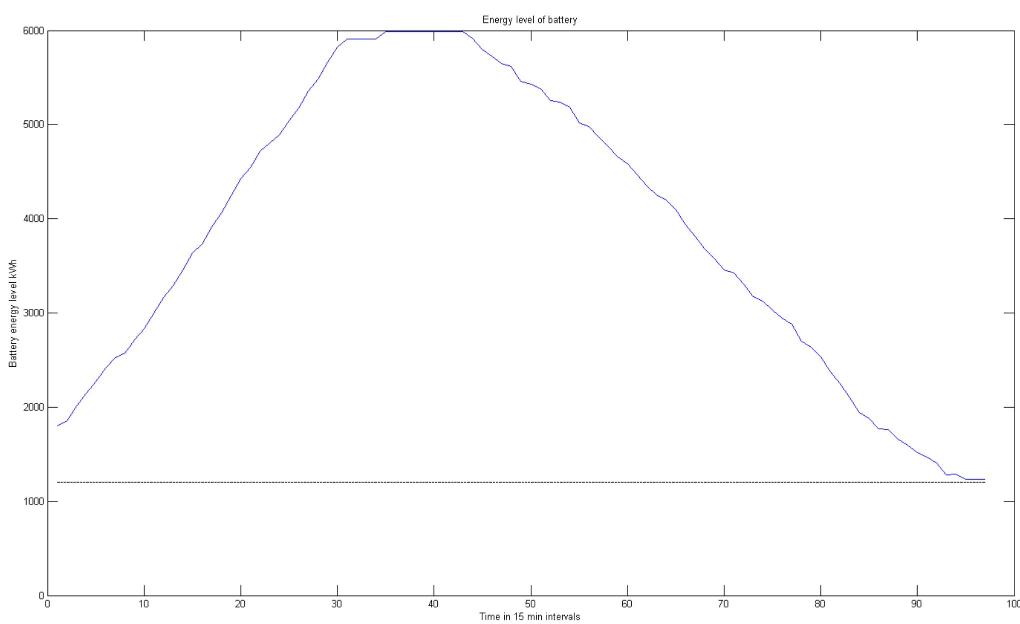

Figure 6.55 Battery state of charge for fifteen minute data with low wind generation in free-running discharge and sustained average load charging

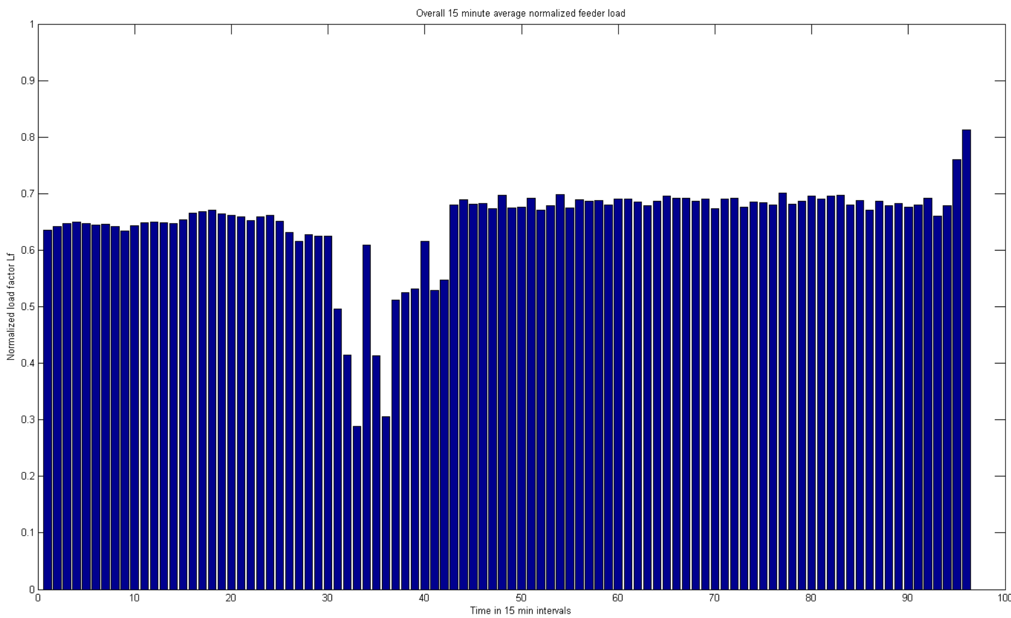

Figure 6.56 Normalized overall fifteen minute demand histogram with low wind generation in free-running discharge and sustained average load charging

As it can be seen from the results described above, free-running mode of discharging does not perform well under low wind conditions. This is one of the reasons that the sustained average load approach was developed in this research as a future alternative to solving the low wind generation problem. But it is also seen that, there are more losses associated with the distribution feeder when sustained average load approach is used to charge up the battery. The results given from figures 6.57 through 6.62 are for low wind generation using conservative discharging with both the kinds of charging methods.

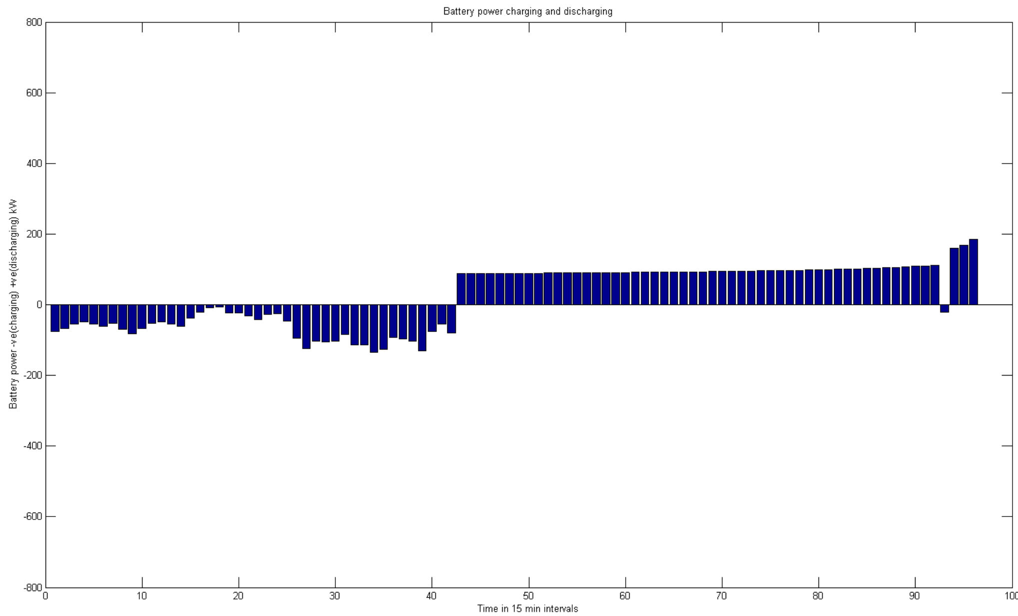

Figure 6.57 Battery charging and discharging for fifteen minute data with low wind generation in conservative discharge and wind charging

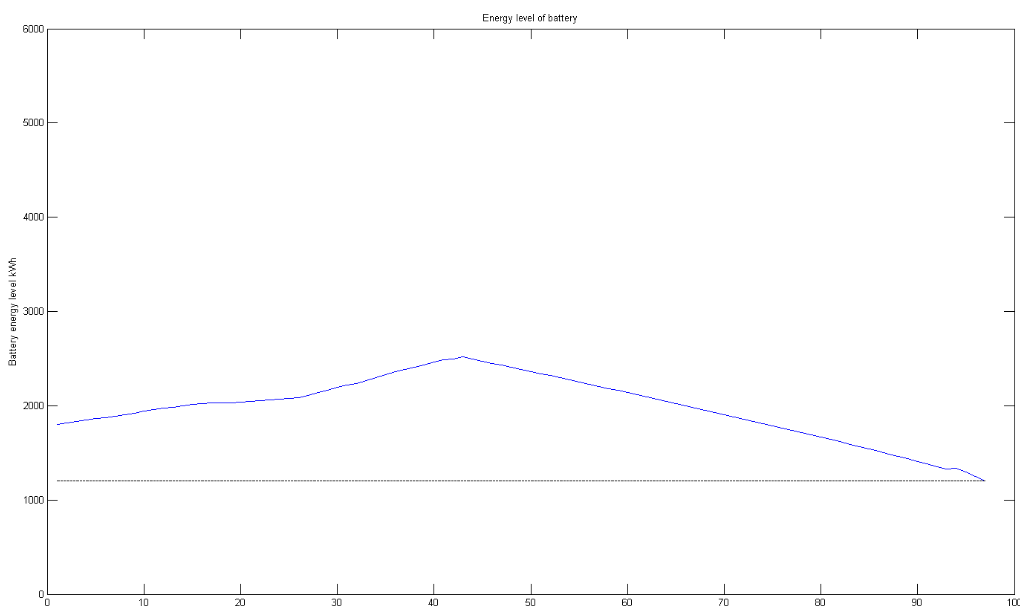

Figure 6.58 Battery state of charge for fifteen minute data with low wind generation in conservative discharge and wind charging

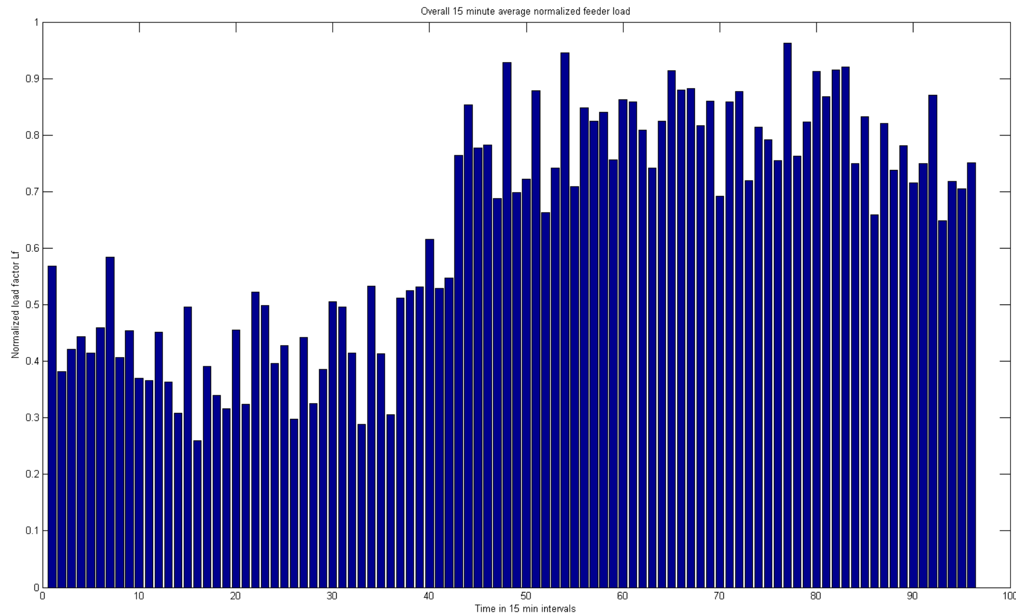

Figure 6.59 Normalized overall fifteen minute demand histogram with low wind generation in conservative discharge and wind charging

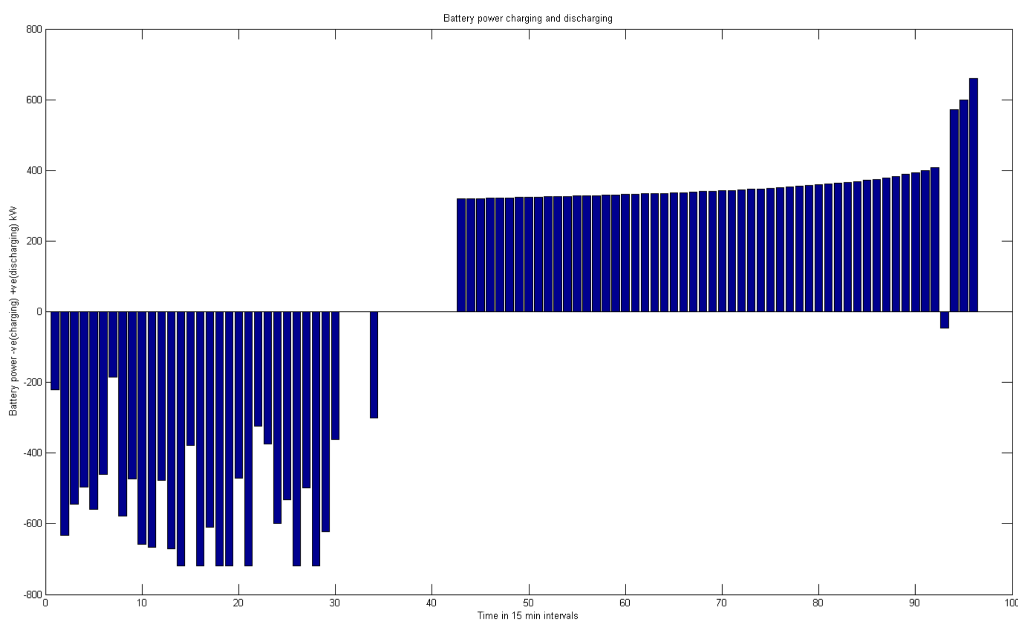

Figure 6.60 Battery charging and discharging for fifteen minute data with medium wind generation in conservative discharge and sustained average load charging

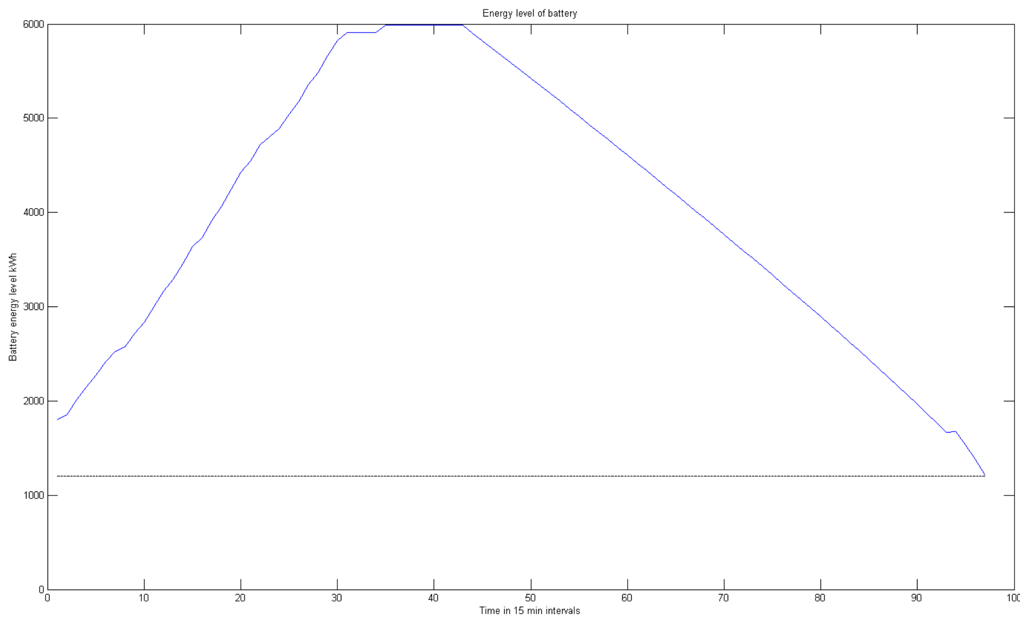

Figure 6.61 Battery state of charge for fifteen minute data with medium wind generation in conservative discharge and sustained average load charging

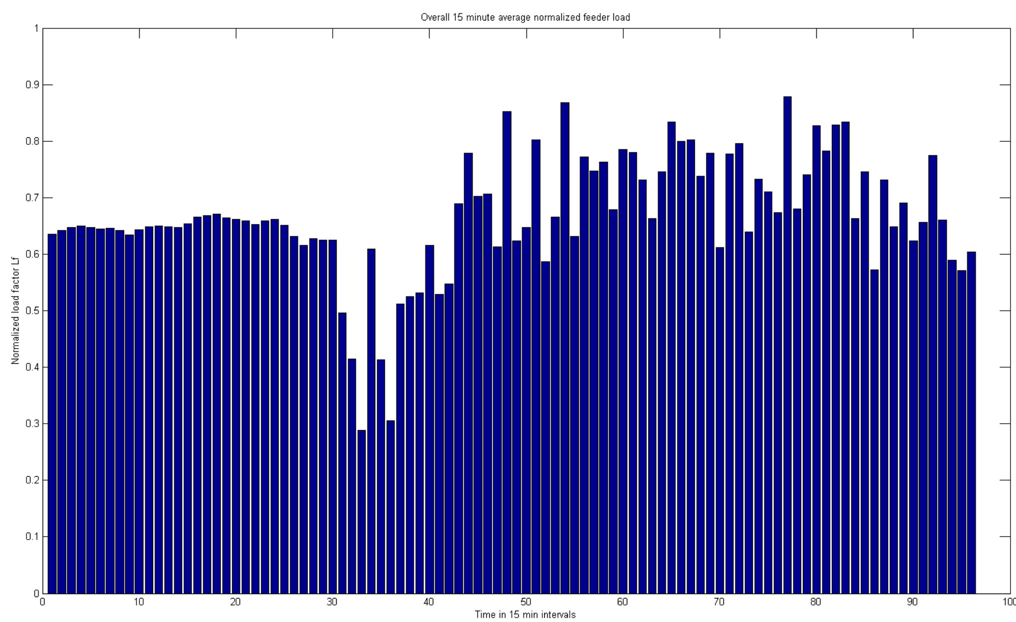

Figure 6.62 Normalized overall fifteen minute demand histogram with medium wind generation in conservative discharge and sustained average load charging

Many observations are made overall when fifteen minute data are used. The battery capacity is used completely most of the time even to the point of not effectively being able to store wind energy when its importance is not high. This is mainly due to the absence of dynamic load information which results in a fifteen minute averaged value of either charging or discharging the battery. The free running mode works best when medium to high level of wind generation is available. The conservative discharging mode of operation is best suited to days on which wind generation is very limited as it becomes possible to conserve battery capacity. Similarly, wind charging mode of operation is ideal for most days as wind generation is available, but if there is little or no wind generation, there might be no storage of wind energy in the battery to ensure peak reduction. This problem is overcome using sustained average load charging. This method is especially suitable for areas where wind generation is low, but under current technology trends, the advanced controller required for the operation in this method may not be available as yet. So, this is not a real time mode of operation.

The differences in performance that can be achieved when one second forecasted load is used are tremendous. The peak reduction, the reduction in average load, and the reduction in the battery capacity used are improved greatly when one second load forecast is used. The four combinations of charging and discharging methods described before have been tested here as well, for one case of wind generation data. Again, results obtained for individual phase demand, losses and voltage profile are not displayed due to redundancy and similarity in results, making then indistinguishable. However, battery charging and discharging, battery state of charge, overall one second demand of the feeder, and fifteen minute average normalized demand have been displayed. Also, the results for all cases have been tabulated for comparison at the end of this section.

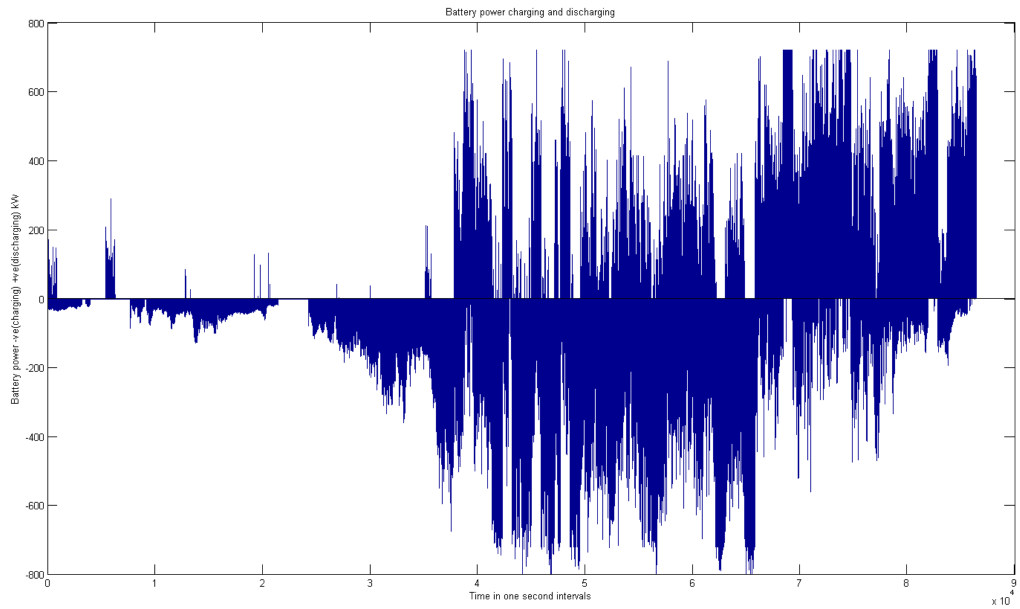

Figure 6.63 Battery charging and discharging for one second forecasted load data in free-running discharging and wind charging modes

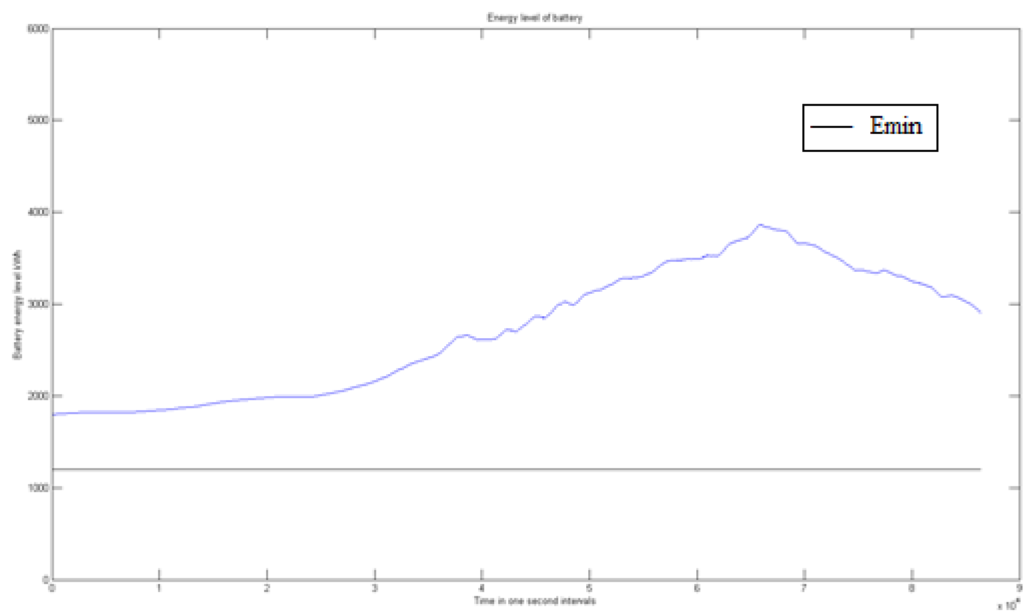

Figure 6.64 Battery state of charge for one second forecasted load data in free-running discharging and wind charging modes

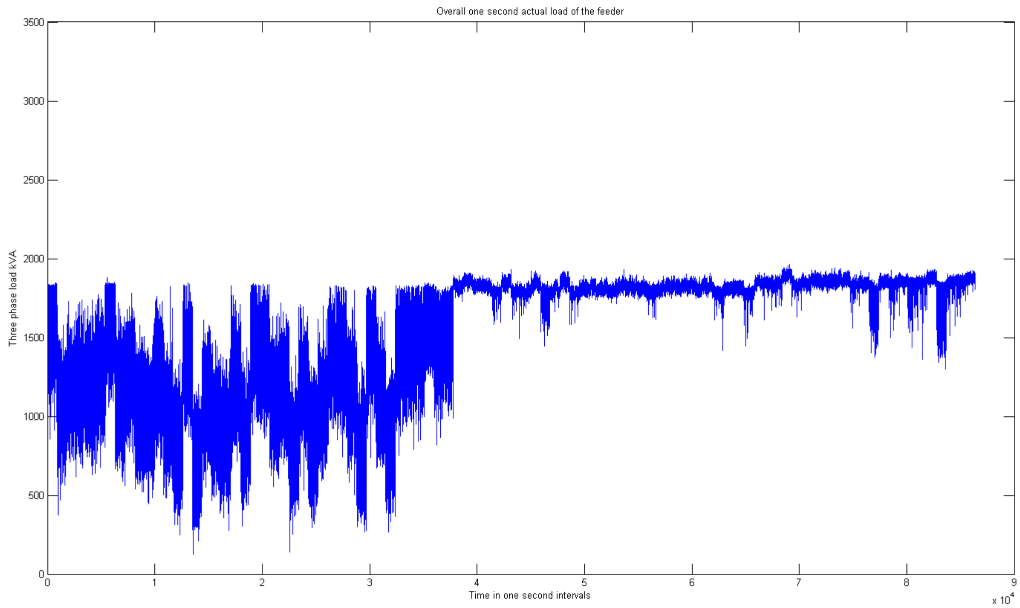

Figure 6.65 Overall one second actual load demand after peak reduction for one second forecasted load data in free-running discharging and wind charging modes

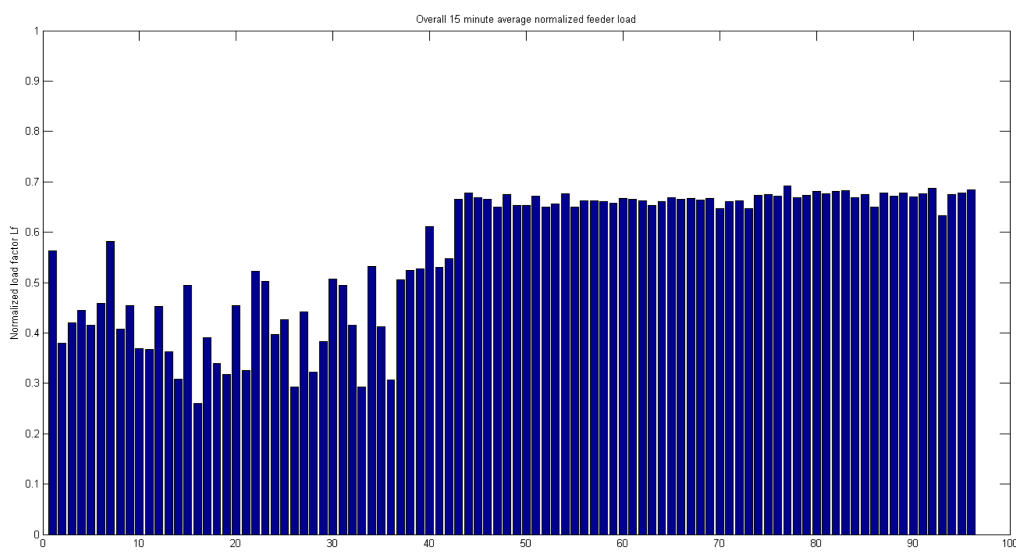

Figure 6.66 Fifteen minute average normalized load demand after peak reduction for one second forecasted load data in free-running discharging and wind charging modes

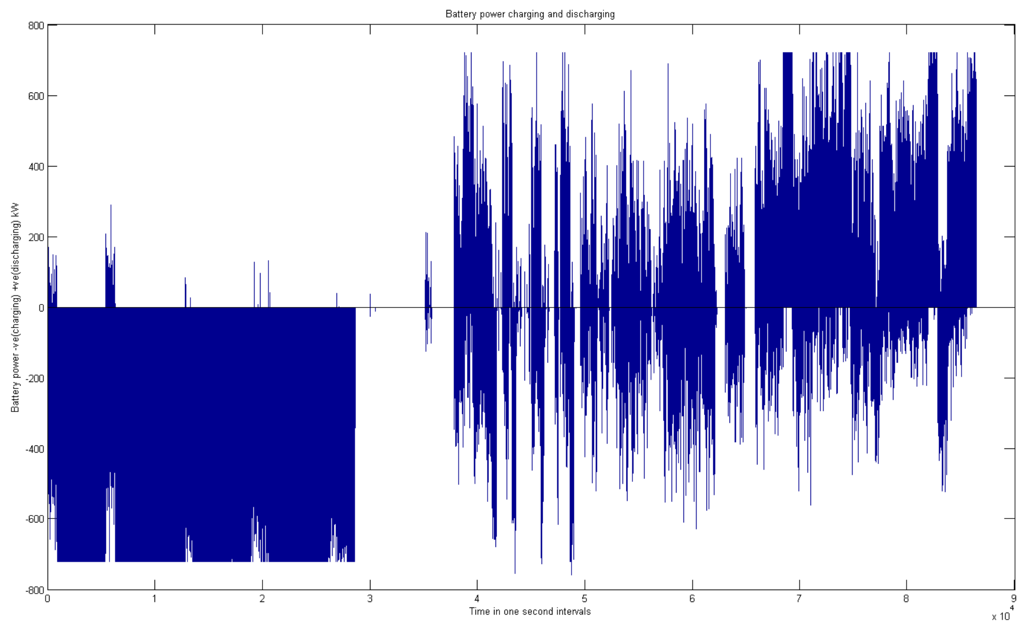

Figure 6.67 Battery charging and discharging for one second forecasted load data in free-running discharging and sustained average load charging modes

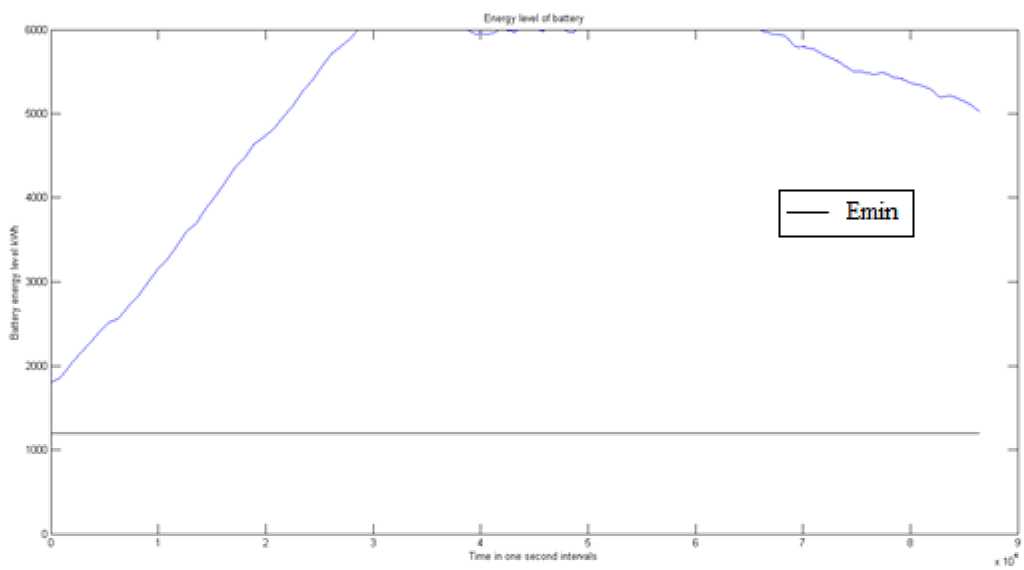

Figure 6.68 Battery state of charge for one second forecasted load data in free-running discharging and sustained average load charging modes

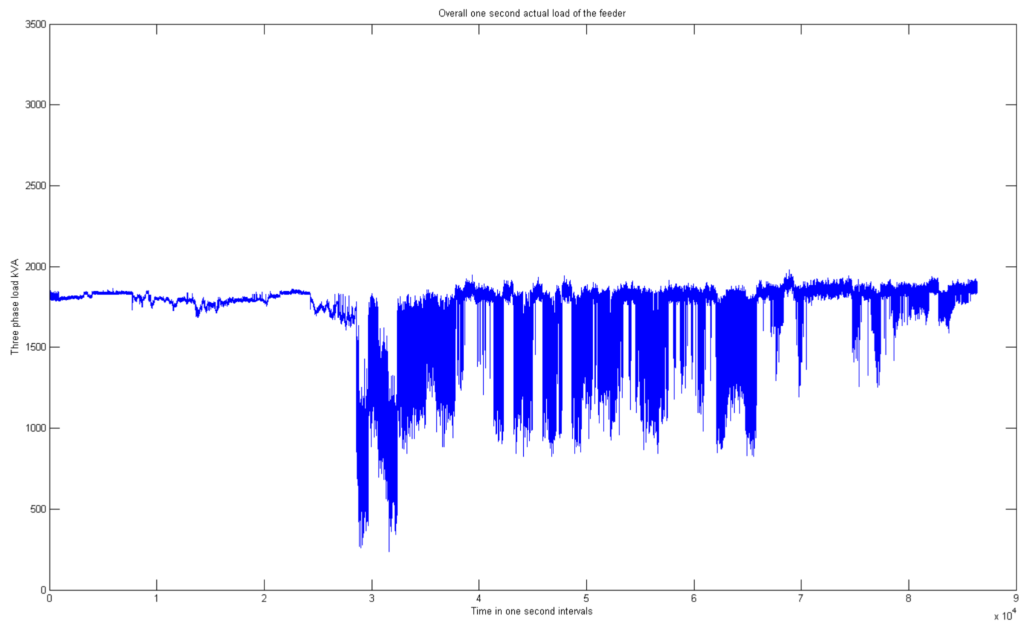

Figure 6.69 Overall one second actual load demand after peak reduction for one second forecasted load data in free-running discharging and sustained average load charging modes

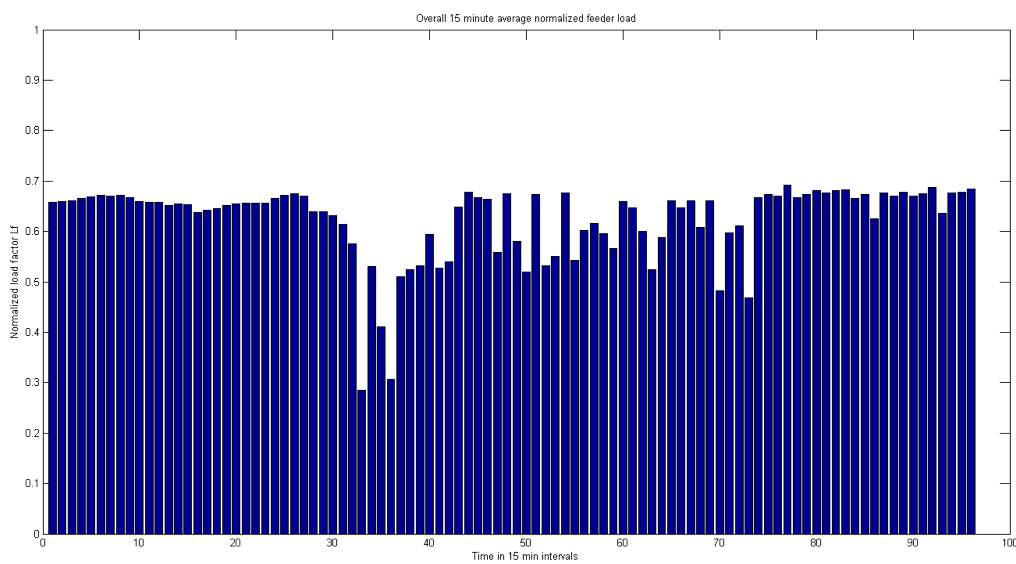

Figure 6.70 Fifteen minute average normalized load demand after peak reduction for one second forecasted load data in free-running discharging and sustained average load charging modes

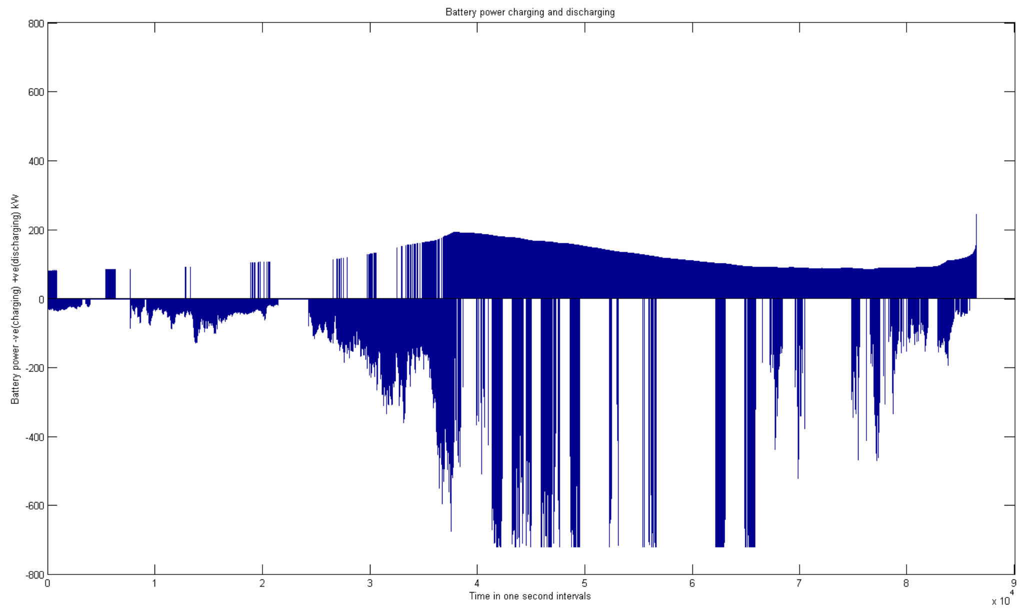

Figure 6.71 Battery charging and discharging for one second forecasted load data in conservative discharging and wind charging modes

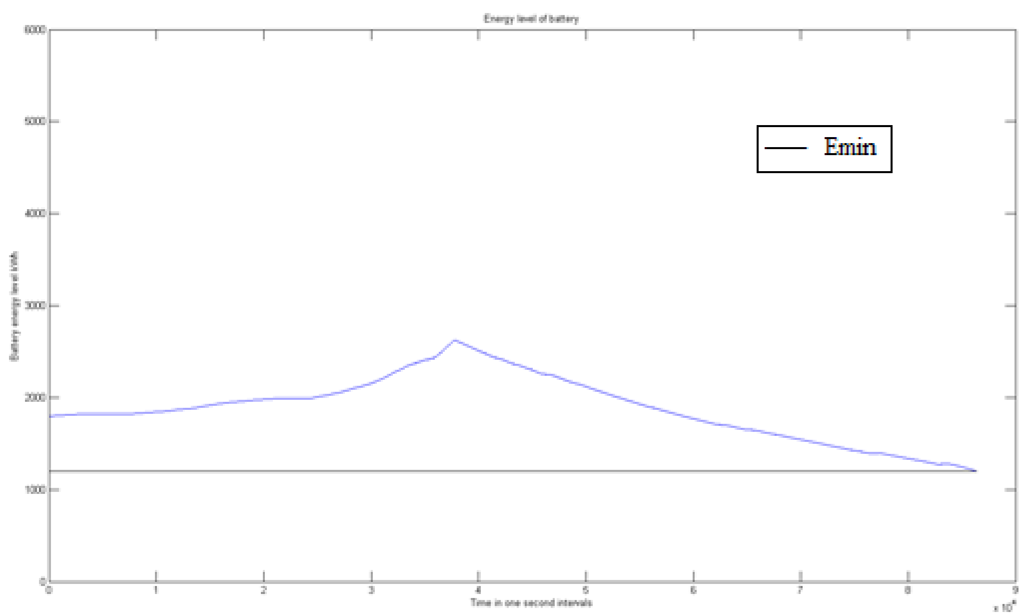

Figure 6.72 Battery state of charge for one second forecasted load data in conservative discharging and wind charging modes

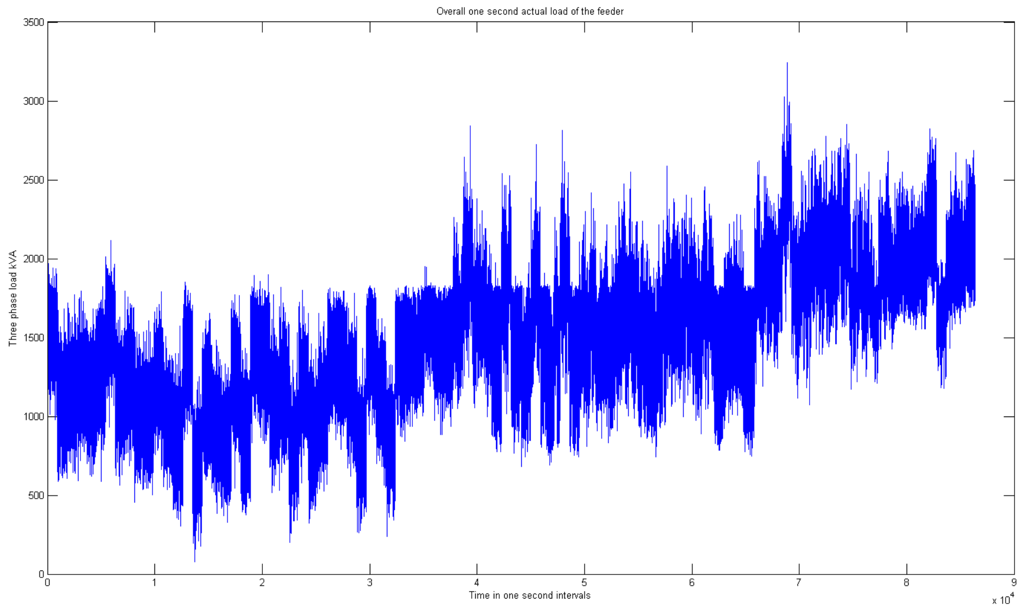

Figure 6.73 Overall one second actual load demand after peak reduction for one second forecasted load data in conservative discharging and wind charging modes

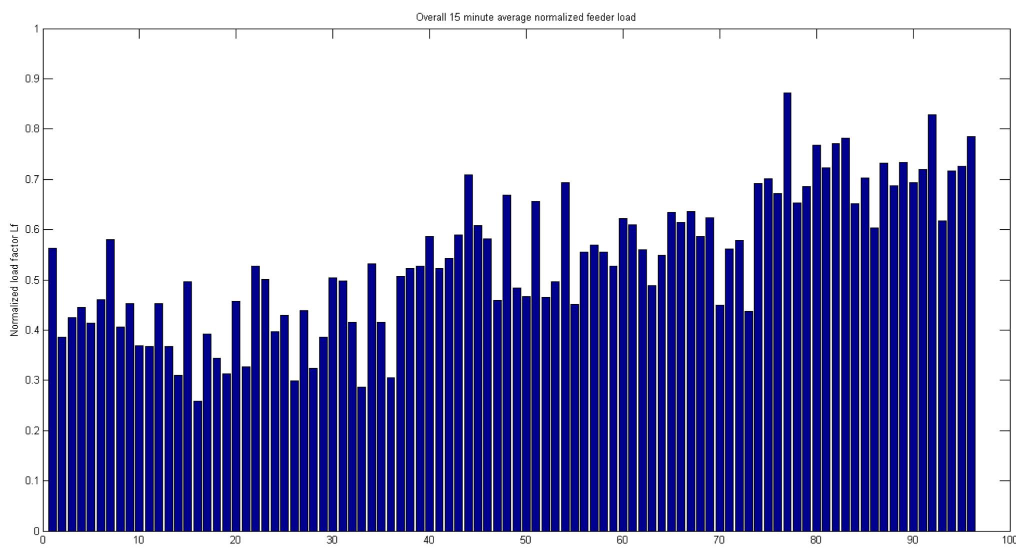

Figure 6.74 Fifteen minute average normalized load demand after peak reduction for one second forecasted load data in conservative discharging and wind charging modes

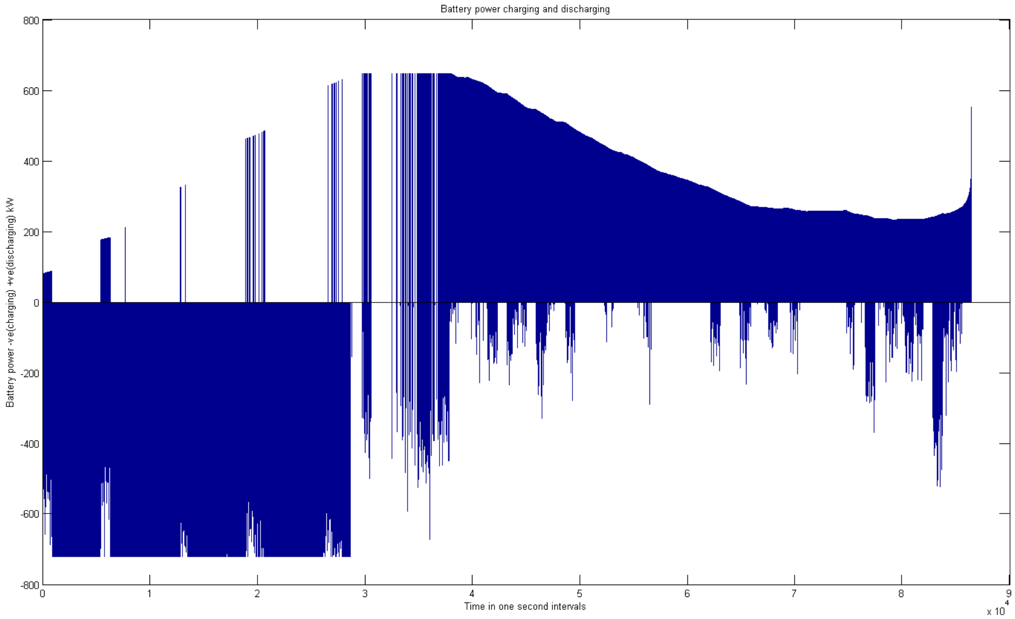

Figure 6.75 Battery charging and discharging for one second forecasted load data in conservative discharging and sustained average load charging modes

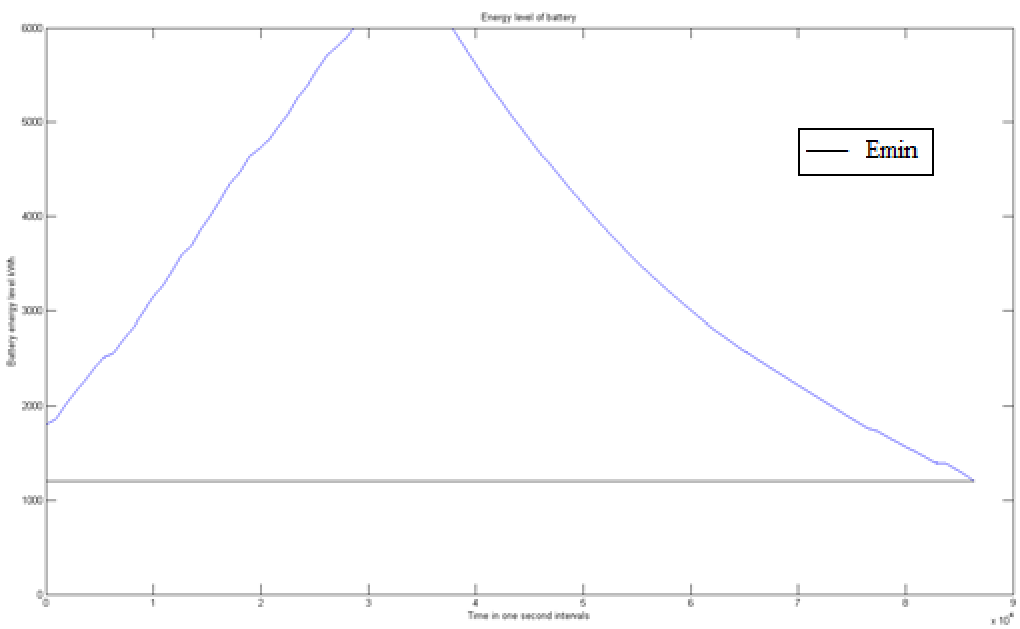

Figure 6.76 Battery state of charge for one second forecasted load data in conservative discharging and sustained average load charging modes

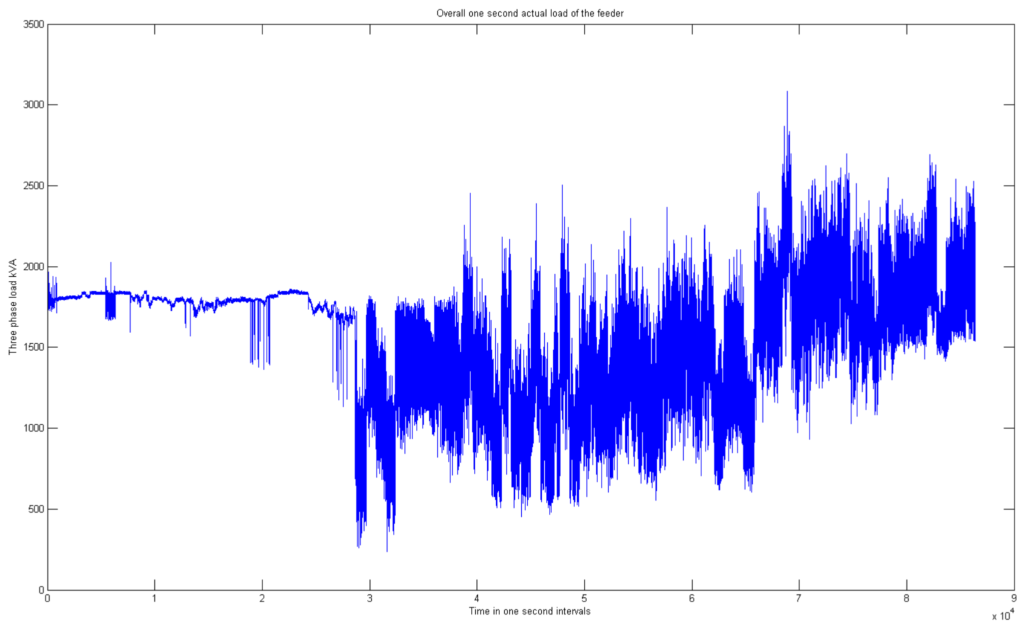

Figure 6.77 Overall one second actual load demand after peak reduction for one second forecasted load data in conservative discharging and sustained average load charging modes

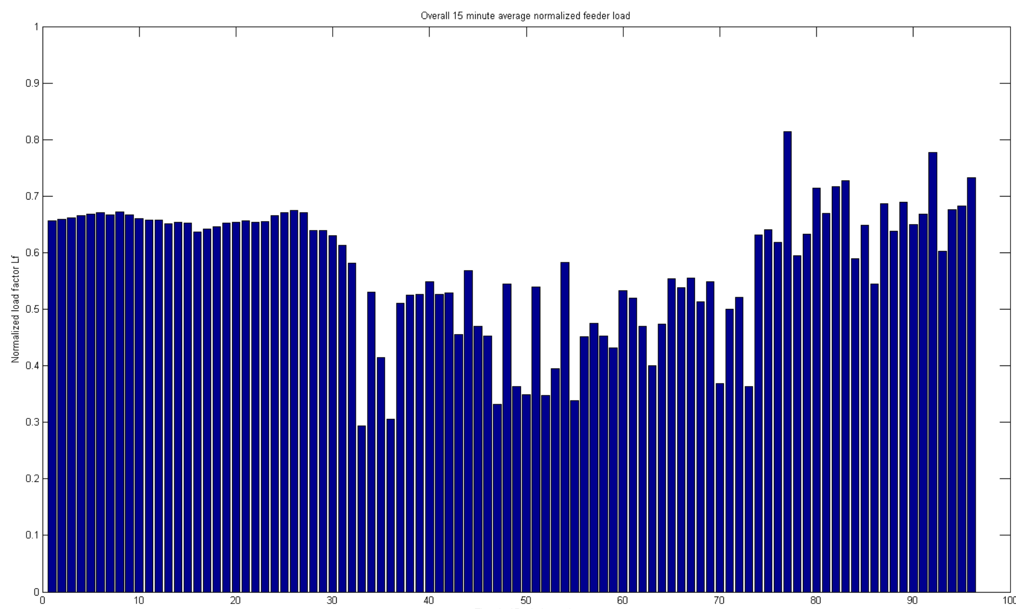

Figure 6.78 Fifteen minute average normalized load demand after peak reduction for one second forecasted load data in conservative discharging and sustained average load charging modes

The following observations were made for the average and maximum demand factors of the feeder and also for the battery capacity utilization. The table containing the comparison of the four methods with the base case of load flow without any wind generation has been given below.

Mode	Charging Method	Discharging Method	Average load factor	Peak load factor	Battery utilization factor
Base	--	--	0.6668	1.0000	--
Mode 1	Wind	Free – running	0.5631	0.6914	0.6431
Mode 2	SAL	Free – running	0.6237	0.6918	1.0000
Mode 3	Wind	Conservative	0.5422	0.8713	0.4376
Mode 4	SAL	Conservative	0.5767	0.8144	1.0000

(SAL – Sustained Average Load)

Table 6.2 Summary of results obtained for one second load forecasted operation of wind generation with battery storage

In the above table, the calculations of average and peak load factors and battery utilization factor were done as given below

Average load factor = Mean(Normalized demand of all time instances during the period of operation)

(6.1)

Peak Load factor = Max(Normalized demand of all time instances during the period of operation)

(6.2)

Battery Utilization factor = (Max(E_{ess}) – Min(E_{ess})) / Emax

(6.3)

In equation 6.3, E_{ess} is the operational energy level of the battery during all the instances of operation, and Emax is the full capacity of the battery. From the results displayed in the table above, we observe that all the methods cause a reduction in the average load as well as the peak load of the feeder. At any given instant of time during the operation of dispatch of battery storage in order to perform peak reduction operations with wind generation, it can be extended from the above results that during discharging, if the battery capacity is substantially available for usage, it is better to use free-running mode of operation. However, if the battery capacity falls below a certain set minimum value necessary for dispatch operations, the performance of the conservative discharging mode seems to be better at reducing peak load by at least a slight margin over the remaining periods of time of the day. The charging methods used prove that battery capacity needs to be used to the highest extent possible within set maximum and minimum levels in order to effectively aid in the peak reduction process. In this regard, the sustained average load approach of battery charging makes sure that absence of wind generation does not render the battery unusable. But, the battery is charged up to maximum levels very quickly and usage of the battery becomes very limited and inefficient especially when wind generation is available. Also, the method is not suited for real time operations at this point of time due to non-availability or commercial unviability of the technology required to make the process a reality. Wind charging is a very viable option as the strategy used makes sure that wind generation is stored when close to base load conditions prevail irrespective of the amount available. Also, only a fraction of the overall battery capacity is always used, providing scope for battery size reduction leading to cost benefits. The lessons learned from the results presented in this section are that in order to have an effectively working real time strategy for dispatch operations of distributed wind generation using battery storage and PMUs in a distribution system, the charging of the battery needs to be done using only wind generation, free-running mode of operation has to be used in the discharging of the battery if capacity is available, and if the battery capacity falls below a certain set minimum value based on wind generation characteristics, conservative discharging of the battery should be carried out for all the remaining time intervals of the day.

6.3 Real time operation of storage dispatch with wind generation based on historical PMU measurements

This section explains the most important results that have been obtained in this research work. The real time operations of battery storage with distributed wind generation using historical data obtained from PMU measurements of previous time instances has been investigated. In the study done here, PMU samples have been taken at the rate of one sample per second. For the purpose of research, PMU measurements have been recorded using the backward forward sweep power flow for every time instant. The sampling interval required to assess the battery dispatch for the next time instant has been set at five minutes or 300 seconds of previous PMU data. The maximum load including wind generation and battery dispatch is calculated from each of these previous 300 time instances, and the difference between this maximum value, average load and wind generation of the immediately preceding time instant has been calculated to be the battery dispatch for the present time instance. For example, for a given time instance k, the battery discharge is calculated as follows.

$$S_{batt,k} = \text{Max}[(S_{pmu} + S_{wind} + S_{batt}) \mid \text{k-1:k-301}] - S_{avg} - S_{wind,k-1} \quad \textbf{(6.4)}$$

For all the cases, for a given power rating and energy rating of the battery, the following assumptions have been followed:

- The minimum permissible energy level of the battery has been set at 20% of the maximum value, and the switching level for this case of wind generation profile has been set at 30% of maximum value after analysis based on forecasted load. Higher switching energy levels may be assumed if wind generation profiles are weaker.
- The maximum power charging and discharging rate of the battery have been set as the power rating of the battery. For the case of 30% wind generation penetration into the feeder described in this research, the battery specifications have been discussed in chapter 4 section 4.1.4.

The only input information that the real time method described here would use are the average load of the feeder, and the switching energy level of battery capacity after which conservative dispatch operations can begin. Both of these values are feeder specific. The average load of the feeder is the recorded average value of load of an immediately preceding day for the given distribution feeder. The switching value of battery capacity can be decided based on the wind generation levels. The switching value of battery capacity and wind generation levels are inversely related, i.e., if wind generation levels are high, the switching capacity can be set at a smaller value and vice-versa.

The results shown below are for full capacity of battery storage. The maximum charge and discharge rates of the battery are equal to the full power rating of the battery equal to installed wind generation capacity. The initial analysis is done completely in free running mode without any conservative discharge in order to demonstrate the ineffective nature of the battery once it hits its minimum level. The total battery capacity and specifications have been tabulated below. The PMU based operation is also time specific as there is a fixed sampling rate associated with the measurements. So, an effort has also been made to recover the execution time required to operate for all the one second intervals in a given day.

Power Rating (P)	800 kW
Maximum Energy Level (Emax)	6000 kWh
Minimum Energy Level (Emin) 20%	1200 kWh
Initial Energy Level (E0) 30%	1800 kWh
Execution time (t)	58 minutes

Table 6.3 Battery Specifications for real time test system in free-running mode only at full capacity

The results obtained for free-running mode of operation of real time storage dispatch based on historical PMU information have been displayed in figures 6.79 through 6.82.

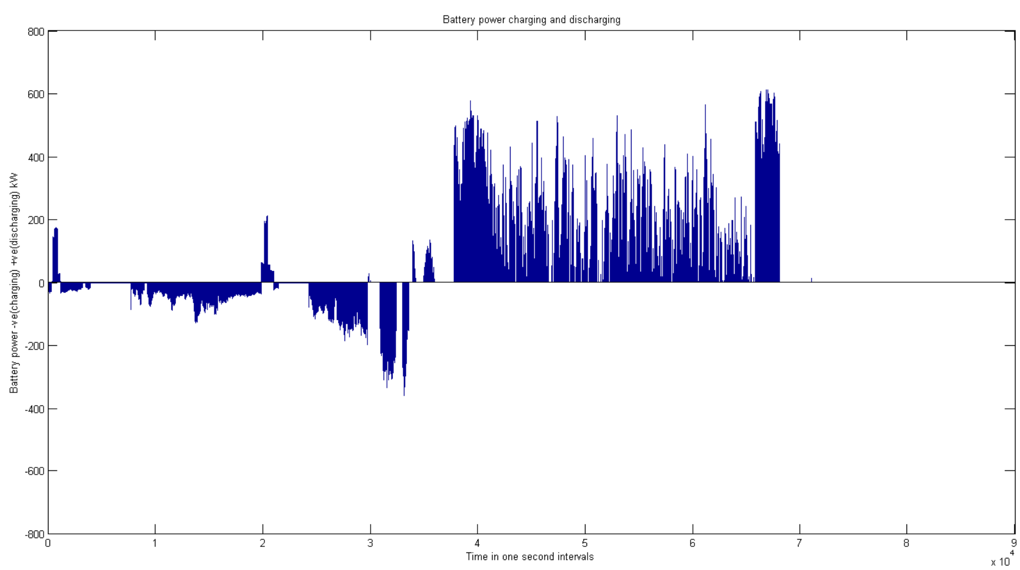

Figure 6.79 Battery power charging and discharging under real time operation at full capacity in free-running mode only

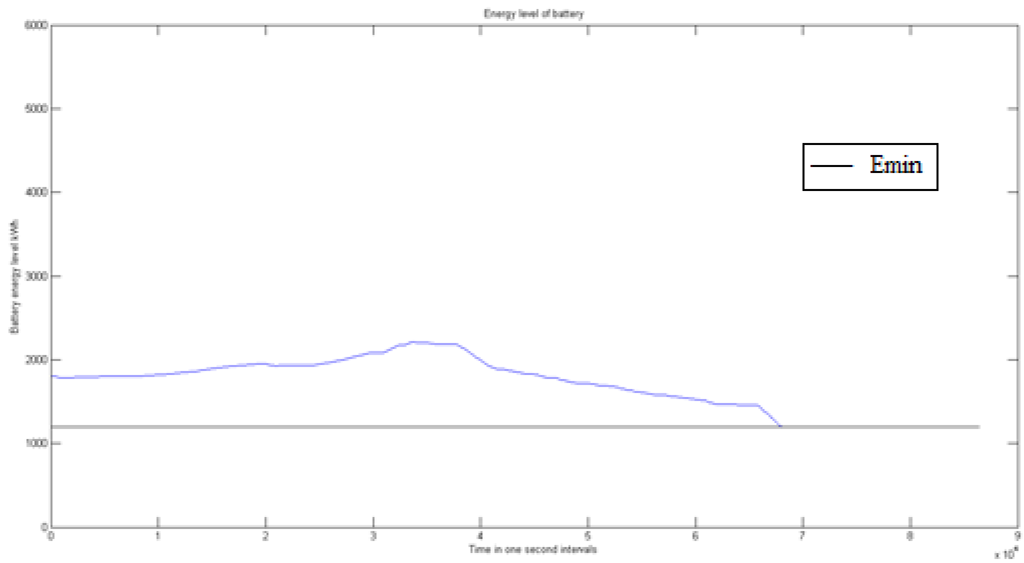

Figure 6.80 Battery state of charge under real time operation at full capacity in free-running mode only

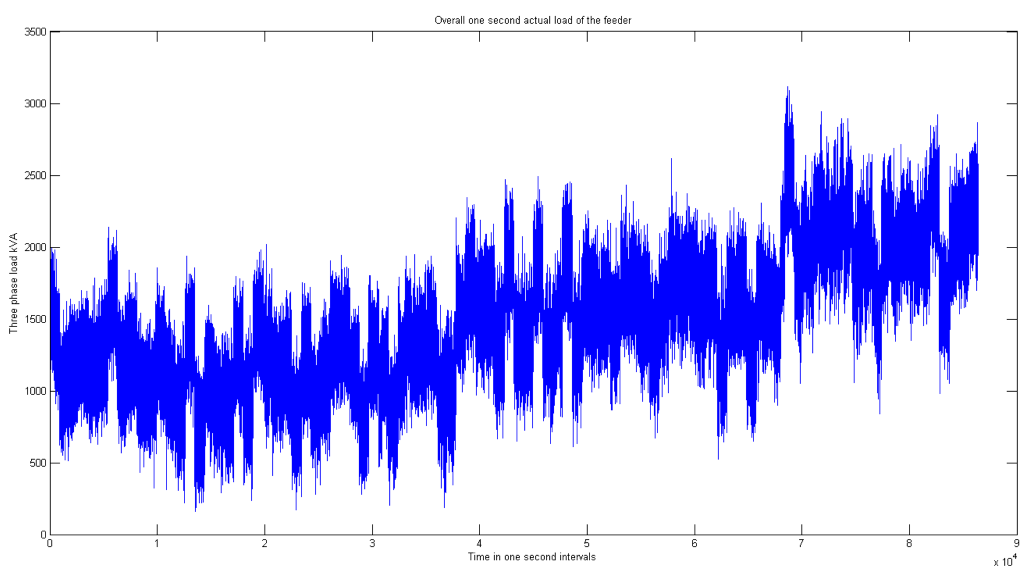

Figure 6.81 Overall actual one second demand under real time operation at full battery capacity in free-running mode only

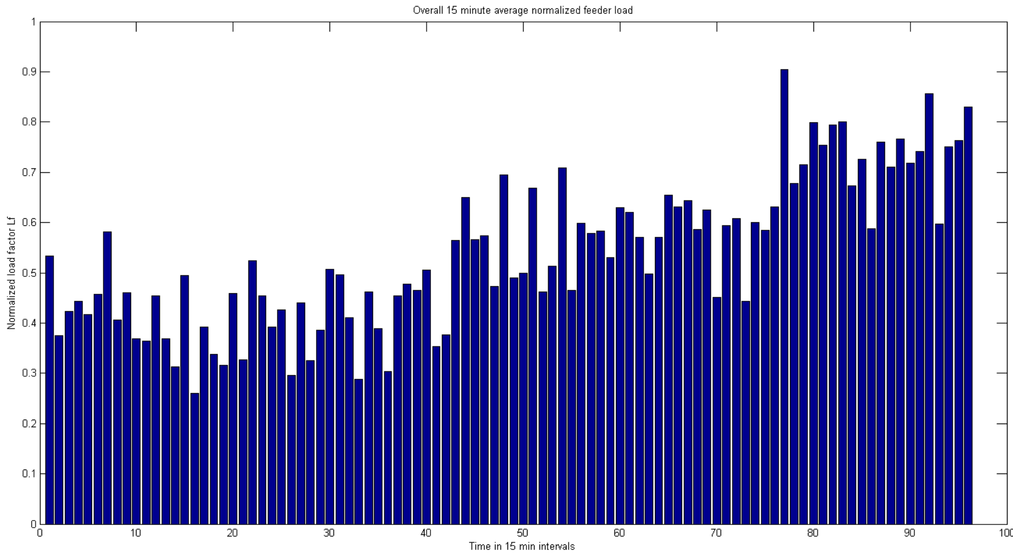

Figure 6.82 Fifteen minute average normalized demand under real time operation at full battery capacity in free-running mode only

The next step in the analysis involves the introduction of conservative discharge into the dispatch process once the battery energy level drops below a set minimum switching value. The table containing the specifications of the test battery is given below. The results are obtained in figures 6.83 through 6.86.

Power Rating (P)	800 kW
Maximum Energy Level (Emax)	6000 kWh
Minimum Energy Level (Emin) 20%	1200 kWh
Initial Energy Level (E0) 30%	1800 kWh
Switching Energy level (Es) 30%	1800 kWh
Execution time (t)	58 minutes

Table 6.4 Battery Specifications for real time test system in free-running mode and conservative discharge at full installed capacity

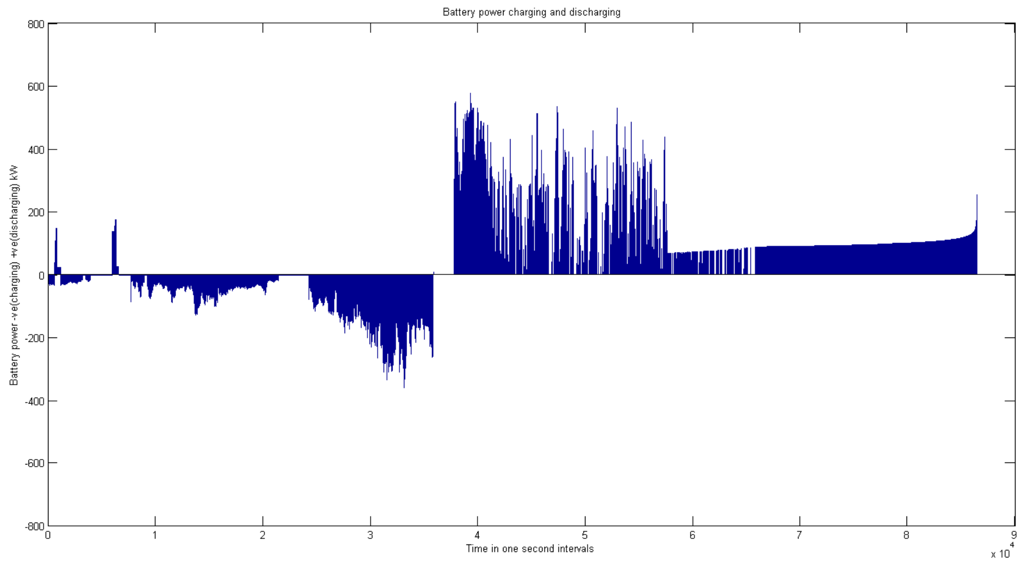

Figure 6.83 Battery power charging and discharging under real time operation at full capacity in free-running mode and conservative discharging

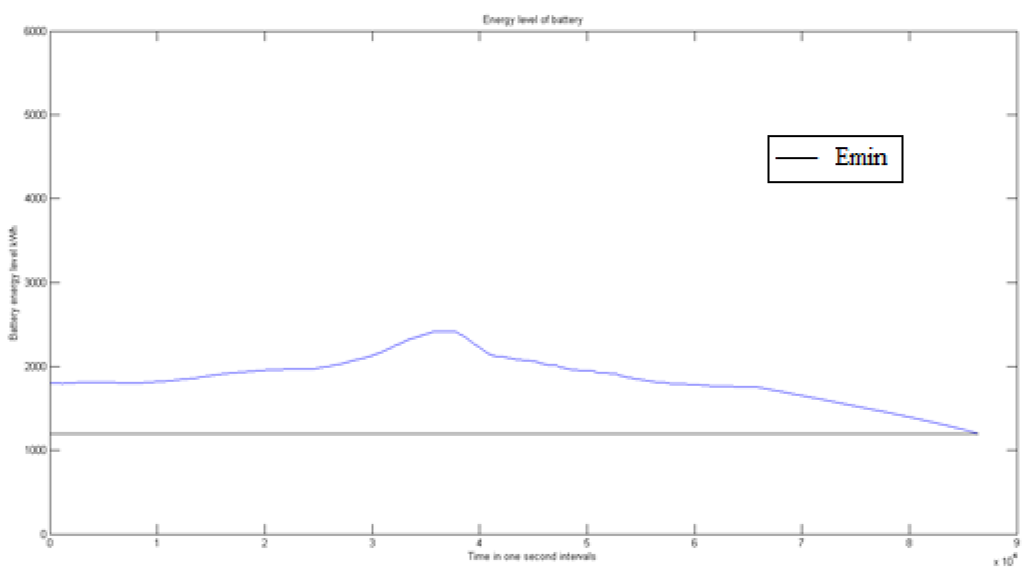

Figure 6.84 Battery state of charge under real time operation at full capacity in free-running mode and conservative discharge

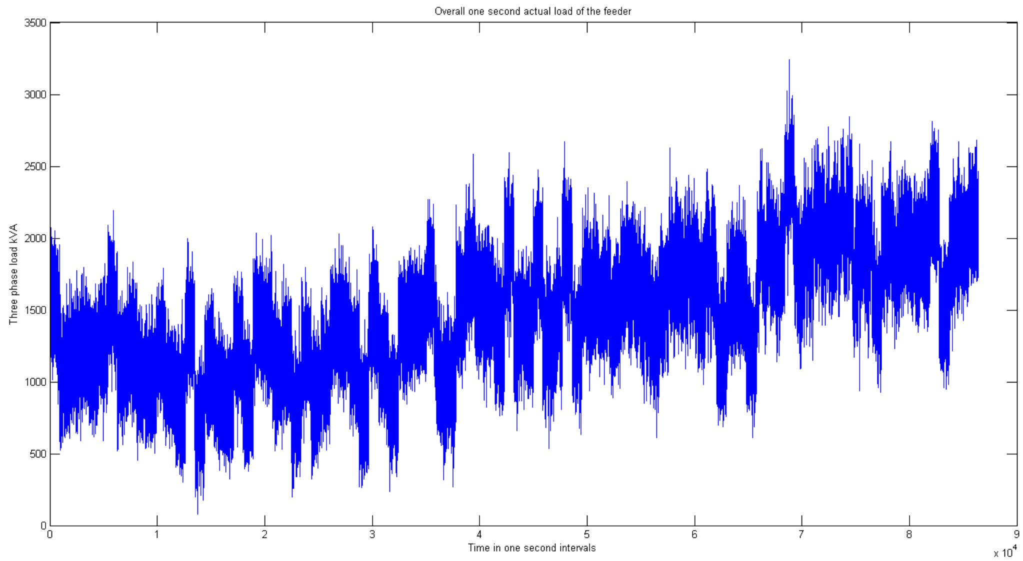

Figure 6.85 Overall actual one second demand under real time operation at full battery capacity in free-running mode and conservative discharge

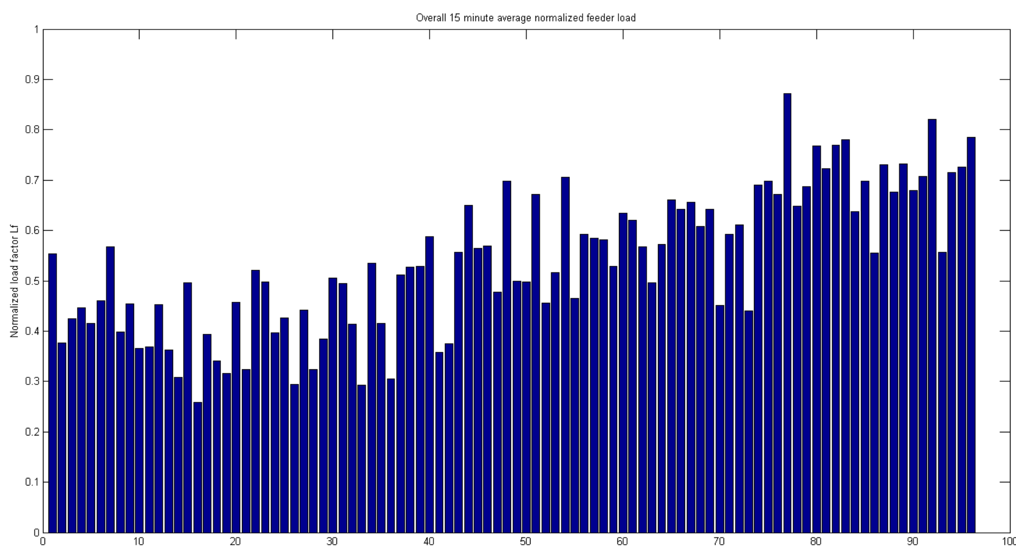

Figure 6.86 Fifteen minute average normalized demand under real time operation at full battery capacity in free-running mode and conservative discharge

From the results obtained above, it is observable that with the implementation of conservative discharge when the battery energy capacity falls below a set minimum switching value, the utilization of battery over the entire time interval of the day becomes possible. There are also better peak reduction characteristics with respect to the average fifteen minute normalized load. More clarity in this regard will be thrown when the results of all the real time analyses are tabulated at the end of this section.

The next analysis involves the reduction of the battery power and energy capacities to half of the actual values. The battery capacity is very minimally utilized in the previous two cases, and this provides the scope for the reduction of battery capacity in the next stage. The battery specifications for this analysis have been given below. The results are obtained in figures 6.87 through 6.90.

Power Rating (P)	400 kW
Maximum Energy Level (Emax)	3000 kWh
Minimum Energy Level (Emin) 20%	600 kWh
Initial Energy Level (E0) 30%	900 kWh
Switching Energy level (Es) 30%	900 kWh
Execution time (t)	58 minutes

Table 6.5 Battery Specifications for real time test system in free-running mode and conservative discharge at half capacity

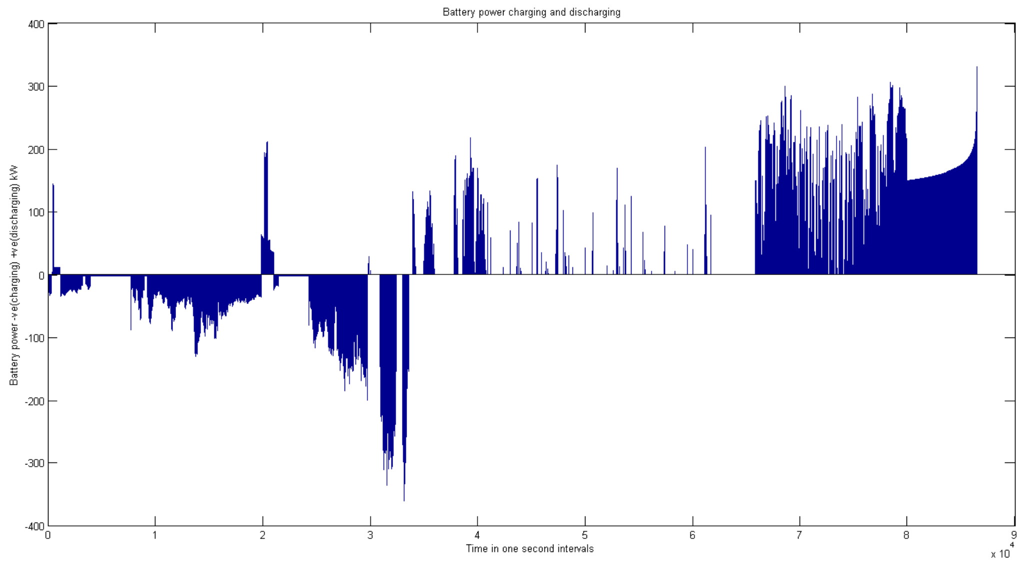

Figure 6.87 Battery power charging and discharging under real time operation at half capacity in free-running mode and conservative discharging

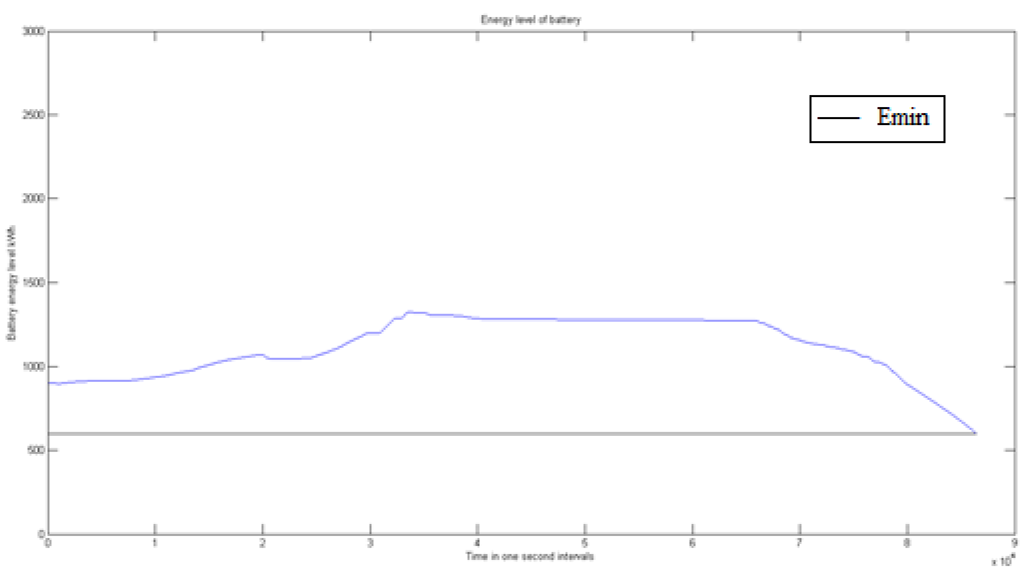

Figure 6.88 Battery state of charge under real time operation at half capacity in free-running mode and conservative discharge

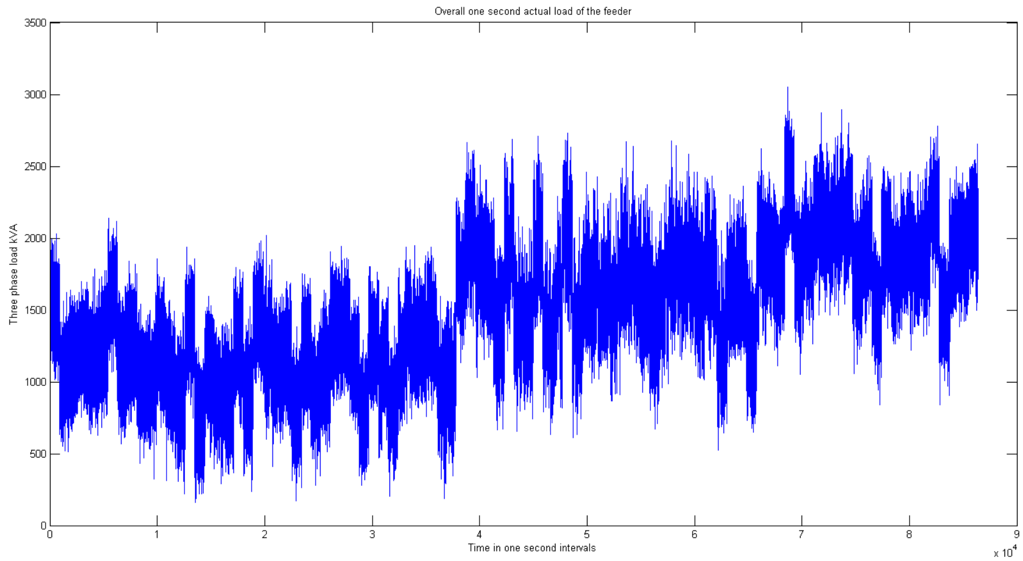

Figure 6.89 Overall actual one second demand under real time operation at half battery capacity in free-running mode and conservative discharge

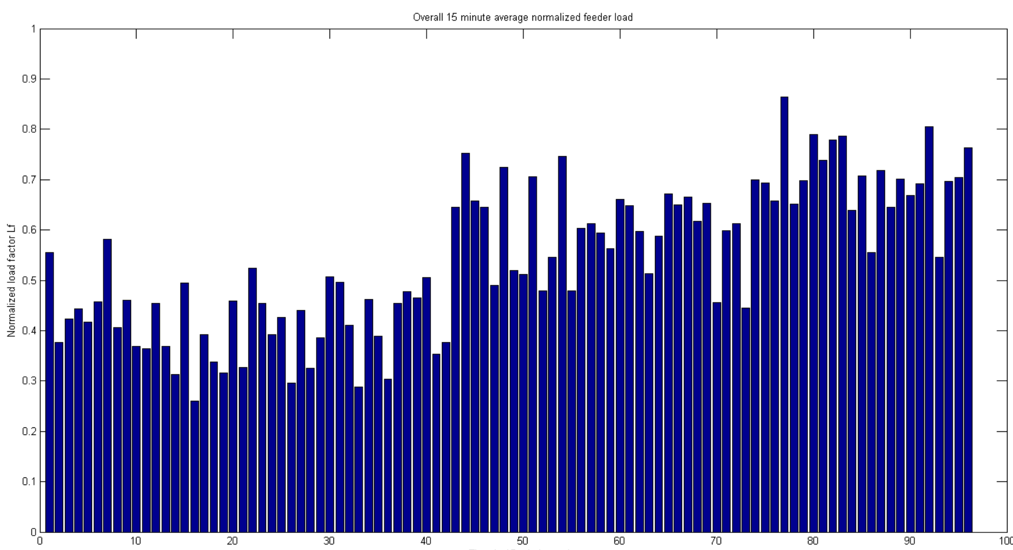

Figure 6.90 Fifteen minute average normalized demand under real time operation at half battery capacity in free-running mode and conservative discharge

It is seen from the results obtained for half battery capacity real time operation that there is a higher peak reduction ratio because of higher capacity utilization of the battery. Also, the average load of the feeder falls slightly more because of the same reason. The result shows that there is scope for further reduction in size of the battery. However, as this research work involves the usage of one particular type of battery, namely, the NAS battery, the effects of battery specific properties can be considered. The specialty of NAS batteries is to be able to pulse discharge at up to four times their rated power capacity for short periods of time. As the scope of real time operation investigated in this research work involves the change of battery discharge level at every second, pulsed operation can be considered in this case. Battery installed capacity is retained as in the previous case at half the original initial value, while the power level is bumped up to twice its value in the previous analysis. The battery specifications used are given below along with the execution time. The results have been obtained in figures 6.91 through 6.94.

Power Rating (2P)	800 kW
Maximum Energy Level (Emax)	3000 kWh
Minimum Energy Level (Emin) 20%	600 kWh
Initial Energy Level (E0) 30%	900 kWh
Switching Energy level (Es) 30%	900 kWh
Execution time (t)	58 minutes

Table 6.6 Battery Specifications for real time test system in free-running mode and conservative discharge at half capacity for double pulse operation

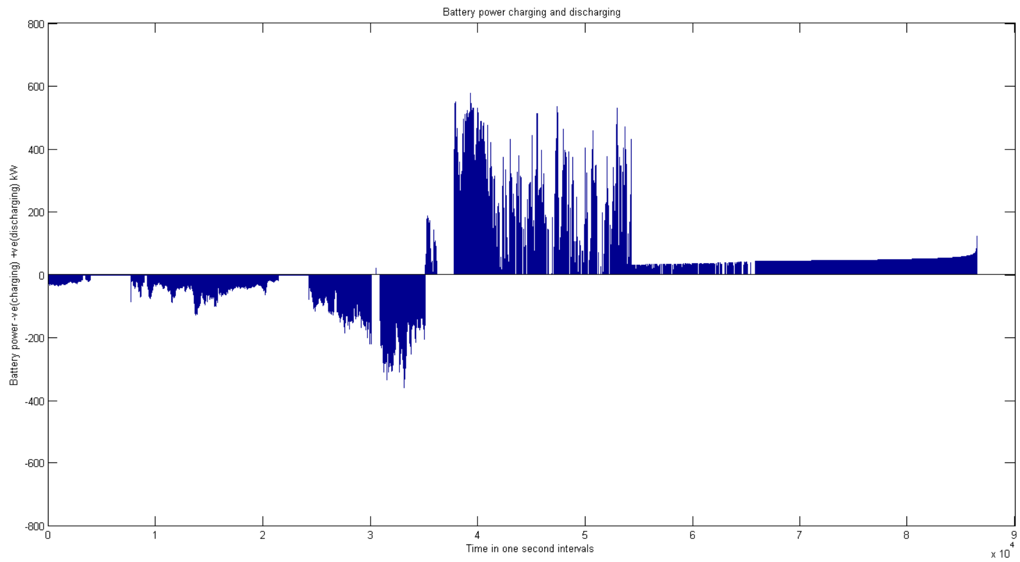

Figure 6.91 Battery power charging and discharging under real time operation at half capacity and double pulse operation in free-running mode and conservative discharging

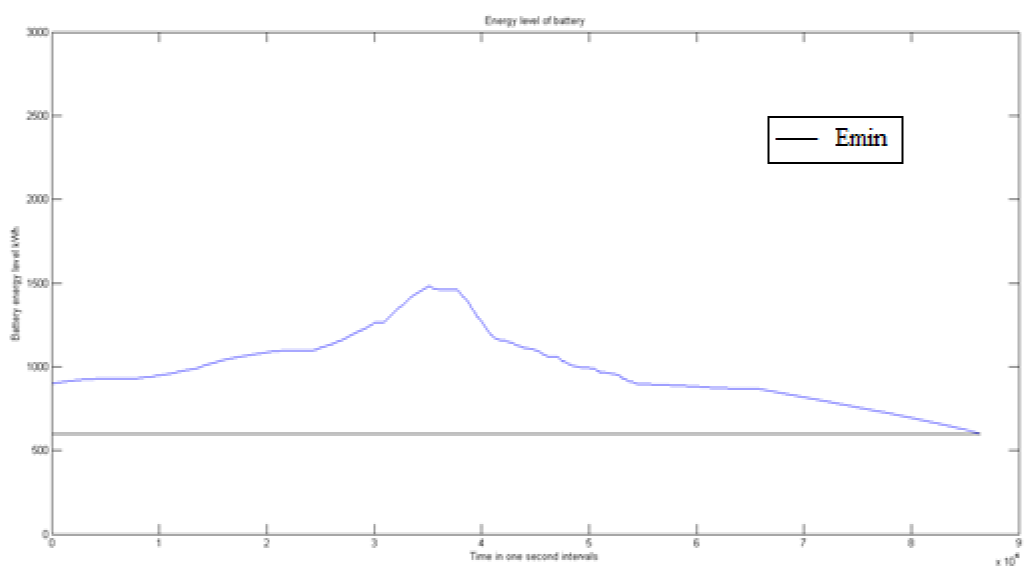

Figure 6.92 Battery state of charge under real time operation at half capacity and double pulse operation in free-running mode and conservative discharge

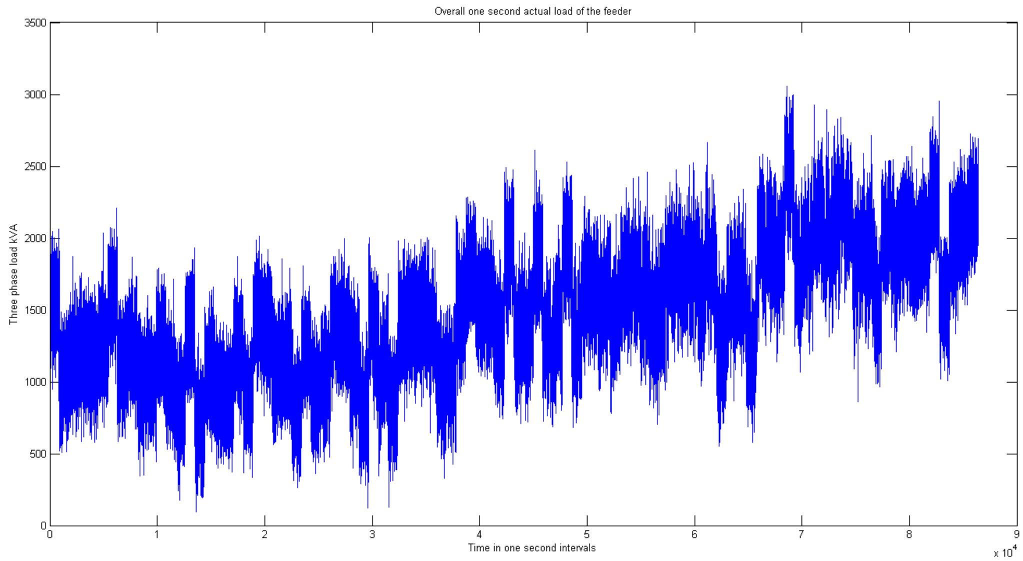

Figure 6.93 Overall actual one second demand under real time operation at half battery capacity and double pulse operation in free-running mode and conservative discharge

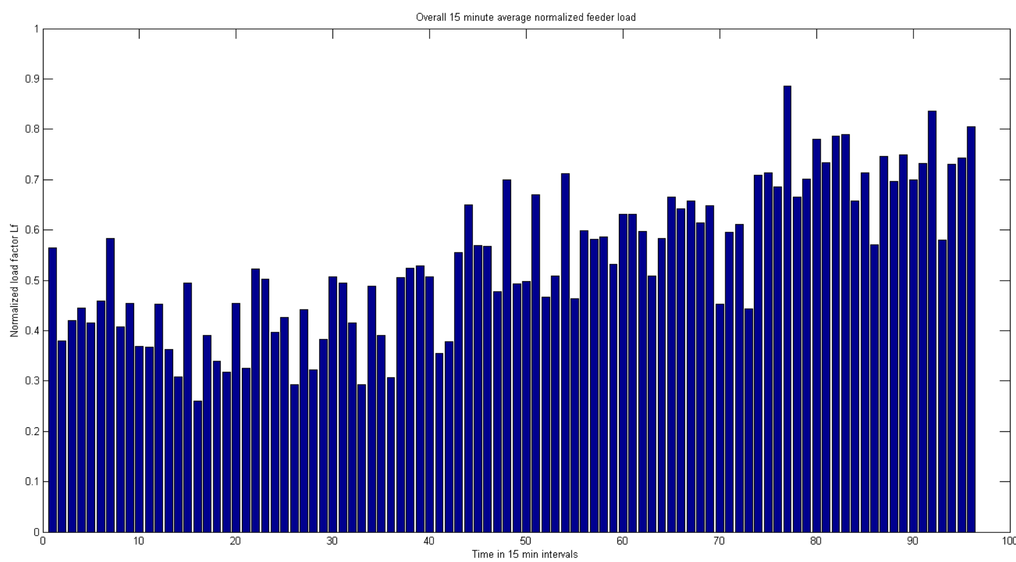

Figure 6.94 Fifteen minute average normalized demand under real time operation at half battery capacity and double pulse operation in free-running mode and conservative discharge

The results obtained above show that the improvements in peak reduction or mean load reduction of the feeder are not very appreciable. There is a slight improvement in the capacity usage of the battery although the battery is mostly unused. So, it may be inferred that the double pulse operation of the battery is unwarranted as there are no significant improvements, and also, prolonged operation of the battery in the double pulse mode could reduce the life span of operation.

The next step in the analysis involves using the battery in the same configuration as before without the double pulse operation. The only difference in this case is that the initial battery capacity is assumed to be at 60%. The analysis is done in this way in order to investigate if any changes occur in capacity utilization with higher initial battery energy level. The specifications in this case are given below. The results are obtained in figures 6.95 through 6.98.

Power Rating (P)	400 kW
Maximum Energy Level (Emax)	3000 kWh
Minimum Energy Level (Emin) 20%	600 kWh
Initial Energy Level (E0) 60%	1800 kWh
Switching Energy level (Es) 30%	900 kWh
Execution time (t)	58 minutes

Table 6.7 Battery Specifications for real time test system in free-running mode and conservative discharge at half capacity for higher initial energy

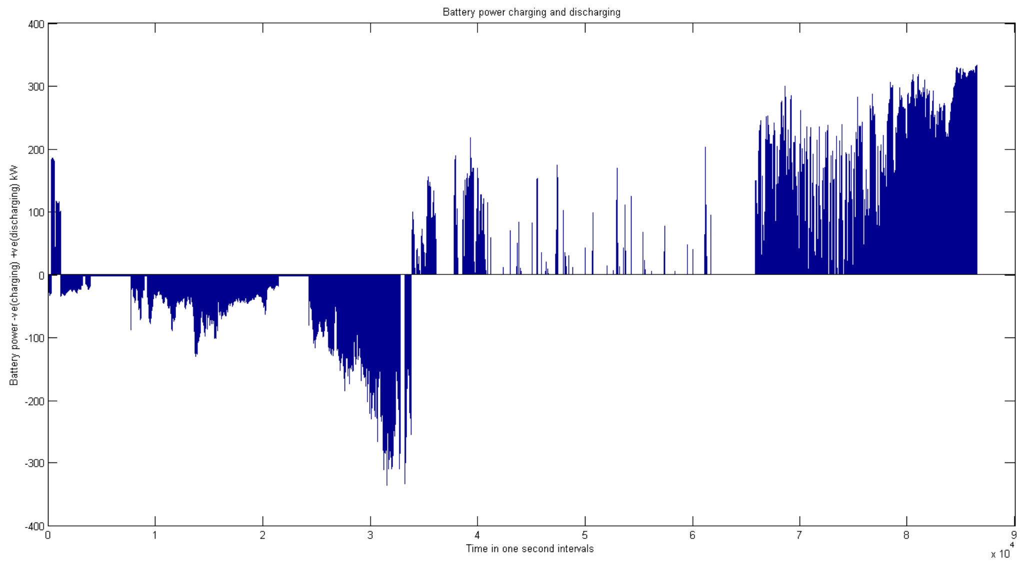

Figure 6.95 Battery power charging and discharging under real time operation at half capacity and higher initial energy in free-running mode and conservative discharging

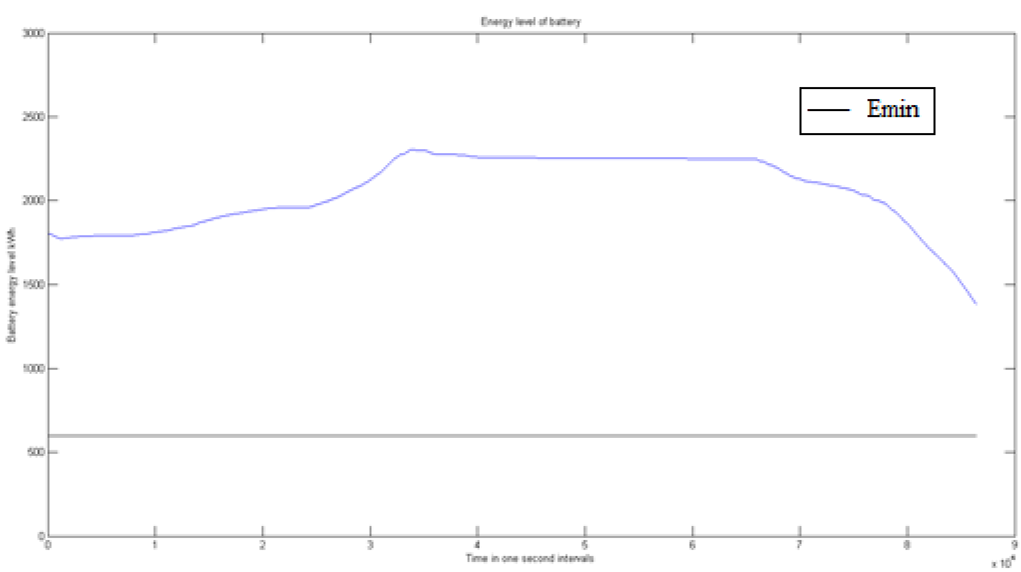

Figure 6.96 Battery state of charge under real time operation at half capacity and higher initial energy in free-running mode and conservative discharge

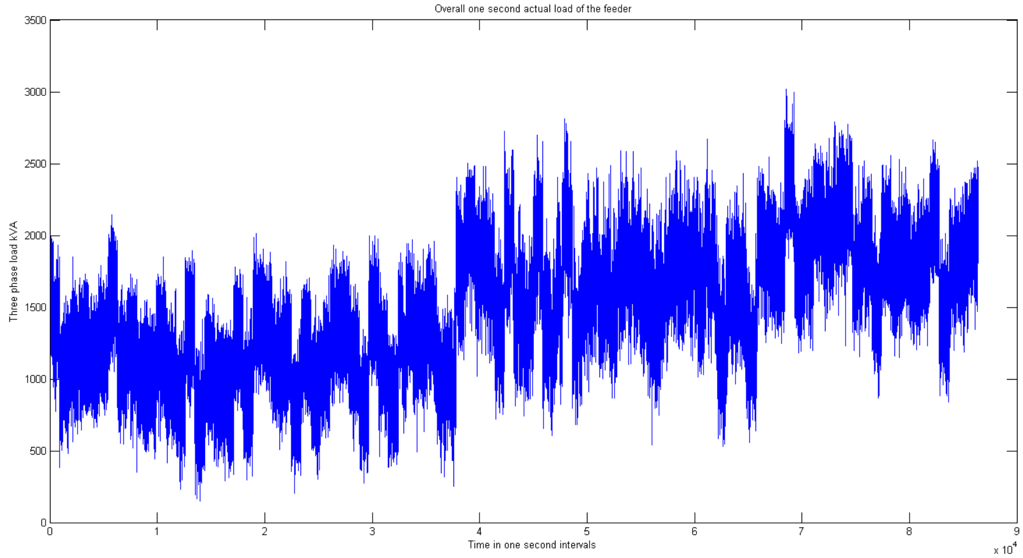

Figure 6.97 Overall actual one second demand under real time operation at half battery capacity and higher initial energy in free-running mode and conservative discharge

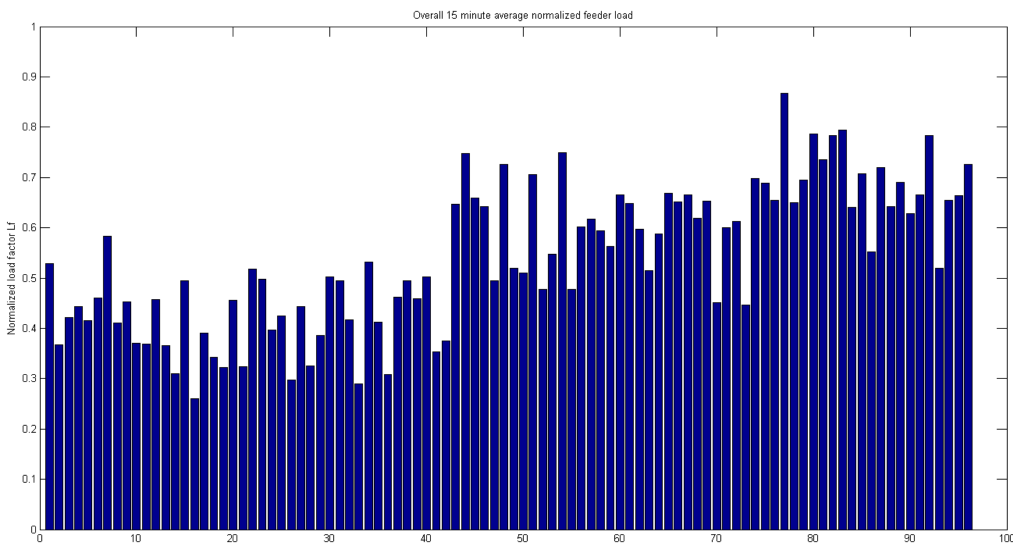

Figure 6.98 Fifteen minute average normalized demand under real time operation at half battery capacity and higher initial energy in free-running mode and conservative discharge

It is observed that in the above case where battery capacity starts at a higher initial energy level, there are no significant improvements in peak reduction and mean load reduction, and also the capacity utilization of the battery reduces as surplus amount of energy is available in the battery. This proves again that the capacity of the battery can be reduced further, which forms the basis for the next and final step in the battery size reduction process investigated along with dispatch operations in this research.

The battery is now reduced to one-fourth or 25% of its original capacity and the real time operation in free-running mode and conservative discharge is done under the following battery specifications. The results are obtained in figures 6.99 through 6.102.

Power Rating (P)	200 kW
Maximum Energy Level (Emax)	1500 kWh
Minimum Energy Level (Emin) 20%	300 kWh
Initial Energy Level (E0) 30%	450 kWh
Switching Energy level (Es) 30%	450 kWh
Execution time (t)	58 minutes

Table 6.8 Battery Specifications for real time test system in free-running mode and conservative discharge at quarter capacity

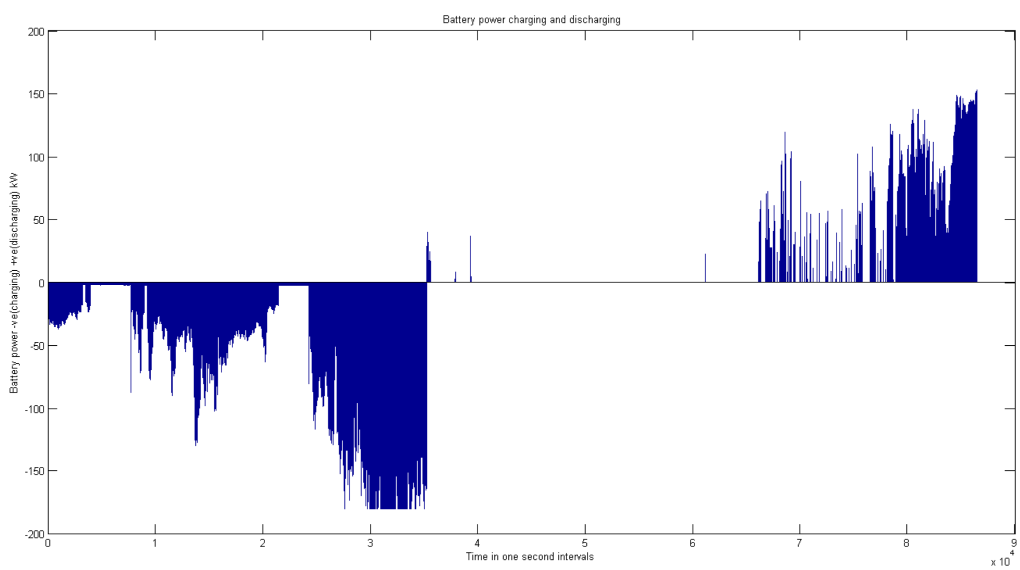

Figure 6.99 Battery power charging and discharging under real time operation at quarter capacity in free-running mode and conservative discharging

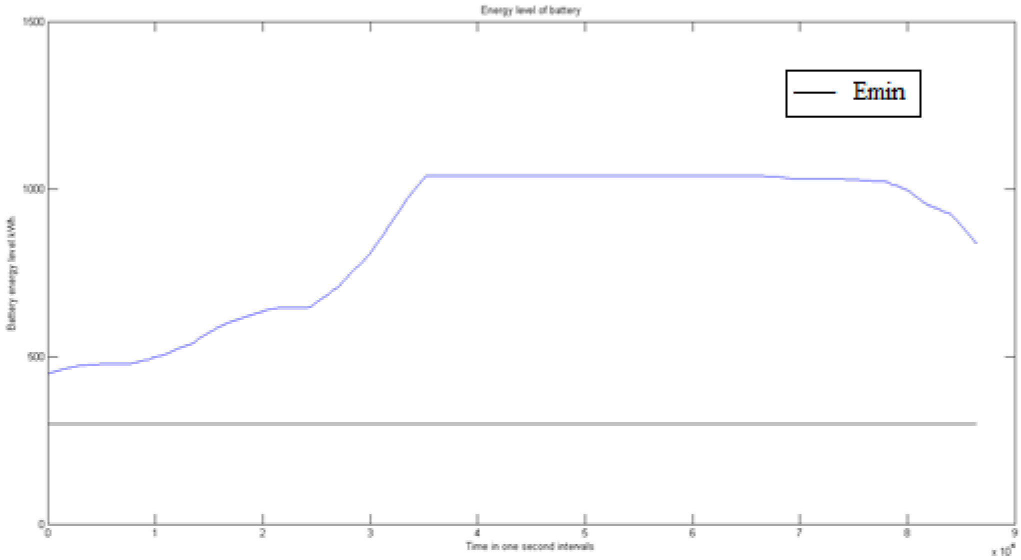

Figure 6.100 Battery state of charge under real time operation at quarter capacity in free-running mode and conservative discharge

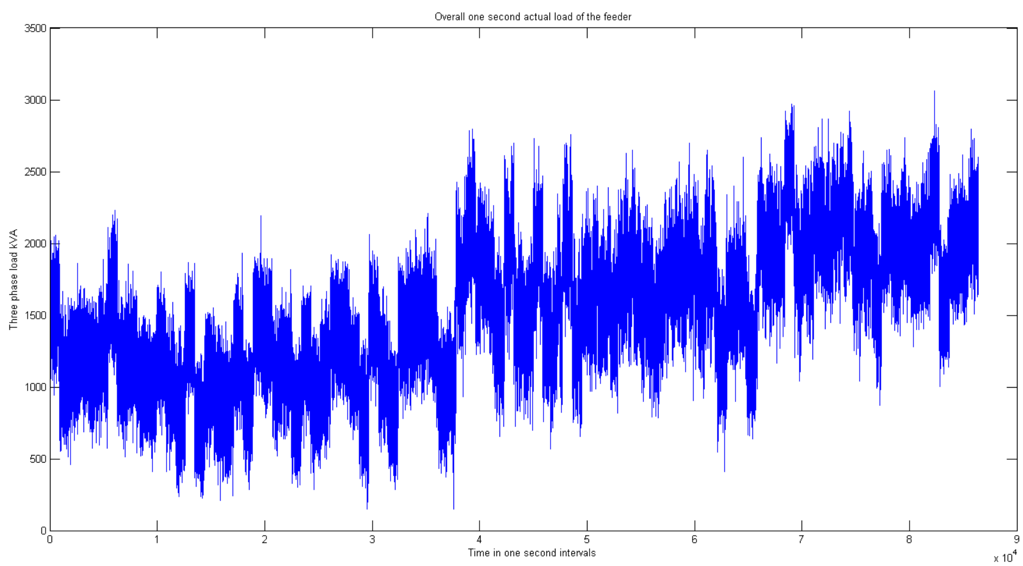

Figure 6.101 Overall actual one second demand under real time operation at quarter battery capacity in free-running mode and conservative discharge

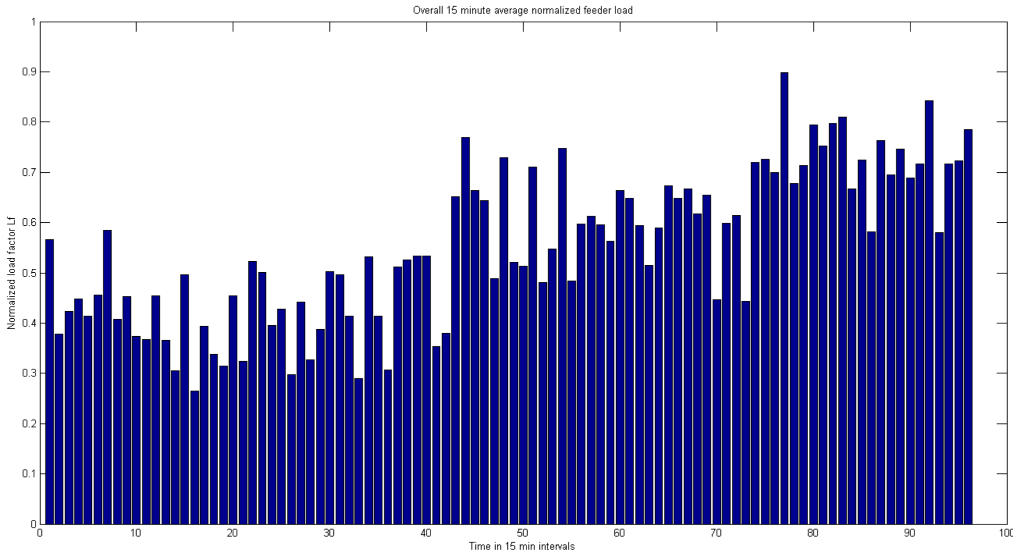

Figure 6.102 Fifteen minute average normalized demand under real time operation at quarter battery capacity in free-running mode and conservative discharge

The final results obtained for 25% of original assumed battery capacity show appreciable peak reduction and average load reduction and also high capacity utilization for the battery when compared to all of the previous results. So, it can be inferred that this could be the best case of battery sizing as the wind generation average for this case is between the medium and high levels and constantly high wind generation could actually end up utilizing the full capacity of the battery on such days.

A final tabulation of the results obtained for all the real time storage dispatch cases discussed so far has been presented below.

Mode	Specifications	Average load factor	Peak load factor	Battery utilization factor	Time of execution (minutes)
Base case	--	0.6668	1.0000	--	--
Free-running only	Full capacity + 30% initial	0.5393	0.9050	0.3681	58
Free-running and conservative discharge below switching energy level	Full capacity + 30% initial	0.5397	0.8716	0.4036	58
	Half capacity + 30% initial	0.5433	0.8641	0.4418	58
	Half capacity + 30% initial + double pulse operation	0.5434	0.8866	0.4940	58
	Half capacity + 60% initial	0.5421	0.8679	0.4681	58
	Quarter capacity + 30% initial	0.5539	0.8981	0.6939	58

Table 6.9 Summary of results obtained for real time operation of wind generation with storage dispatch using historical PMU information

In the analysis that has been done in this research work, PMU information of the previous 300 time instances or seconds is used to calculate the battery dispatch for the current time instant. So, it can be inferred that during every one second interval, one calculation for dispatch of the battery happens. For a total processing time of 58 minutes for all the 86400 time instances of dispatch calculation, the processing time per instance is calculated by dividing the total time by the total number of time instances. The processing time per time instant is calculated to be 40.27 milliseconds, which is slightly higher than the maximum PMU sampling time of 33.33 milliseconds. So, for this particular test feeder, it is possible to work with a high resolution of up to 15 samples per second of PMU data. This proves the dynamic real time characteristics of the calculations analyzed in this research. Actual on field applications could be much faster with system components such as distribution SCADA computers which could put the full potential of the dynamic nature of PMU measurements to use.

Chapter 7 - Conclusions and Future Work

7.1 Conclusions

The integration of distributed storage into the distribution system in order to support wind generation provides some exciting advantages. The following contributions have been made in this research work.

- The possibility of storing wind generation and using it when it is most required is a valuable asset in the proper and efficient operation of a distribution system and has been accomplished with some degree of success in this research work.
- The unbalanced operation of power flow in a distribution system for dynamic load intervals in order to regulate storage and wind generation has been undocumented so far in literature and has been investigated in this research.
- The advantages of using dynamic load information available from advanced measurement devices in order to effectively achieve wind generation storage and dispatch operations have been established. The usage of Phasor Measurement Units (PMU) in order to perform the same function, especially in a distribution system has been handled newly in this research work.
- Some of the battery charging and discharging strategies developed in order to effectively support wind generation and achieve peak reduction in feeder load such as sustained average load approach and conservative discharging are unique to this research.
- The real time operation of battery storage dispatch using historical PMU information has also been newly developed in this research work. All of the methods developed here are purely based on math functions and involve no optimization, making them well suited to on field real time applications.
- When battery storage is to be used with wind generation in order to perform load support operations, battery size and cost can be a concern to be addressed. The step by step attempts made in the reduction of battery size for real time applications of load support, and the results obtained in the process greatly addressed this issue, and the stage is now set for other researchers trying to improve the methods and resources developed in this research even further.

7.2 Future Work

The usage of PMUs in distribution systems is still a relatively unexplored area of study, and there might be a lot more scope for future research work in this area. As the PMU technology becomes cheaper, its usage in distribution systems can be expected to increase, as the benefits of this technology far outweigh the costs involved. Talking specifically in terms of the research done so far, the techniques and strategies used in this research can be applied through simulation to larger test feeders as well as for on field operation through test beds and actual experimental feeders. The techniques developed in this research have been applied primarily to centralized location of wind generation and storage technologies due to the size of the test feeder. But present trends in distributed generation are growing towards placement of distributed resources at multiple locations. So, there might be avenues for further studies in multiple sighting as well as measurement locations for PMUs, wind farms and storage. There is also scope for further optimization of storage installations with increasing penetration of renewables such as wind and solar energy. The entire power system has been moving towards smart grid technologies, and all the elements of the power system addressed in this research will need further investigation and validation with time.

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Appendix A – Test Feeder Information

A.1 Test feeder Line, Load and Transformer details

Configuration	Phasing	Cable	Spacing ID
721	A B C	1,000,000 AA, CN	515
722	A B C	500,000 AA, CN	515
723	A B C	2/0 AA, CN	515
724	A B C	#2 AA, CN	515

Table A.1 Underground Cable Configuration

Node	Load Model	Ph-1 kW	Ph-1 kVAR	Ph-2 kW	Ph-2 kVAR	Ph-3 kW	Ph-3 kVAR
701	D-PQ	140	70	140	70	350	175
712	D-PQ	0	0	0	0	85	40
713	D-PQ	0	0	0	0	85	40
714	D-I	17	8	21	10	0	0
718	D-Z	85	40	0	0	0	0
720	D-PQ	0	0	0	0	85	40
722	D-I	0	0	140	70	21	10
724	D-Z	0	0	42	21	0	0
725	D-PQ	0	0	42	21	0	0
727	D-PQ	0	0	0	0	42	21
728	D-PQ	42	21	42	21	42	21
729	D-I	42	21	0	0	0	0
730	D-Z	0	0	0	0	85	40
731	D-Z	0	0	85	40	0	0
732	D-PQ	0	0	0	0	42	21
733	D-I	85	40	0	0	0	0
734	D-PQ	0	0	0	0	42	21
735	D-PQ	0	0	0	0	85	40
736	D-Z	0	0	42	21	0	0
737	D-I	140	70	0	0	0	0
738	D-PQ	126	62	0	0	0	0
740	D-PQ	0	0	0	0	85	40
741	D-I	0	0	0	0	42	21
742	D-Z	8	4	85	40	0	0
744	D-PQ	42	21	0	0	0	0
Total		727	357	639	314	1091	530

Table A.2 Spot Loads

	kVA	kV-high	kV-low	R - %	X - %
Substation:	2,500	230 D	4.8 D	2	8
XFM -1	500	4.8 D	.480 D	0.09	1.81

Table A.3 Transformer data

Node A	Node B	Length(ft.)	Configuration
701	702	960	722
702	705	400	724
702	713	360	723
702	703	1320	722
703	727	240	724
703	730	600	723
704	714	80	724
704	720	800	723
705	742	320	724
705	712	240	724
706	725	280	724
707	724	760	724
707	722	120	724
708	733	320	723
708	732	320	724
709	731	600	723
709	708	320	723
710	735	200	724
710	736	1280	724
711	741	400	723
711	740	200	724
713	704	520	723
714	718	520	724
720	707	920	724
720	706	600	723
727	744	280	723
730	709	200	723
733	734	560	723
734	737	640	723
734	710	520	724
737	738	400	723
738	711	400	723
744	728	200	724
744	729	280	724
775	709	0	XFM-1
799	701	1850	721

Table A.4 Line Segment data

A.2 Phase Impedance Matrices for various configurations

Configuration 721:

Z (R +jX) in ohms per mile

[0.2926+j0.1973	0.0673-j0.0368	0.0337-j0.0417
0.0673-j0.0368	0.2646+j0.1900	0.0673-j0.0368
0.0337-j0.0417	0.0673-j0.0368	0.2926+j0.1973]

Configuration 722:

Z (R +jX) in ohms per mile

[0.4751+j0.2973	0.1629-j0.0326	0.1234-j0.0607
0.1629-j0.0326	0.4488+j0.2678	0.1629-j0.0326
0.1234-j0.0607	0.1629-j0.0326	0.4751+j0.2973]

Configuration 723:

Z (R +jX) in ohms per mile

[1.2936+j0.6713	0.4871+j0.2111	0.4585+j0.1521
0.4871+j0.2111	1.3022+j0.6326	0.4871+j0.2111
0.4585+j0.1521	0.4871+j0.2111	1.2936+j0.6713]

Configuration 724:

Z (R +jX) in ohms per mile

[2.0952+j0.7758	0.5204+j0.2738	0.4926+j0.2123
0.5204+j0.2738	2.1068+j0.7398	0.5204+j0.2738
0.4926+j0.2123	0.5204+j0.2738	2.0952+j0.7758]

Appendix B – Input Files and Software Code

B.1 Code for Input file used in Fifteen-minute Analysis

```
%Data Files creation for 3-ph load flow BFS method with wind and storage
%combined in the system - Manoaj Vijayarengan
clear all
clc

Sb = 2500000;
    Vb = 4800;
    Zb = (Vb^2)/Sb;
                            %Load
    %   Node  Renum     Model   kW   kVAr     kW   kVAr     kW   kVAr
Node = [701     2        1       140  70       140  70       350  175
        712     5        1       0    0        0    0        85   40
        713     7        1       0    0        0    0        85   40
        714     9        3       17   8        21   10       0    0
        718     10       2       85   40       0    0        0    0
        720     11       1       0    0        0    0        85   40
        722     13       3       0    0        140  70       21   10
        724     14       2       0    0        42   21       0    0
        725     16       1       0    0        42   21       0    0
        727     18       1       0    0        0    0        42   21
        728     20       1       42   21       42   21       42   21
        729     21       3       42   21       0    0        0    0
        730     22       2       0    0        0    0        85   40
        731     24       2       0    0        85   40       0    0
        732     36       1       0    0        0    0        42   21
        733     26       3       85   40       0    0        0    0
        734     27       1       0    0        0    0        42   21
        735     30       1       0    0        0    0        85   40
        736     29       2       0    0        42   21       0    0
        737     31       3       140  70       0    0        0    0
        738     32       1       126  62       0    0        0    0
        740     34       1       0    0        0    0        85   40
        741     35       3       0    0        0    0        42   21
        742     6        2       8    4        85   40       0    0
        744     19       1       42   21       0    0        0    0   ];

S_peak = [0;0;0];
for i = 1:size(Node,1);
        S_peak = S_peak + 1000*[Node(i,4)+1j*Node(i,5) Node(i,6)+1j*Node(i,7)
Node(i,8)+1j*Node(i,9)].';
end


                            %Branch
   %        NodeA  RenumA    NodeB  RenumB    Length(ft.) Config.
Branch = [   701    2         702    3         960          722
             702    3         705    4         400          724
             702    3         713    7         360          723
             702    3         703    17        1320         722
             703    17        727    18        240          724
             703    17        730    22        600          723
             704    8         714    9         80           724
             704    8         720    11        800          723
```

```
            705    4       742     6       320          724
            705    4       712     5       240          724
            706    15      725     16      280          724
            707    12      724     14      760          724
            707    12      722     13      120          724
            708    25      733     26      320          723
            708    25      732     36      320          724
            709    23      731     24      600          723
            709    23      708     25      320          723
            710    28      735     30      200          724
            710    28      736     29      1280         724
            711    33      741     35      400          723
            711    33      740     34      200          724
            713    7       704     8       520          723
            714    9       718     10      520          724
            720    11      707     12      920          724
            720    11      706     15      600          723
            727    18      744     19      280          723
            730    22      709     23      200          723
            733    26      734     27      560          723
            734    27      737     31      640          723
            734    27      710     28      520          724
            737    31      738     32      400          723
            738    32      711     33      400          723
            744    19      728     20      200          724
            744    19      729     21      280          724
            709    23      775     37      0            1
            799    1       701     2       1850         721   ];

           % Impedance matrices
z721 = [ 0.2926+1j*0.1973   0.0673-1j*0.0368   0.0337-1j*0.0417
         0.0673-1j*0.0368   0.2646+1j*0.1900   0.0673-1j*0.0368
         0.0337-1j*0.0417   0.0673-1j*0.0368   0.2926+1j*0.1973 ];
     z721 = {z721};

z722 = [ 0.4751+1j*0.2973   0.1629-1j*0.0326   0.1234-1j*0.0607
         0.1629-1j*0.0326   0.4488+1j*0.2678   0.1629-1j*0.0326
         0.1234-1j*0.0607   0.1629-1j*0.0326   0.4751+1j*0.2973 ];
     z722 = {z722};

z723 = [ 1.2936+1j*0.6713   0.4871+1j*0.2111   0.4585+1j*0.1521
         0.4871+1j*0.2111   1.3022+1j*0.6326   0.4871+1j*0.2111
         0.4585+1j*0.1521   0.4871+1j*0.2111   1.2936+1j*0.6713 ];
     z723 = {z723};

z724 = [ 2.0952+1j*0.7758   0.5204+1j*0.2738   0.4926+1j*0.2123
         0.5204+1j*0.2738   2.1068+1j*0.7398   0.5204+1j*0.2738
         0.4926+1j*0.2123   0.5204+1j*0.2738   2.0952+1j*0.7758 ];
     z724 = {z724};

Z = [z721;z722;z723;z724];

ftmi = 1.8939e-4;


% Transformer matrices
```

```
% For D-D transformer (in branch 709-775),
% at = (nt/3)*[2 -1 -1;-1 2 -1;-1 -1 2]
% bt = W*AV*Zabc*G1
% where W = (1/3)*[2 1 0;0 2 1;1 0 2]
%       AV = [nt 0 0;0 nt 0;0 0 nt]
%       Zabc = diagonal(Zab,Zbc,Zca)
%       G1 = (1/(Zab+Zbc+Zca))*[Zca -Zbc 0;Zca Zab+Zca 0;-Zab-Zbc -Zbc 0]
% dt = (1/nt)*eye(3)
% At = (1/(3*nt))*[2 -1 -1;-1 2 -1;-1 2 -1]
% Bt = W*Zabc*G1
nt = 10;
Zab = 0.0009+1j*0.0181;
Zbc = Zab;
Zca = Zab;
W = (1/3)*[2 1 0;0 2 1;1 0 2];
AV = [nt 0 0;0 nt 0;0 0 nt];
Zabc = [Zab 0 0;0 Zbc 0;0 0 Zca];
G1 = (1/(Zab+Zbc+Zca))*[Zca -Zbc 0;Zca Zab+Zca 0;-Zab-Zbc -Zbc 0];
at = (nt/3)*[2 -1 -1;-1 2 -1;-1 -1 2];
bt = W*AV*Zabc*G1;
dt = (1/nt)*eye(3);
At = (1/(3*nt))*[2 -1 -1;-1 2 -1;-1 -1 2];
Bt = W*Zabc*G1;

         %Normalized Load fractions for 15-min divisions from profile 1
AggDem_Norm_1 = [   0.5667
                    0.3805
                    0.4207
                    0.4425
                    0.4138
                    0.4586
                    0.5828
                    0.4057
                    0.4529
                    0.3690
                    0.3655
                    0.4506
                    0.3632
                    0.3080
                    0.4954
                    0.2598
                    0.3908
                    0.3391
                    0.3161
                    0.4540
                    0.3230
                    0.5207
                    0.4977
                    0.3954
                    0.4264
                    0.2966
                    0.4414
                    0.3241
                    0.3851
                    0.5034
                    0.4943
                    0.4138
                    0.2885
```

0.5310
0.4126
0.3057
0.5103
0.5241
0.5299
0.6138
0.5276
0.5460
0.8218
0.9080
0.8299
0.8402
0.7586
0.9897
0.7667
0.7989
0.9529
0.7379
0.8080
1.0000
0.7667
0.9126
0.8770
0.8943
0.8149
0.9230
0.9149
0.8690
0.7943
0.8736
0.9598
0.9310
0.9414
0.8782
0.9207
0.7552
0.9069
0.9241
0.7609
0.8552
0.8310
0.7931
0.9954
0.7989
0.8598
0.9471
0.8977
0.9448
0.9506
0.7816
0.8644
0.6920
0.8529
0.7713
0.8149
0.7494
0.7839

```
                     0.9080
                     0.6460
                     0.7793
                     0.7805
                     0.8414 ];

%                   %Medium wind generation for a single day - 8 100kW
%                   %Northwind Turbines
MedGen = [      69.6000   68.1067   69.4133   31.3200   30.6480   31.2360
                68.8533   67.3600   68.7200   30.9840   30.3120   30.9240
                66.4267   64.9333   66.3200   29.8920   29.2200   29.8440
                83.8133   82.2133   83.9200   37.7160   36.9960   37.7640
                73.4133   72.1067   73.5200   33.0360   32.4480   33.0840
                68.6667   67.4667   68.7733   30.9000   30.3600   30.9480
                55.5200   54.4800   55.7333   24.9840   24.5160   25.0800
                45.7067   44.5600   45.6533   20.5680   20.0520   20.5440
                43.2533   42.1600   43.1200   19.4640   18.9720   19.4040
                61.4933   60.2400   61.4667   27.6720   27.1080   27.6600
                80.1067   78.7200   80.2400   36.0480   35.4240   36.1080
                94.1867   92.4267   94.2133   42.3840   41.5920   42.3960
               101.7600  100.0533  101.8133   45.7920   45.0240   45.8160
               122.1867  120.5867  122.4533   54.9840   54.2640   55.1040
               151.9200  149.7067  152.0533   68.3640   67.3680   68.4240
               153.1467  150.8267  153.0667   68.9160   67.8720   68.8800
               160.2133  157.9733  160.0000   72.0960   71.0880   72.0000
               161.8667  159.5733  161.6000   72.8400   71.8080   72.7200
               132.1333  129.9733  131.8133   59.4600   58.4880   59.3160
               129.5733  127.5733  129.0933   58.3080   57.4080   58.0920
               127.2800  125.6000  127.0133   57.2760   56.5200   57.1560
               132.7200  131.0400  132.4000   59.7240   58.9680   59.5800
               144.6933  143.0133  144.5600   65.1120   64.3560   65.0520
               141.3867  139.5467  141.2533   63.6240   62.7960   63.5640
               146.9867  145.2000  146.9067   66.1440   65.3400   66.1080
               132.0533  130.4267  131.8667   59.4240   58.6920   59.3400
               117.2267  115.7867  117.1467   52.7520   52.1040   52.7160
                93.1733   91.7867   93.0933   41.9280   41.3040   41.8920
                83.7067   82.5333   83.7067   37.6680   37.1400   37.6680
                87.3333   86.1600   87.3867   39.3000   38.7720   39.3240
                82.2133   80.8800   82.0267   36.9960   36.3960   36.9120
               110.8000  109.1467  110.4533   49.8600   49.1160   49.7040
                95.5467   93.5467   95.1200   42.9960   42.0960   42.8040
                99.8667   97.9200   99.4933   44.9400   44.0640   44.7720
               101.8667  100.0267  101.4667   45.8400   45.0120   45.6600
               106.9867  105.0400  106.6933   48.1440   47.2680   48.0120
               111.4933  109.4400  111.2800   50.1720   49.2480   50.0760
                95.6533   93.8133   95.4400   43.0440   42.2160   42.9480
                86.8000   85.1467   86.6667   39.0600   38.3160   39.0000
                72.4000   70.9600   72.2667   32.5800   31.9320   32.5200
                70.1333   68.8000   70.1600   31.5600   30.9600   31.5720
                53.5467   52.4800   53.6800   24.0960   23.6160   24.1560
                60.9867   59.6800   61.0400   27.4440   26.8560   27.4680
                61.3067   60.1067   61.4667   27.5880   27.0480   27.6600
                82.6933   80.9333   82.3733   37.2120   36.4200   37.0680
                70.2667   68.8267   70.0533   31.6200   30.9720   31.5240
                65.3067   64.1867   65.1733   29.3880   28.8840   29.3280
                76.7733   75.4933   76.8533   34.5480   33.9720   34.5840
                76.1333   74.4000   76.2667   34.2600   33.4800   34.3200
                67.0133   65.2800   66.9333   30.1560   29.3760   30.1200
```

```
                43.7067   42.6133   43.3867   19.6680   19.1760   19.5240
                42.7467   41.9733   42.5333   19.2360   18.8880   19.1400
                40.4533   39.7867   40.3200   18.2040   17.9040   18.1440
                53.4133   52.2133   52.9600   24.0360   23.4960   23.8320
                47.1733   46.0800   46.8267   21.2280   20.7360   21.0720
                46.8000   45.8133   46.2933   21.0600   20.6160   20.8320
                59.8933   58.8267   59.6000   26.9520   26.4720   26.8200
                59.4667   58.3467   59.2267   26.7600   26.2560   26.6520
                54.1867   52.9333   53.5733   24.3840   23.8200   24.1080
                56.1600   54.9600   55.8133   25.2720   24.7320   25.1160
                64.7467   63.3067   64.4533   29.1360   28.4880   29.0040
                78.5067   76.8533   78.0000   35.3280   34.5840   35.1000
                80.4533   79.3600   80.4000   36.2040   35.7120   36.1800
                73.5733   72.3733   73.6800   33.1080   32.5680   33.1560
                79.7600   78.2933   79.7067   35.8920   35.2320   35.8680
                90.0533   88.6933   89.8933   40.5240   39.9120   40.4520
               110.5333  108.5867  110.2933   49.7400   48.8640   49.6320
                85.6267   84.0533   85.3867   38.5320   37.8240   38.4240
                62.8000   61.4133   62.5867   28.2600   27.6360   28.1640
                62.5867   61.0933   62.2667   28.1640   27.4920   28.0200
                63.9467   62.4267   63.4933   28.7760   28.0920   28.5720
                77.3867   75.7067   76.9867   34.8240   34.0680   34.6440
                80.5600   78.9067   80.0533   36.2520   35.5080   36.0240
               102.3200  100.4533  101.9200   46.0440   45.2040   45.8640
                63.9733   62.4800   63.4133   28.7880   28.1160   28.5360
                63.3333   62.1600   63.1467   28.5000   27.9720   28.4160
                60.4267   59.2800   60.4000   27.1920   26.6760   27.1800
                71.3600   70.1600   71.3867   32.1120   31.5720   32.1240
                38.1067   37.3600   38.0267   17.1480   16.8120   17.1120
                52.0800   51.2800   52.0533   23.4360   23.0760   23.4240
                87.5733   86.3733   87.7867   39.4080   38.8680   39.5040
                60.0000   59.1200   60.1600   27.0000   26.6040   27.0720
                47.0400   46.1067   46.8533   21.1680   20.7480   21.0840
                35.2533   34.3200   34.7467   15.8640   15.4440   15.6360
                38.9067   37.9733   38.4800   17.5080   17.0880   17.3160
                26.8000   26.0267   26.4267   12.0600   11.7120   11.8920
                36.8000   35.7600   36.5067   16.5600   16.0920   16.4280
                30.7733   29.7867   30.4800   13.8480   13.4040   13.7160
                36.8800   35.9733   36.6133   16.5960   16.1880   16.4760
                41.7333   40.7733   41.6800   18.7800   18.3480   18.7560
                32.8533   32.1333   32.8000   14.7840   14.4600   14.7600
                37.7067   36.7733   37.4400   16.9680   16.5480   16.8480
                18.8267   18.0800   18.4533    8.4720    8.1360    8.3040
                30.0267   29.0667   29.7067   13.5120   13.0800   13.3680
                24.5867   23.5733   24.0800   11.0640   10.6080   10.8360
                30.7733   29.6533   30.2133   13.8480   13.3440   13.5960 ];

%            %     High wind generation for a single day - 8 100kW
%                 %Northwind Turbines
HighGen = [       281.5501  275.5605  279.9189  126.6976  124.0022  125.9635
                  257.9286  252.7216  256.1336  116.0679  113.7247  115.2601
                  258.8540  254.7260  257.4784  116.4843  114.6267  115.8653
                  249.5892  245.2773  248.4009  112.3151  110.3748  111.7804
                  166.1852  163.1836  166.3977   74.7834   73.4326   74.8790
                  246.7829  242.1951  245.9837  111.0523  108.9878  110.6927
                  289.5928  285.1840  288.8539  130.3168  128.3328  129.9843
                  259.3332  255.5449  258.7695  116.6999  114.9952  116.4463
                  251.2633  247.5916  250.6554  113.0685  111.4162  112.7949
```

241.1937	237.3907	240.4628	108.5372	106.8258	108.2083
220.4890	216.7499	220.5590	99.2200	97.5374	99.2515
170.5276	167.2932	170.4710	76.7374	75.2819	76.7119
194.6946	190.9874	193.6259	87.6126	85.9443	87.1317
201.4305	197.2865	200.4182	90.6437	88.7789	90.1882
166.5257	163.6487	166.1027	74.9365	73.6419	74.7462
173.8276	171.2013	173.1800	78.2224	77.0406	77.9310
157.8256	155.1120	157.0649	71.0215	69.8004	70.6792
160.5729	157.9383	159.8133	72.2578	71.0722	71.9160
156.6348	154.0328	155.9338	70.4856	69.3148	70.1702
132.6656	130.3142	131.9406	59.6995	58.6414	59.3733
146.6556	143.6675	145.5267	65.9950	64.6504	65.4870
166.8968	163.6652	165.5689	75.1036	73.6493	74.5060
195.1793	191.8074	194.5388	87.8307	86.3133	87.5425
182.2967	179.2603	181.3677	82.0335	80.6672	81.6155
135.7996	133.3230	135.1459	61.1098	59.9954	60.8157
181.2490	177.8670	180.0255	81.5620	80.0401	81.0115
139.0507	136.1839	137.9074	62.5728	61.2828	62.0583
147.1830	144.2861	146.3829	66.2323	64.9288	65.8723
180.0165	176.5430	178.3378	81.0074	79.4444	80.2520
192.7610	189.0588	191.4471	86.7424	85.0765	86.1512
219.4664	215.4934	217.7267	98.7599	96.9720	97.9770
205.5480	201.7413	203.5906	92.4966	90.7836	91.6158
188.9781	186.0578	187.8556	85.0401	83.7260	84.5350
185.5239	182.8132	184.8639	83.4858	82.2659	83.1887
214.6119	211.3663	213.8163	96.5753	95.1148	96.2173
169.9298	166.8443	169.4745	76.4684	75.0799	76.2635
151.4000	148.5034	150.7789	68.1300	66.8265	67.8505
158.1906	155.3850	157.6438	71.1858	69.9232	70.9397
154.8747	152.3742	154.9013	69.6936	68.5684	69.7056
145.7215	143.2940	145.5506	65.5747	64.4823	65.4978
119.7136	117.7068	119.7499	53.8711	52.9681	53.8875
107.8217	106.1186	108.0676	48.5198	47.7534	48.6304
109.1439	107.3334	109.4081	49.1148	48.3000	49.2337
119.0752	116.7744	119.0558	53.5839	52.5485	53.5751
120.4739	117.9034	120.2289	54.2133	53.0565	54.1030
167.4364	164.3039	166.7815	75.3464	73.9368	75.0517
201.9840	199.1634	201.9390	90.8928	89.6235	90.8725
164.5809	162.0136	164.4520	74.0614	72.9061	74.0034
121.5801	119.6726	121.5301	54.7110	53.8527	54.6885
160.3128	157.8708	160.2114	72.1408	71.0418	72.0951
154.5830	152.1322	154.5418	69.5623	68.4595	69.5438
136.8201	134.5896	136.7365	61.5690	60.5653	61.5314
192.0582	188.4824	191.3688	86.4262	84.8171	86.1160
192.5512	188.6248	191.3867	86.6480	84.8812	86.1240
177.6566	174.1032	177.0777	79.9455	78.3464	79.6850
186.3555	182.8996	185.9392	83.8600	82.3048	83.6726
223.9334	219.7368	222.7411	100.7700	98.8815	100.2335
202.5944	198.5224	201.8154	91.1675	89.3351	90.8169
207.0331	203.2247	206.2358	93.1649	91.4511	92.8061
201.2881	197.6263	200.5627	90.5796	88.9318	90.2532
248.7264	244.3014	248.0414	111.9269	109.9356	111.6186
247.3148	242.4722	245.9475	111.2917	109.1125	110.6764
248.9380	244.0643	247.3982	112.0221	109.8289	111.3292
250.8993	245.9372	249.3291	112.9047	110.6717	112.1981
242.5997	238.1248	241.7165	109.1698	107.1561	108.7724
248.3843	243.9465	247.2201	111.7730	109.7759	111.2490
273.0356	267.9197	271.5799	122.8660	120.5639	122.2110

```
                    282.2504  277.0619  280.8363  127.0127  124.6779  126.3763
                    280.8353  275.4991  279.5669  126.3759  123.9746  125.8051
                    249.7466  245.0150  248.9040  112.3860  110.2567  112.0068
                    222.9976  219.4022  222.7584  100.3489   98.7310  100.2413
                    233.4804  229.5232  233.4604  105.0662  103.2855  105.0572
                    240.6930  236.2265  240.3427  108.3119  106.3019  108.1542
                    239.6281  235.0626  239.1987  107.8327  105.7782  107.6394
                    253.7524  249.1953  253.1141  114.1886  112.1379  113.9014
                    267.4458  262.6631  266.6065  120.3506  118.1984  119.9729
                    250.3672  245.8844  249.7498  112.6652  110.6480  112.3874
                    223.5473  219.6609  223.3517  100.5963   98.8474  100.5083
                    209.9352  206.4430  209.7836   94.4708   92.8994   94.4026
                    210.1597  206.7353  209.8198   94.5719   93.0309   94.4189
                    175.5417  172.6081  174.9504   78.9937   77.6737   78.7277
                    194.6614  191.3548  194.0840   87.5976   86.1096   87.3378
                    182.8304  179.4926  182.4156   82.2737   80.7717   82.0870
                    158.5451  155.5843  158.4632   71.3453   70.0129   71.3085
                    162.9233  160.0625  162.9225   73.3155   72.0281   73.3151
                    170.2485  167.0910  169.9036   76.6118   75.1910   76.4566
                    159.4286  156.3825  159.0667   71.7428   70.3721   71.5800
                    139.9951  137.1489  139.8089   62.9978   61.7170   62.9140
                    146.8990  144.0561  146.6753   66.1046   64.8253   66.0039
                    114.5270  112.1761  114.4074   51.5372   50.4793   51.4833
                     86.0956   83.9931   86.1375   38.7430   37.7969   38.7619
                     77.5236   75.4881   77.3301   34.8856   33.9697   34.7985
                     99.6748   97.2950   99.3048   44.8536   43.7827   44.6871
                     93.7251   91.4118   93.2710   42.1763   41.1353   41.9720
                     88.5965   86.6787   88.0478   39.8684   39.0054   39.6215
                     71.7157   70.0427   71.3719   32.2721   31.5192   32.1174
];

%                    %Low wind generation for a single day - 8 100kW
%                 %Northwind Turbines
LowGen = [      28.8333   27.6133   28.5033   12.9750   12.4260   12.8265
                25.3200   24.1000   25.1033   11.3940   10.8450   11.2965
                20.8133   19.6267   20.5167    9.3660    8.8320    9.2325
                18.1467   17.3067   17.9833    8.1660    7.7880    8.0925
                20.3633   19.6500   20.3867    9.1635    8.8425    9.1740
                22.7167   21.8700   22.5933   10.2225    9.8415   10.1670
                20.1600   19.2833   20.0900    9.0720    8.6775    9.0405
                25.6467   24.6367   25.7167   11.5410   11.0865   11.5725
                31.1167   29.8367   30.9600   14.0025   13.4265   13.9320
                25.2833   24.1633   25.2800   11.3775   10.8735   11.3760
                19.9667   19.1700   20.0600    8.9850    8.6265    9.0270
                17.9733   16.9500   17.8533    8.0880    7.6275    8.0340
                21.0533   19.8467   20.9733    9.4740    8.9310    9.4380
                22.7133   21.5533   22.3533   10.2210    9.6990   10.0590
                14.2600   13.6800   14.2167    6.4170    6.1560    6.3975
                 7.8333    8.1200    7.8233    3.5250    3.6540    3.5205
                 3.2933    3.6833    3.0633    1.4820    1.6575    1.3785
                 2.5667    2.8100    2.2767    1.1550    1.2645    1.0245
                 8.3900    8.4900    8.3567    3.7755    3.8205    3.7605
                 8.1833    8.5633    8.3233    3.6825    3.8535    3.7455
                11.9600   11.7833   12.1900    5.3820    5.3025    5.4855
                15.6400   15.0767   15.6500    7.0380    6.7845    7.0425
                 9.8967    9.6967    9.8567    4.4535    4.3635    4.4355
                 9.5700    9.3300    9.6367    4.3065    4.1985    4.3365
                17.4833   16.8033   17.0933    7.8675    7.5615    7.6920
```

35.5367	34.3500	35.1733	15.9915	15.4575	15.8280
46.2867	44.8000	45.9500	20.8290	20.1600	20.6775
38.4333	37.1333	38.3300	17.2950	16.7100	17.2485
39.6133	38.2333	39.4100	17.8260	17.2050	17.7345
38.3133	36.9467	38.2100	17.2410	16.6260	17.1945
31.4667	30.2600	31.3933	14.1600	13.6170	14.1270
42.4000	40.9867	42.1467	19.0800	18.4440	18.9660
42.2300	41.0067	42.0600	19.0035	18.4530	18.9270
50.4767	49.0533	50.1667	22.7145	22.0740	22.5750
47.1867	46.0767	47.0733	21.2340	20.7345	21.1830
34.2733	33.2900	34.1600	15.4230	14.9805	15.3720
35.7900	34.8733	35.9100	16.1055	15.6930	16.1595
38.2500	36.9933	38.2633	17.2125	16.6470	17.2185
48.4467	47.0167	48.6500	21.8010	21.1575	21.8925
28.0533	27.0500	28.3367	12.6240	12.1725	12.7515
20.0133	19.3900	20.3933	9.0060	8.7255	9.1770
29.5467	28.5567	29.7733	13.2960	12.8505	13.3980
26.7867	25.9400	26.9633	12.0540	11.6730	12.1335
24.3600	23.3933	24.4433	10.9620	10.5270	10.9995
22.4233	21.2067	22.2700	10.0905	9.5430	10.0215
26.9567	26.0133	26.8900	12.1305	11.7060	12.1005
36.5900	35.3233	36.5700	16.4655	15.8955	16.4565
30.4100	29.3233	30.4567	13.6845	13.1955	13.7055
34.5200	33.2500	34.8100	15.5340	14.9625	15.6645
41.2800	39.9367	41.5500	18.5760	17.9715	18.6975
40.6333	39.7967	41.2233	18.2850	17.9085	18.5505
39.7267	38.7900	40.2500	17.8770	17.4555	18.1125
32.3500	31.3000	32.6700	14.5575	14.0850	14.7015
24.8833	24.0467	25.0167	11.1975	10.8210	11.2575
26.0467	25.0467	25.9567	11.7210	11.2710	11.6805
31.2333	30.4600	31.1767	14.0550	13.7070	14.0295
21.6933	20.9500	21.7567	9.7620	9.4275	9.7905
22.6800	21.8300	22.6033	10.2060	9.8235	10.1715
26.0967	25.4233	26.1867	11.7435	11.4405	11.7840
28.1433	27.3967	28.3933	12.6645	12.3285	12.7770
24.5467	23.8067	24.7300	11.0460	10.7130	11.1285
27.2200	26.3733	27.4700	12.2490	11.8680	12.3615
21.0100	20.3833	21.2867	9.4545	9.1725	9.5790
18.5700	17.9033	18.9067	8.3565	8.0565	8.5080
16.3667	15.8300	16.4267	7.3650	7.1235	7.3920
20.6400	20.0300	20.7067	9.2880	9.0135	9.3180
27.2433	26.4700	27.1733	12.2595	11.9115	12.2280
27.8900	27.0500	28.0933	12.5505	12.1725	12.6420
28.1833	27.3467	28.4633	12.6825	12.3060	12.8085
28.9367	28.3200	29.2567	13.0215	12.7440	13.1655
17.0367	16.5533	17.2300	7.6665	7.4490	7.7535
15.5900	15.3533	15.8767	7.0155	6.9090	7.1445
9.8733	9.9533	9.8933	4.4430	4.4790	4.4520
10.7467	10.6600	10.7467	4.8360	4.7970	4.8360
8.3633	8.5033	8.2533	3.7635	3.8265	3.7140
7.0700	7.2100	6.8333	3.1815	3.2445	3.0750
4.7967	5.1167	4.5167	2.1585	2.3025	2.0325
5.7233	6.0633	5.2700	2.5755	2.7285	2.3715
5.6633	6.1333	5.4300	2.5485	2.7600	2.4435
4.9700	5.4467	4.7433	2.2365	2.4510	2.1345
0.9867	1.0933	0.5833	0.4440	0.4920	0.2625
0.9800	1.1000	0.5633	0.4410	0.4950	0.2535
0.9800	1.0967	0.5633	0.4410	0.4935	0.2535

```
                  0.9800    1.1033    0.5633    0.4410    0.4965    0.2535
                  0.9900    1.1100    0.5733    0.4455    0.4995    0.2580
                  0.9900    1.1100    0.5867    0.4455    0.4995    0.2640
                  0.9900    1.1167    0.5733    0.4455    0.5025    0.2580
                  0.9900    1.1167    0.5733    0.4455    0.5025    0.2580
                  0.9933    1.1167    0.5933    0.4470    0.5025    0.2670
                  0.9933    1.1100    0.5933    0.4470    0.4995    0.2670
                  0.9900    1.1100    0.5767    0.4455    0.4995    0.2595
                  3.8767    3.9967    3.4967    1.7445    1.7985    1.5735
                  7.5000    7.9433    7.4333    3.3750    3.5745    3.3450
                  9.1400    9.1833    9.0400    4.1130    4.1325    4.0680
                 18.8133   18.2167   18.8200    8.4660    8.1975    8.4690
                 27.0667   26.0567   26.9267   12.1800   11.7255   12.1170 ];

%             %Load file creation for 24 hours on 15-minute basis with wind
%             %included
L = Node(1:size(Node,1),1:3);
C_Low = [];
C_Med = [];
C_High = [];
MeanDem = mean(AggDem_Norm_1);
S_avg = MeanDem.*S_peak;
for i = 1:length(AggDem_Norm_1)
    Load = [L(1:13,1:3) Node(1:13,4:9).*AggDem_Norm_1(i); L(14:25,1:3)
Node(14:25,4:9).*AggDem_Norm_1(i)];
    Load = [Load; 1000  32  1  LowGen(i,1)  LowGen(i,4)  LowGen(i,2)
LowGen(i,5)  LowGen(i,3)  LowGen(i,6)];
    Load = {Load};
    C_Low = [C_Low;Load];
    Load = cell2mat(Load);
    Load = [L(1:13,1:3) Node(1:13,4:9).*AggDem_Norm_1(i); L(14:25,1:3)
Node(14:25,4:9).*AggDem_Norm_1(i)];
    Load = [Load; 1000  32  1  MedGen(i,1)  MedGen(i,4)  MedGen(i,2)
MedGen(i,5)  MedGen(i,3)  MedGen(i,6)];
    Load = {Load};
    C_Med = [C_Med;Load];
    Load = cell2mat(Load);
    Load = [L(1:13,1:3) Node(1:13,4:9).*AggDem_Norm_1(i); L(14:25,1:3)
Node(14:25,4:9).*AggDem_Norm_1(i)];
    Load = [Load; 1000  32  1  HighGen(i,1)  HighGen(i,4)  HighGen(i,2)
HighGen(i,5)  HighGen(i,3)  HighGen(i,6)];
    Load = {Load};
    C_High = [C_High;Load];
    Load = cell2mat(Load);
end

%Proximity matrix creation
N = max(max(Branch(:,2)), max(Branch(:,4)));
Prox = zeros(N,N);
for i = 1:N-1
    if Branch(i,6) == 1
        Prox(Branch(i,2),Branch(i,4)) = 0.5;
    else
        Prox(Branch(i,2),Branch(i,4)) = 1;
    end
    Prox(i,i) = 1;
end
```

```
Prox(N,N) = 1;

Zline = {N};
    for i = 1:size(Branch,1)
        if Branch(i,6) ~= 1
            Zline{Branch(i,2),Branch(i,4)} =
Branch(i,5)*ftmi*cell2mat(Z(Branch(i,6)-720))./Zb;
        end
    end
```

B.2 Code for Input file used in One-second Analysis

```
%Data Files creation for 3-ph load flow BFS method with wind and storage
%combined in the system - Manoaj Vijayarengan
clear all
clc
tic
Sb = 2500000;
    Vb = 4800;
    Zb = (Vb^2)/Sb;
                            %Load
    %   Node   Renum      Model    kW   kVAr      kW   kVAr      kW   kVAr
Node = [701     2          1        140  70        140  70        350  175
        712     5          1        0    0         0    0         85   40
        713     7          1        0    0         0    0         85   40
        714     9          3        17   8         21   10        0    0
        718     10         2        85   40        0    0         0    0
        720     11         1        0    0         0    0         85   40
        722     13         3        0    0         140  70        21   10
        724     14         2        0    0         42   21        0    0
        725     16         1        0    0         42   21        0    0
        727     18         1        0    0         0    0         42   21
        728     20         1        42   21        42   21        42   21
        729     21         3        42   21        0    0         0    0
        730     22         2        0    0         0    0         85   40
        731     24         2        0    0         85   40        0    0
        732     36         1        0    0         0    0         42   21
        733     26         3        85   40        0    0         0    0
        734     27         1        0    0         0    0         42   21
        735     30         1        0    0         0    0         85   40
        736     29         2        0    0         42   21        0    0
        737     31         3        140  70        0    0         0    0
        738     32         1        126  62        0    0         0    0
        740     34         1        0    0         0    0         85   40
        741     35         3        0    0         0    0         42   21
        742     6          2        8    4         85   40        0    0
        744     19         1        42   21        0    0         0    0    ];


S_peak = [0;0;0];
for i = 1:size(Node,1);
        S_peak = S_peak + 1000.*[Node(i,4)+1j*Node(i,5)
Node(i,6)+1j*Node(i,7) Node(i,8)+1j*Node(i,9)].';
end

                             %Branch
```

```
   %         NodeA  RenumA   NodeB  RenumB   Length(ft.) Config.
Branch = [   701     2        702     3        960          722
             702     3        705     4        400          724
             702     3        713     7        360          723
             702     3        703     17       1320         722
             703     17       727     18       240          724
             703     17       730     22       600          723
             704     8        714     9        80           724
             704     8        720     11       800          723
             705     4        742     6        320          724
             705     4        712     5        240          724
             706     15       725     16       280          724
             707     12       724     14       760          724
             707     12       722     13       120          724
             708     25       733     26       320          723
             708     25       732     36       320          724
             709     23       731     24       600          723
             709     23       708     25       320          723
             710     28       735     30       200          724
             710     28       736     29       1280         724
             711     33       741     35       400          723
             711     33       740     34       200          724
             713     7        704     8        520          723
             714     9        718     10       520          724
             720     11       707     12       920          724
             720     11       706     15       600          723
             727     18       744     19       280          723
             730     22       709     23       200          723
             733     26       734     27       560          723
             734     27       737     31       640          723
             734     27       710     28       520          724
             737     31       738     32       400          723
             738     32       711     33       400          723
             744     19       728     20       200          724
             744     19       729     21       280          724
             709     23       775     37       0            1
             799     1        701     2        1850         721    ];


           % Impedance matrices
z721 = [ 0.2926+1j*0.1973   0.0673-1j*0.0368   0.0337-1j*0.0417
         0.0673-1j*0.0368   0.2646+1j*0.1900   0.0673-1j*0.0368
         0.0337-1j*0.0417   0.0673-1j*0.0368   0.2926+1j*0.1973 ];
     z721 = {z721};

z722 = [ 0.4751+1j*0.2973   0.1629-1j*0.0326   0.1234-1j*0.0607
         0.1629-1j*0.0326   0.4488+1j*0.2678   0.1629-1j*0.0326
         0.1234-1j*0.0607   0.1629-1j*0.0326   0.4751+1j*0.2973 ];
     z722 = {z722};

z723 = [ 1.2936+1j*0.6713   0.4871+1j*0.2111   0.4585+1j*0.1521
         0.4871+1j*0.2111   1.3022+1j*0.6326   0.4871+1j*0.2111
         0.4585+1j*0.1521   0.4871+1j*0.2111   1.2936+1j*0.6713 ];
     z723 = {z723};

z724 = [ 2.0952+1j*0.7758   0.5204+1j*0.2738   0.4926+1j*0.2123
         0.5204+1j*0.2738   2.1068+1j*0.7398   0.5204+1j*0.2738
```

```
         0.4926+1j*0.2123   0.5204+1j*0.2738   2.0952+1j*0.7758 ];
     z724 = {z724};

Z = [z721;z722;z723;z724];

ftmi = 1.8939e-4;




% Transformer matrices
% For D-D transformer (in branch 709-775),
% at = (nt/3)*[2 -1 -1;-1 2 -1;-1 -1 2]
% bt = W*AV*Zabc*G1
% where W = (1/3)*[2 1 0;0 2 1;1 0 2]
%       AV = [nt 0 0;0 nt 0;0 0 nt]
%       Zabc = diagonal(Zab,Zbc,Zca)
%       G1 = (1/(Zab+Zbc+Zca))*[Zca -Zbc 0;Zca Zab+Zca 0;-Zab-Zbc -Zbc 0]
% dt = (1/nt)*eye(3)
% At = (1/(3*nt))*[2 -1 -1;-1 2 -1;-1 2 -1]
% Bt = W*Zabc*G1
nt = 10;
Zab = 0.0009+1j*0.0181;
Zbc = Zab;
Zca = Zab;
W = (1/3)*[2 1 0;0 2 1;1 0 2];
AV = [nt 0 0;0 nt 0;0 0 nt];
Zabc = [Zab 0 0;0 Zbc 0;0 0 Zca];
G1 = (1/(Zab+Zbc+Zca))*[Zca -Zbc 0;Zca Zab+Zca 0;-Zab-Zbc -Zbc 0];
at = (nt/3)*[2 -1 -1;-1 2 -1;-1 -1 2];
bt = W*AV*Zabc*G1;
dt = (1/nt)*eye(3);
At = (1/(3*nt))*[2 -1 -1;-1 2 -1;-1 -1 2];
Bt = W*Zabc*G1;

         %Normalized Load fractions for 15-min divisions from profile 1
AggDem_Norm_1 = [   0.5667
                    0.3805
                    0.4207
                    0.4425
                    0.4138
                    0.4586
                    0.5828
                    0.4057
                    0.4529
                    0.3690
                    0.3655
                    0.4506
                    0.3632
                    0.3080
                    0.4954
                    0.2598
                    0.3908
                    0.3391
                    0.3161
                    0.4540
                    0.3230
                    0.5207
```

0.4977
0.3954
0.4264
0.2966
0.4414
0.3241
0.3851
0.5034
0.4943
0.4138
0.2885
0.5310
0.4126
0.3057
0.5103
0.5241
0.5299
0.6138
0.5276
0.5460
0.8218
0.9080
0.8299
0.8402
0.7586
0.9897
0.7667
0.7989
0.9529
0.7379
0.8080
1.0000
0.7667
0.9126
0.8770
0.8943
0.8149
0.9230
0.9149
0.8690
0.7943
0.8736
0.9598
0.9310
0.9414
0.8782
0.9207
0.7552
0.9069
0.9241
0.7609
0.8552
0.8310
0.7931
0.9954
0.7989
0.8598
0.9471

```
                    0.8977
                    0.9448
                    0.9506
                    0.7816
                    0.8644
                    0.6920
                    0.8529
                    0.7713
                    0.8149
                    0.7494
                    0.7839
                    0.9080
                    0.6460
                    0.7793
                    0.7805
                    0.8414 ];


pmudem = [];
for i = 1:length(AggDem_Norm_1)
    pmudem = [pmudem; AggDem_Norm_1(i) + 0.065.*randn(900,1)];
end

WindGen = [10.25572044  9.80057883  10.33032044 4.615074197 4.410260473
4.6486442
10.28637074 9.783267048 10.1704822  4.628866834 4.402470172 4.576716992
10.46965067 9.722066756 10.32026748 4.7113428   4.37493004  4.644120368
% 86400 lines of data
10.61390701 9.938559808 10.51708218 4.776258154 4.472351914 4.732686981
10.33531363 9.640236161 10.28735141 4.650891136 4.338106272 4.629308135 ];


%            %Load file creation for 24 hours on 1-second basis with wind
%            %included
L = Node(1:size(Node,1),1:3);
C = [];
MeanDem = mean(AggDem_Norm_1);
S_avg = MeanDem.*S_peak;
for i = 1:length(pmudem)
    Load = [L(1:13,1:3) Node(1:13,4:9).*pmudem(i); L(14:25,1:3)
Node(14:25,4:9).*pmudem(i)];
    Load = [Load; 1000  32  1  WindGen(i,1)  WindGen(i,4)  WindGen(i,2)
WindGen(i,5)  WindGen(i,3)  WindGen(i,6)];
    Load = {Load};
    C = [C;Load];
    Load = cell2mat(Load);
end

%Proximity matrix creation
N = max(max(Branch(:,2)), max(Branch(:,4)));
Prox = zeros(N,N);
for i = 1:N-1
    if Branch(i,6) == 1
        Prox(Branch(i,2),Branch(i,4)) = 0.5;
    else
        Prox(Branch(i,2),Branch(i,4)) = 1;
    end
```

```
    Prox(i,i) = 1;
end
Prox(N,N) = 1;
Zline = {N};
    for i = 1:size(Branch,1)
        if Branch(i,6) ~= 1
            Zline{Branch(i,2),Branch(i,4)} =
Branch(i,5)*ftmi*cell2mat(Z(Branch(i,6)-720))./Zb;
        end
    end
```

B.3 Code for Analysis used for fifteen-minute forecasted load data

```
% 3-ph load flow BFS method %% with wind and storage combined in the system
% - Manoaj Vijayarengan
tic
VRes_Low = [];
VRes_Med = [];
VRes_High = [];
IRes_Low = [];
IRes_Med = [];
IRes_High = [];
Iplot = zeros(96,3);
Vplot = zeros(96,3);
P = 800;
Emax = 6000;
Emin = 1200;
E0 = 1800;
E_ess = [E0; zeros(96,1)];
P_ess = zeros(96,1);
State = zeros(96,1);
count = zeros(96,1);
ILoss = zeros(96,1);
% S_batt = [0;0;0];
for m = 1:96
%     Node = cell2mat(C_Low(m));
%     Node = cell2mat(C_Med(m));
    Node = cell2mat(C_High(m));
    V = ones(3,N);
    I = zeros(3,N);
    Inode = zeros(3,N);
    znode = zeros(3,N);
    S = zeros(4,N);

    V_nom = [1; exp(-1j*120*pi/180); exp(1j*120*pi/180)];
    Wind = size(Node,1);
    for i = 1:Wind-1
        S(1:3,Node(i,2)) = 1000*[Node(i,4)+1j*Node(i,5)
Node(i,6)+1j*Node(i,7) Node(i,8)+1j*Node(i,9)].';
        S(4,Node(i,2)) = Node(i,3);
    end
%     % Battery integration
    % % Charging
    % % % Always charging in Free-running mode
%     if E_ess(m)>Emin && E_ess(m)<=Emax && AggDem_Norm_1(m) <= MeanDem
%         State(m) = -1;
```

```
%         %Sustained Average load approach in next 2 lines
% %         P_mains = max([[0;0;0] S_avg -
1000.*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].' - sum(S(1:3,:),2)], [], 2);
% %         P_ess(m) = 0.9*(max(-1*P, (-1.*real(Node(Wind,4)+1j*Node(Wind,5)
+ Node(Wind,6)+1j*Node(Wind,7) + Node(Wind,8)+1j*Node(Wind,9)) -
(1/1000).*real(sum(P_mains,1)))));
%         P_ess(m) = 0.9*(max(-1*P, (-1.*real(Node(Wind,4)+1j*Node(Wind,5) +
Node(Wind,6)+1j*Node(Wind,7) + Node(Wind,8)+1j*Node(Wind,9))))); %This line
only for no mains compensation
%         Elevel = E_ess(m) - P_ess(m)*0.25;
%         if Elevel <= Emax && Elevel > Emin
% %             S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) + P_mains; % This
line only for mains compensation
%             for l = m+1:length(E_ess)
%                 E_ess(l) = Elevel;
%             end
%         else
%             P_ess(m) = 0;
%             for l = m+1:length(E_ess)
%                 E_ess(l) = E_ess(m);
%             end
%         end
%       % % Discharging
%       % % % Optimal Discharging
% %       elseif E_ess(m)>Emin && E_ess(m)<=Emax && AggDem_Norm_1(m) > MeanDem
% %           State(m) = 1;
% %           S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
1000*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].';
% %           count(m) = 0;
% %           Snod = zeros(3,1);
% %           S_crit = zeros(3,1);
% %           for ins = m:96
% % %               Rem = cell2mat(C_Low(ins));
% % %               Rem = cell2mat(C_Med(ins));
% %               Rem = cell2mat(C_High(ins));
% %               Wind = size(Rem,1);
% %               for i = 1:Wind-1
% %                   Snod = Snod + 1000.*[Rem(i,4)+1j*Rem(i,5)
Rem(i,6)+1j*Rem(i,7) Rem(i,8)+1j*Rem(i,9)].';
% %               end
% %               Snod = Snod - 1000.*[Rem(Wind,4)+1j*Rem(Wind,5)
Rem(Wind,6)+1j*Rem(Wind,7) Rem(Wind,8)+1j*Rem(Wind,9)].';
% %               if abs(sum(Snod,1)) >= abs(sum(S_avg,1))
% %                   count(m) = count(m) + 1;
% %                   S_crit = S_crit + Snod;
% %               end
% %           end
% %           S_req = real(S_crit)./count(m);
% %           P_req = 1000.*(E_ess(m) - Emin)/(count(m)*0.25);
% % %           Netload(S_batt,S);
% % %           S_batt = fmincon(@Netload,[-50;-50;-50],[],[],[],[],[-50;-50;-
50],min(S_req./1000,(P_req/(sum(S_req,1))).*S_req./1000));
% %           S_batt = 0.9*min([(P./(sum(S_req,1))).*S_req S_req./1000
(P_req/(sum(S_req,1))).*S_req./1000],[], 2);
% %           S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) - 1000.*S_batt;
% %           P_ess(m) = sum(S_batt,1);
```

```
% %           Elevel = E_ess(m) - P_ess(m).*0.25;
% %           if Elevel <= Emax && Elevel > Emin
% %              for l = m+1:length(E_ess)
% %                  E_ess(l) = Elevel;
% %              end
% %           else
% %              P_ess(m) = 0;
% %              for l = m+1:length(E_ess)
% %                  E_ess(l) = E_ess(m);
% %              end
% %           end
%       % % % Free-running mode
%     elseif E_ess(m)>Emin && E_ess(m)<=Emax && AggDem_Norm_1(m) > MeanDem
%         State(m) = 1;
%         S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
1000*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].';
%         P_ess(m) = 0.9*min(P, (real(sum(sum(S(1:3,:),2) -
S_avg,1)))./1000);
%         Elevel = E_ess(m) - P_ess(m)*0.25;
%         if Elevel <= Emax && Elevel > Emin
%             S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
0.9*(sum(S(1:3,:),2) - S_avg);
%             for l = m+1:length(E_ess)
%                 E_ess(l) = Elevel;
%             end
%         else
%             P_ess(m) = 0;
%             for l = m+1:length(E_ess)
%                 E_ess(l) = E_ess(m);
%             end
%         end
%     else
%         State(m) = 0;
%         S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
1000*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].';
%     end
    %upto here
    S(4,Node(Wind,2)) = Node(Wind,3);
    S(1:3,:) = S(1:3,:)./Sb;
    Iline = {N};


    % Forward sweep
    for i = 1:N
        if sum(Prox(i,:)) == 1 || sum(Prox(i,:)) == 0.5
            V(:,i) = V_nom;
        end
    end
    for i = 1:N-1
        if S(4,N-i+1) == 1
            I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
        elseif S(4,N-i+1) == 2
            znode(:,N-i+1) = (abs(V_nom).^2)./conj(S(1:3,N-i+1));
            I(:,N-i+1) = V(:,N-i+1)./znode(:,N-i+1);
        elseif S(4,N-i+1) == 3
```

```
            Inode(:,N-i+1) = conj(S(1:3,N-i+1))./V_nom;
            I(:,N-i+1) = Inode(:,N-i+1);
        end
        Iline{N-i+1,N-i+1} = I(:,N-i+1);
        if sum(Prox(N-i+1,:)) == 1 || sum(Prox(N-i+1,:)) == 0.5
            for k = 1:N-i+1
                if (Prox(k,N-i+1) == 1 || Prox(k,N-i+1) == 0.5) && k ~= N-i+1
                    Iline{k,N-i+1} = I(:,N-i+1);
                    if Prox(k,N-i+1) == 0.5
                        V(:,k) = at*V(:,N-i+1)*0.1 + bt*I(:,N-i+1)*0.1;
                    else
                        V(:,k) = V(:,N-i+1) + cell2mat(Zline(k,N-
i+1))*cell2mat(Iline(k,N-i+1));
                    end
                end
            end
        elseif sum(Prox(N-i+1,:)) > 1
            Temp = zeros(3,1);
            for j = N-i+1:N
                if Prox(N-i+1,j) == 1 || Prox(k,N-i+1) == 0.5
                    Temp = Temp + cell2mat(Iline(N-i+1,j));
                    if N-i+1~=j
                        if Prox(N-i+1,j) == 0.5
                            V(:,N-i+1) = (at*V(:,j) + bt*I(:,j))*0.1;
                        else
                            V(:,N-i+1) = V(:,j) + cell2mat(Zline(N-
i+1,j))*cell2mat(Iline(N-i+1,j));
                        end
                    end
                end
            end
            for j = 1:N-i+1
                if Prox(j,N-i+1) == 1 && j ~= N-i+1
                    Iline{j,N-i+1} = Temp;
                end
            end
        end
    end
    V(:,1) = V(:,2) + cell2mat(Zline(1,2))*cell2mat(Iline(1,2));

    % Loop for tolerance check of source node
    for n = 1:5
        delV = abs(V(:,1) - V_nom);
        if delV(1)>1e-5 || delV(2)>1e-5 || delV(3)>1e-5
            %Backward Sweep
            V(:,1) = V_nom;
            for i = 1:N
                for j = i:N
                    if (Prox(i,j) == 1 || Prox(i,j) == 0.5) && i ~= j
                        if Prox(i,j) == 0.5
                            V(:,j) = (At*V(:,i) - Bt*I(:,i))*10;
                        else
                            V(:,j) = V(:,i) -
cell2mat(Zline(i,j))*cell2mat(Iline(i,j));
                        end
                    end
                end
            end
```

```
            %Forward Sweep
            for i = 1:N-1
                if S(4,N-i+1) == 1
                    I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
                elseif S(4,N-i+1) == 2
                    I(:,N-i+1) = V(:,N-i+1)./znode(:,N-i+1);
                elseif S(4,N-i+1) == 3
                    I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
                    I(:,N-i+1) = abs(Inode(:,N-i+1)).*exp(1j.*angle(I(:,N-
i+1)));
                end
                Iline{N-i+1,N-i+1} = I(:,N-i+1);
                if sum(Prox(N-i+1,:)) == 1 || sum(Prox(N-i+1,:)) == 0.5
                    for k = 1:N-i+1
                        if (Prox(k,N-i+1) == 1 || Prox(k,N-i+1) == 0.5) && k
~= N-i+1
                            Iline{k,N-i+1} = I(:,N-i+1);
                            if Prox(k,N-i+1) == 0.5
                                V(:,k) = at*V(:,N-i+1)*0.1 + bt*I(:,N-
i+1)*0.1;
                            else
                                V(:,k) = V(:,N-i+1) + cell2mat(Zline(k,N-
i+1))*cell2mat(Iline(k,N-i+1));
                            end
                        end
                    end
                elseif sum(Prox(N-i+1,:)) > 1
                    Temp = zeros(3,1);
                    for j = N-i+1:N
                        if Prox(N-i+1,j) == 1 || Prox(k,N-i+1) == 0.5
                            Temp = Temp + cell2mat(Iline(N-i+1,j));
                            if N-i+1~=j
                                if Prox(N-i+1,j) == 0.5
                                    V(:,N-i+1) = (at*V(:,j) + bt*I(:,j))*0.1;
                                else
                                    V(:,N-i+1) = V(:,j) + cell2mat(Zline(N-
i+1,j))*cell2mat(Iline(N-i+1,j));
                                end
                            end
                        end
                    end
                    for j = 1:N-i+1
                        if Prox(j,N-i+1) == 1 && j ~= N-i+1
                            Iline{j,N-i+1} = Temp;
                        end
                    end
                end
            end
            V(:,1) = V(:,2) + cell2mat(Zline(1,2))*cell2mat(Iline(1,2));
        end
    end

    %Backward Sweep
    V(:,1) = V_nom;
    for i = 1:N
        for j = i:N
            if (Prox(i,j) == 1 || Prox(i,j) == 0.5) && i ~= j
                if Prox(i,j) == 0.5
```

```
                    V(:,j) = (At*V(:,i) - Bt*I(:,i))*10;
                else
                    V(:,j) = V(:,i) -
cell2mat(Zline(i,j))*cell2mat(Iline(i,j));
                end
            end
        end
    end

    VRes = [(1:N)' (abs(V))' (angle(V)*180/pi)'];
    VRes = {VRes};
%     VRes_Low = [VRes_Low; VRes];
    Vplot(m,:) = abs(V(:,32))';
%     VRes_Med = [VRes_Med; VRes];
    VRes_High = [VRes_High; VRes];
    IRes = zeros(N-1,8);
    Loss = zeros(3,1);
    for k = 1:N-1
        IRes(k,:) = [Branch(k,2) Branch(k,4)
(abs(cell2mat(Iline(Branch(k,2),Branch(k,4))))*Sb/Vb)'
(angle(cell2mat(Iline(Branch(k,2),Branch(k,4))))*180/pi)'];
        if k ~= N-2
            Loss = Loss +
real(cell2mat(Zline(Branch(k,2),Branch(k,4))))*((abs(cell2mat(Iline(Branch(k,
2),Branch(k,4))))).^2).*Sb;
        end
    end
    ILoss(m) = sum(Loss,1);
    Iplot(m,:) = Vb*IRes(size(IRes,1),3:5);
    IRes = {IRes};
%     IRes_Low = [IRes_Low; IRes];
%     IRes_Med = [IRes_Med; IRes];
    IRes_High = [IRes_High; IRes];
end
toc
plot(1:96,Iplot(:,1)./1000)
hold on
plot(1:96,HighGen(:,1),'b--')
hold on
plot(1:96,Iplot(:,2)./1000,'r')
hold on
plot(1:96,HighGen(:,2),'r--')
hold on
plot(1:96,Iplot(:,3)./1000,'g')
hold on
plot(1:96,HighGen(:,3),'g--')
title('Individual phase load demand and wind generation')
xlabel('Time in 15 min intervals')
ylabel('Load and wind generation kVA')
axis([0 100 0 1600])
figure(2)
plot(1:96,Vplot(:,1))
hold on
plot(1:96,Vplot(:,2),'r')
hold on
plot(1:96,Vplot(:,3),'g')
title('Individual phase voltage profile for wind node & battery node')
xlabel('Time in 15 min intervals')
```

```
ylabel('Voltage in p.u.')
axis([0 100 0.95 1.05])
figure(3)
bar(1:length(P_ess),P_ess)
title('Battery power charging and discharging')
xlabel('Time in 15 min intervals')
ylabel('Battery power -ve(charging) +ve(discharging) kW')
axis([0 100 -P P])
figure(4)
plot(1:length(E_ess),E_ess)
hold on
plot(1:0.1:length(E_ess),1200,'k')
title('Energy level of battery')
xlabel('Time in 15 min intervals')
ylabel('Battery energy level kWh')
axis([0 100 0 6000])
figure(5)
plot(1:length(ILoss),ILoss./1000)
title('Power loss of the feeder')
xlabel('Time in 15 min intervals')
ylabel('Power loss kW')
axis([0 100 0 80])
figure(6)
bar(1:96,sum(Iplot(:,1:3),2)./(1000*abs(sum(S_peak./1000,1))))
title('Overall 15 minute average normalized feeder load')
xlabel('Time in 15 min intervals')
ylabel('Normalized load factor Lf')
axis([0 100 0 1])
```

B.4 Code for Analysis used for one-second forecasted load data

```
% 3-ph load flow BFS method %% with wind and storage combined in the system
% - Manoaj Vijayarengan
tic
VRes_1s = [];
IRes_1s = [];
Iplot = zeros(86400,3);
Vplot = zeros(86400,3);
P = 800;
Emax = 6000;
Emin = 1200;
E0 = 1800;
E_ess = [E0; zeros(86400,1)];
P_ess = zeros(86400,1);
State = zeros(86400,1);
count = zeros(86400,1);
ILoss = zeros(86400,1);
% S_batt = [0;0;0];
for m = 1:86400
    Node = cell2mat(C(m));
    V = ones(3,N);
    I = zeros(3,N);
```

```
    Inode = zeros(3,N);
    znode = zeros(3,N);
    S = zeros(4,N);

    V_nom = [1; exp(-1j*120*pi/180); exp(1j*120*pi/180)];
    Wind = size(Node,1);
    for i = 1:Wind-1
        S(1:3,Node(i,2)) = 1000*[Node(i,4)+1j*Node(i,5)
Node(i,6)+1j*Node(i,7) Node(i,8)+1j*Node(i,9)].';
        S(4,Node(i,2)) = Node(i,3);
    end
%      % Battery integration
    % % Charging
    % % % Always charging in Free-running mode
    if E_ess(m)>Emin && E_ess(m)<=Emax && pmudem(m) <= MeanDem
        State(m) = -1;
        %Sustained Average load approach in next 2 lines
        P_mains = max([[0;0;0] S_avg - 1000.*[Node(Wind,4)+1j*Node(Wind,5)
Node(Wind,6)+1j*Node(Wind,7) Node(Wind,8)+1j*Node(Wind,9)].' -
sum(S(1:3,:),2)], [], 2);
        P_ess(m) = 0.9*(max(-1*P, (-1.*real(Node(Wind,4)+1j*Node(Wind,5) +
Node(Wind,6)+1j*Node(Wind,7) + Node(Wind,8)+1j*Node(Wind,9)) -
(1/1000).*real(sum(P_mains,1)))));
%          P_ess(m) = 0.9*(max(-1*P, (-1.*real(Node(Wind,4)+1j*Node(Wind,5) +
Node(Wind,6)+1j*Node(Wind,7) + Node(Wind,8)+1j*Node(Wind,9)))));% This line
only for no mains compensation
        Elevel = E_ess(m) - P_ess(m)*(1/3600);
        if Elevel <= Emax && Elevel > Emin
            S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) + P_mains; % This line
only for mains compensation
            for l = m+1:length(E_ess)
                E_ess(l) = Elevel;
            end
        else
            P_ess(m) = 0;
            for l = m+1:length(E_ess)
                E_ess(l) = E_ess(m);
            end
        end
     % % Discharging
     % % % Optimal Discharging
     elseif E_ess(m)>Emin && E_ess(m)<=Emax && pmudem(m) > MeanDem
         State(m) = 1;
         S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
1000*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].';
         count(m) = 0;
         S_crit = zeros(3,1);
         Snod = zeros(3,1);
         for ins = m:86400
             Rem = cell2mat(C(ins));
%              Wind = size(Rem,1);
%              for i = 1:Wind-1
%                  Snod = Snod + 1000.*[Rem(i,4)+1j*Rem(i,5)
Rem(i,6)+1j*Rem(i,7) Rem(i,8)+1j*Rem(i,9)].';
%              end
             Snod = pmudem(ins).*S_peak;
```

```
                Snod = Snod - 1000.*[Rem(Wind,4)+1j*Rem(Wind,5)
Rem(Wind,6)+1j*Rem(Wind,7) Rem(Wind,8)+1j*Rem(Wind,9)].';
                if abs(sum(Snod,1)) >= abs(sum(S_avg,1))
                    count(m) = count(m) + 1;
                    S_crit = S_crit + Snod;
                end
            end
            S_req = real(S_crit)./count(m);
            P_req = 1000.*(E_ess(m) - Emin)/(count(m)*(1/3600));
%             Netload(S_batt,S);
%             S_batt = fmincon(@Netload,[-50;-50;-50],[],[],[],[],[-50;-50;-
50],min(S_req./1000,(P_req/(sum(S_req,1))).*S_req./1000));
            S_batt = 0.9*min([(P./(sum(S_req,1))).*S_req S_req./1000
(P_req./(sum(S_req,1))).*S_req./1000],[], 2);
            S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) - 1000.*S_batt;
            P_ess(m) = sum(S_batt,1);
            Elevel = E_ess(m) - P_ess(m).*(1/3600);
            if Elevel <= Emax && Elevel > Emin
               for l = m+1:length(E_ess)
                   E_ess(l) = Elevel;
               end
            else
               P_ess(m) = 0;
               for l = m+1:length(E_ess)
                   E_ess(l) = E_ess(m);
               end
            end
        % % Free-running mode
%       elseif E_ess(m)>Emin && E_ess(m)<=Emax && pmudem(m) > MeanDem
%           State(m) = 1;
%           S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
1000*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].';
%           P_ess(m) = 0.9*min(P, (real(sum(sum(S(1:3,:),2) -
S_avg,1)))./1000);
%           Elevel = E_ess(m) - P_ess(m)*(1/3600);
%           if Elevel <= Emax && Elevel > Emin
%               S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
0.9*(sum(S(1:3,:),2) - S_avg);
%               for l = m+1:length(E_ess)
%                   E_ess(l) = Elevel;
%               end
%           else
%               P_ess(m) = 0;
%               for l = m+1:length(E_ess)
%                   E_ess(l) = E_ess(m);
%               end
%           end
    else
        State(m) = 0;
        S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
1000*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].';
    end
    %upto here
    S(4,Node(Wind,2)) = Node(Wind,3);
    S(1:3,:) = S(1:3,:)./Sb;
    Iline = {N};
```

```
    % Forward sweep
    for i = 1:N
        if sum(Prox(i,:)) == 1 || sum(Prox(i,:)) == 0.5
            V(:,i) = V_nom;
        end
    end
    for i = 1:N-1
        if S(4,N-i+1) == 1
            I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
        elseif S(4,N-i+1) == 2
            znode(:,N-i+1) = (abs(V_nom).^2)./conj(S(1:3,N-i+1));
            I(:,N-i+1) = V(:,N-i+1)./znode(:,N-i+1);
        elseif S(4,N-i+1) == 3
            Inode(:,N-i+1) = conj(S(1:3,N-i+1))./V_nom;
            I(:,N-i+1) = Inode(:,N-i+1);
        end
        Iline{N-i+1,N-i+1} = I(:,N-i+1);
        if sum(Prox(N-i+1,:)) == 1 || sum(Prox(N-i+1,:)) == 0.5
            for k = 1:N-i+1
                if (Prox(k,N-i+1) == 1 || Prox(k,N-i+1) == 0.5) && k ~= N-i+1
                    Iline{k,N-i+1} = I(:,N-i+1);
                    if Prox(k,N-i+1) == 0.5
                        V(:,k) = at*V(:,N-i+1)*0.1 + bt*I(:,N-i+1)*0.1;
                    else
                        V(:,k) = V(:,N-i+1) + cell2mat(Zline(k,N-
i+1))*cell2mat(Iline(k,N-i+1));
                    end
                end
            end
        elseif sum(Prox(N-i+1,:)) > 1
            Temp = zeros(3,1);
            for j = N-i+1:N
                if Prox(N-i+1,j) == 1 || Prox(k,N-i+1) == 0.5
                    Temp = Temp + cell2mat(Iline(N-i+1,j));
                    if N-i+1~=j
                        if Prox(N-i+1,j) == 0.5
                            V(:,N-i+1) = (at*V(:,j) + bt*I(:,j))*0.1;
                        else
                            V(:,N-i+1) = V(:,j) + cell2mat(Zline(N-
i+1,j))*cell2mat(Iline(N-i+1,j));
                        end
                    end
                end
            end
            for j = 1:N-i+1
                if Prox(j,N-i+1) == 1 && j ~= N-i+1
                    Iline{j,N-i+1} = Temp;
                end
            end
        end
    end
    V(:,1) = V(:,2) + cell2mat(Zline(1,2))*cell2mat(Iline(1,2));

    % Loop for tolerance check of source node
    for n = 1:5
```

```
        delV = abs(V(:,1) - V_nom);
        if delV(1)>1e-5 || delV(2)>1e-5 || delV(3)>1e-5
            %Backward Sweep
            V(:,1) = V_nom;
            for i = 1:N
                for j = i:N
                    if (Prox(i,j) == 1 || Prox(i,j) == 0.5) && i ~= j
                        if Prox(i,j) == 0.5
                            V(:,j) = (At*V(:,i) - Bt*I(:,i))*10;
                        else
                            V(:,j) = V(:,i) -
cell2mat(Zline(i,j))*cell2mat(Iline(i,j));
                        end
                    end
                end
            end
            %Forward Sweep
            for i = 1:N-1
                if S(4,N-i+1) == 1
                    I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
                elseif S(4,N-i+1) == 2
                    I(:,N-i+1) = V(:,N-i+1)./znode(:,N-i+1);
                elseif S(4,N-i+1) == 3
                    I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
                    I(:,N-i+1) = abs(Inode(:,N-i+1)).*exp(1j.*angle(I(:,N-
i+1)));
                end
                Iline{N-i+1,N-i+1} = I(:,N-i+1);
                if sum(Prox(N-i+1,:)) == 1 || sum(Prox(N-i+1,:)) == 0.5
                    for k = 1:N-i+1
                        if (Prox(k,N-i+1) == 1 || Prox(k,N-i+1) == 0.5) && k
~= N-i+1
                            Iline{k,N-i+1} = I(:,N-i+1);
                            if Prox(k,N-i+1) == 0.5
                                V(:,k) = at*V(:,N-i+1)*0.1 + bt*I(:,N-
i+1)*0.1;
                            else
                                V(:,k) = V(:,N-i+1) + cell2mat(Zline(k,N-
i+1))*cell2mat(Iline(k,N-i+1));
                            end
                        end
                    end
                elseif sum(Prox(N-i+1,:)) > 1
                    Temp = zeros(3,1);
                    for j = N-i+1:N
                        if Prox(N-i+1,j) == 1 || Prox(k,N-i+1) == 0.5
                            Temp = Temp + cell2mat(Iline(N-i+1,j));
                            if N-i+1~=j
                                if Prox(N-i+1,j) == 0.5
                                    V(:,N-i+1) = (at*V(:,j) + bt*I(:,j))*0.1;
                                else
                                    V(:,N-i+1) = V(:,j) + cell2mat(Zline(N-
i+1,j))*cell2mat(Iline(N-i+1,j));
                                end
                            end
                        end
                    end
                    for j = 1:N-i+1
```

```
                        if Prox(j,N-i+1) == 1 && j ~= N-i+1
                            Iline{j,N-i+1} = Temp;
                        end
                    end
                end
            end
            V(:,1) = V(:,2) + cell2mat(Zline(1,2))*cell2mat(Iline(1,2));
        end
    end

    %Backward Sweep
    V(:,1) = V_nom;
    for i = 1:N
        for j = i:N
            if (Prox(i,j) == 1 || Prox(i,j) == 0.5) && i ~= j
                if Prox(i,j) == 0.5
                    V(:,j) = (At*V(:,i) - Bt*I(:,i))*10;
                else
                    V(:,j) = V(:,i) -
cell2mat(Zline(i,j))*cell2mat(Iline(i,j));
                end
            end
        end
    end

    VRes = [(1:N)' (abs(V))' (angle(V)*180/pi)'];
    VRes = {VRes};
    Vplot(m,:) = abs(V(:,32))';
    VRes_1s = [VRes_1s; VRes];
    IRes = zeros(N-1,8);
    Loss = zeros(3,1);
    for k = 1:N-1
        IRes(k,:) = [Branch(k,2) Branch(k,4)
(abs(cell2mat(Iline(Branch(k,2),Branch(k,4)))))*Sb/Vb)'
(angle(cell2mat(Iline(Branch(k,2),Branch(k,4))))*180/pi)'];
        if k ~= N-2
            Loss = Loss +
real(cell2mat(Zline(Branch(k,2),Branch(k,4))))*((abs(cell2mat(Iline(Branch(k,
2),Branch(k,4)))))).^2).*Sb;
        end
    end
    ILoss(m) = sum(Loss,1);
    Iplot(m,:) = Vb*IRes(size(IRes,1),3:5);
    IRes = {IRes};
    IRes_1s = [IRes_1s; IRes];
end
toc
plot(1:86400,Iplot(:,1)./1000)
hold on
plot(1:86400,WindGen(:,1),'b--')
hold on
plot(1:86400,Iplot(:,2)./1000,'r')
hold on
plot(1:86400,WindGen(:,2),'r--')
hold on
plot(1:86400,Iplot(:,3)./1000,'g')
hold on
```

```
plot(1:86400,WindGen(:,3),'g--')
title('Individual phase load demand and wind generation')
xlabel('Time in one second intervals')
ylabel('Load and wind generation kVA')
axis([0 90000 0 1600])
figure(2)
plot(1:86400,Vplot(:,1))
hold on
plot(1:86400,Vplot(:,2),'r')
hold on
plot(1:86400,Vplot(:,3),'g')
title('Individual phase voltage profile for wind & battery node')
xlabel('Time in one second intervals')
ylabel('Voltage in p.u.')
axis([0 90000 0.95 1.05])
figure(3)
bar(1:length(P_ess),P_ess)
title('Battery power charging and discharging')
xlabel('Time in one second intervals')
ylabel('Battery power -ve(charging) +ve(discharging) kW')
axis([0 90000 -P P])
figure(4)
plot(1:length(E_ess),E_ess)
hold on
plot(1:length(E_ess),1200,'k')
title('Energy level of battery')
xlabel('Time in one second intervals')
ylabel('Battery energy level kWh')
axis([0 90000 0 6000])
figure(5)
plot(1:length(ILoss),ILoss./1000)
title('Power loss of the feeder')
xlabel('Time in one second intervals')
ylabel('Power loss kW')
axis([0 90000 0 80])
F = sum(Iplot(:,1:3),2)./1000;
figure(6)
plot(1:86400,F)
title('Overall one second actual load of the feeder')
xlabel('Time in one second intervals')
ylabel('Three phase load kVA')
axis([0 90000 0 3500])
F_15 = [];
out = 0;
for i = 1:96
    out = out + 1;
    F_15 = [F_15;mean(F(out:i*900))./abs(sum(S_peak,1)./1000)];
    out = out + 900;
end
figure(7)
bar(1:96,F_15)
title('Overall 15 minute average normalized feeder load')
xlabel('Time in 15 min intervals')
ylabel('Normalized load factor Lf')
axis([0 100 0 1])
Avg_Dem = mean(F_15)
Peak_Dem = max(F_15)
Batt_util = max(E_ess)./Emax
```

B.5 Code for Analysis used for one-second load data based on historical PMU measurements

```
% 3-ph load flow BFS method %% with wind and storage combined in the system
% - Manoaj Vijayarengan
tic
VRes_1s = [];
IRes_1s = [];
Iplot = zeros(86400,3);
Vplot = zeros(86400,3);
P = 200;
Emax = 1500;
Emin = 300;
E0 = 450;
E_ess = [E0; zeros(86400,1)];
P_ess = zeros(86400,1);
State = zeros(86400,1);
count = zeros(86400,1);
ILoss = zeros(86400,1);
Vpmu2 = [];
x = 60;
for m = 1:86400
    Node = cell2mat(C(m));
    V = ones(3,N);
    I = zeros(3,N);
    Inode = zeros(3,N);
    znode = zeros(3,N);
    S = zeros(4,N);

    V_nom = [1; exp(-1j*120*pi/180); exp(1j*120*pi/180)];
    Wind = size(Node,1);
    for i = 1:Wind-1
        S(1:3,Node(i,2)) = 1000*[Node(i,4)+1j*Node(i,5)
Node(i,6)+1j*Node(i,7) Node(i,8)+1j*Node(i,9)].';
        S(4,Node(i,2)) = Node(i,3);
    end
    % Battery integration
    if m <= x && E_ess(m) <= Emax % Preliminary
        State(m) = -1;
        P_ess(m) = 0.9*(max(-1*P, (-1.*real(Node(Wind,4)+1j*Node(Wind,5) +
Node(Wind,6)+1j*Node(Wind,7) + Node(Wind,8)+1j*Node(Wind,9)))));
        Elevel = E_ess(m) - P_ess(m)*(1/3600);
        if Elevel <= Emax && Elevel > Emin
            for l = m+1:length(E_ess)
                E_ess(l) = Elevel;
            end
        else
            P_ess(m) = 0;
            for l = m+1:length(E_ess)
                E_ess(l) = E_ess(m);
            end
        end
```

```
    elseif m > x && E_ess(m) >= Emin && E_ess(m) <= Emax
        S_det = [];
        for ins = m-x:m-1
            Inod = (cell2mat(Zline(1,2)))\(V_nom - (Vpmu2(ins,:)).');
            Snod = V_nom.*conj(Inod).*Sb;
            if P_ess(ins) >= 0;
                S_det = [S_det (Snod +
1000.*P_ess(ins).*real(Snod)./sum(real(Snod),1)) +
1000.*[WindGen(ins,1)+1j*WindGen(ins,4) WindGen(ins,2)+1j*WindGen(ins,5)
WindGen(ins,3)+1j*WindGen(ins,6)].'];
            end
        end
        S_crit = max(S_det, [],2);
        if abs(sum(S_crit,1)) >= abs(sum(S_avg,1)) % Discharging
            State(m) = 1;
            S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
1000*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].';
            S_batt = 0.9.*min([(1000*P.*real(S_crit -
S_avg))./(sum(real(S_crit - S_avg))) real(S_crit - S_avg)],[],2) -
1000.*[WindGen(m-1,1) WindGen(m-1,2) WindGen(m-1,3)].';
            if E_ess(m) <= 0.3*Emax
                S_batt = min([S_batt (0.9*1000.*(E_ess(m) - Emin)/((86400-
m)*(1/3600))).*S_batt./sum(S_batt,1)], [],2);
            end
            if sum(S_batt,1)>0
                P_ess(m) = sum(S_batt,1)./1000;
                Elevel = E_ess(m) - P_ess(m).*(1/3600);
                if Elevel <= Emax && Elevel > Emin
                    S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) - S_batt;
                    for l = m+1:length(E_ess)
                        E_ess(l) = Elevel;
                    end
                else
                    P_ess(m) = 0;
                    State(m) = 0;
                    for l = m+1:length(E_ess)
                        E_ess(l) = E_ess(m);
                    end
                end
            end
        elseif abs(sum(S_crit,1)) < abs(sum(S_avg,1)) % Charging
            State(m) = -1;
            P_ess(m) = 0.9*(max(-1*P, (-1.*real(Node(Wind,4)+1j*Node(Wind,5)
+ Node(Wind,6)+1j*Node(Wind,7) + Node(Wind,8)+1j*Node(Wind,9)))));
            Elevel = E_ess(m) - P_ess(m)*(1/3600);
            if Elevel <= Emax && Elevel > Emin
                for l = m+1:length(E_ess)
                    E_ess(l) = Elevel;
                end
            else
                P_ess(m) = 0;
                for l = m+1:length(E_ess)
                    E_ess(l) = E_ess(m);
                end
            end
        end
    else % Default
```

```
        State(m) = 0;
        S(1:3,Node(Wind,2)) = S(1:3,Node(Wind,2)) -
1000*[Node(Wind,4)+1j*Node(Wind,5) Node(Wind,6)+1j*Node(Wind,7)
Node(Wind,8)+1j*Node(Wind,9)].';
    end
    %upto here

    S(4,Node(Wind,2)) = Node(Wind,3);
    S(1:3,:) = S(1:3,:)./Sb;
    Iline = {N};


    % Forward sweep
    for i = 1:N
        if sum(Prox(i,:)) == 1 || sum(Prox(i,:)) == 0.5
            V(:,i) = V_nom;
        end
    end
    for i = 1:N-1
        if S(4,N-i+1) == 1
            I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
        elseif S(4,N-i+1) == 2
            znode(:,N-i+1) = (abs(V_nom).^2)./conj(S(1:3,N-i+1));
            I(:,N-i+1) = V(:,N-i+1)./znode(:,N-i+1);
        elseif S(4,N-i+1) == 3
            Inode(:,N-i+1) = conj(S(1:3,N-i+1))./V_nom;
            I(:,N-i+1) = Inode(:,N-i+1);
        end
        Iline{N-i+1,N-i+1} = I(:,N-i+1);
        if sum(Prox(N-i+1,:)) == 1 || sum(Prox(N-i+1,:)) == 0.5
            for k = 1:N-i+1
                if (Prox(k,N-i+1) == 1 || Prox(k,N-i+1) == 0.5) && k ~= N-i+1
                    Iline{k,N-i+1} = I(:,N-i+1);
                    if Prox(k,N-i+1) == 0.5
                        V(:,k) = at*V(:,N-i+1)*0.1 + bt*I(:,N-i+1)*0.1;
                    else
                        V(:,k) = V(:,N-i+1) + cell2mat(Zline(k,N-
i+1))*cell2mat(Iline(k,N-i+1));
                    end
                end
            end
        elseif sum(Prox(N-i+1,:)) > 1
            Temp = zeros(3,1);
            for j = N-i+1:N
                if Prox(N-i+1,j) == 1 || Prox(k,N-i+1) == 0.5
                    Temp = Temp + cell2mat(Iline(N-i+1,j));
                    if N-i+1~=j
                        if Prox(N-i+1,j) == 0.5
                            V(:,N-i+1) = (at*V(:,j) + bt*I(:,j))*0.1;
                        else
                            V(:,N-i+1) = V(:,j) + cell2mat(Zline(N-
i+1,j))*cell2mat(Iline(N-i+1,j));
                        end
                    end
                end
            end
            for j = 1:N-i+1
```

```
                if Prox(j,N-i+1) == 1 && j ~= N-i+1
                    Iline{j,N-i+1} = Temp;
                end
            end
        end
    end
    V(:,1) = V(:,2) + cell2mat(Zline(1,2))*cell2mat(Iline(1,2));

    % Loop for tolerance check of source node
    for n = 1:5
        delV = abs(V(:,1) - V_nom);
        if delV(1)>1e-5 || delV(2)>1e-5 || delV(3)>1e-5
            %Backward Sweep
            V(:,1) = V_nom;
            for i = 1:N
                for j = i:N
                    if (Prox(i,j) == 1 || Prox(i,j) == 0.5) && i ~= j
                        if Prox(i,j) == 0.5
                            V(:,j) = (At*V(:,i) - Bt*I(:,i))*10;
                        else
                            V(:,j) = V(:,i) -
cell2mat(Zline(i,j))*cell2mat(Iline(i,j));
                        end
                    end
                end
            end
            %Forward Sweep
            for i = 1:N-1
                if S(4,N-i+1) == 1
                    I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
                elseif S(4,N-i+1) == 2
                    I(:,N-i+1) = V(:,N-i+1)./znode(:,N-i+1);
                elseif S(4,N-i+1) == 3
                    I(:,N-i+1) = conj(S(1:3,N-i+1)./V(:,N-i+1));
                    I(:,N-i+1) = abs(Inode(:,N-i+1)).*exp(1j.*angle(I(:,N-
i+1)));
                end
                Iline{N-i+1,N-i+1} = I(:,N-i+1);
                if sum(Prox(N-i+1,:)) == 1 || sum(Prox(N-i+1,:)) == 0.5
                    for k = 1:N-i+1
                        if (Prox(k,N-i+1) == 1 || Prox(k,N-i+1) == 0.5) && k
~= N-i+1
                            Iline{k,N-i+1} = I(:,N-i+1);
                            if Prox(k,N-i+1) == 0.5
                                V(:,k) = at*V(:,N-i+1)*0.1 + bt*I(:,N-
i+1)*0.1;
                            else
                                V(:,k) = V(:,N-i+1) + cell2mat(Zline(k,N-
i+1))*cell2mat(Iline(k,N-i+1));
                            end
                        end
                    end
                elseif sum(Prox(N-i+1,:)) > 1
                    Temp = zeros(3,1);
                    for j = N-i+1:N
                        if Prox(N-i+1,j) == 1 || Prox(k,N-i+1) == 0.5
                            Temp = Temp + cell2mat(Iline(N-i+1,j));
                            if N-i+1~=j
```

```
                                if Prox(N-i+1,j) == 0.5
                                    V(:,N-i+1) = (at*V(:,j) + bt*I(:,j))*0.1;
                                else
                                    V(:,N-i+1) = V(:,j) + cell2mat(Zline(N-
i+1,j))*cell2mat(Iline(N-i+1,j));
                                end
                            end
                        end
                    end
                    for j = 1:N-i+1
                        if Prox(j,N-i+1) == 1 && j ~= N-i+1
                            Iline{j,N-i+1} = Temp;
                        end
                    end
                end
            end
            V(:,1) = V(:,2) + cell2mat(Zline(1,2))*cell2mat(Iline(1,2));
        end
    end

    %Backward Sweep
    V(:,1) = V_nom;
    for i = 1:N
        for j = i:N
            if (Prox(i,j) == 1 || Prox(i,j) == 0.5) && i ~= j
                if Prox(i,j) == 0.5
                    V(:,j) = (At*V(:,i) - Bt*I(:,i))*10;
                else
                    V(:,j) = V(:,i) -
cell2mat(Zline(i,j))*cell2mat(Iline(i,j));
                end
            end
        end
    end

    Vpmu2 = [Vpmu2; V(:,2).'];
    VRes = [(1:N)' (abs(V))' (angle(V)*180/pi)'];
    VRes = {VRes};
    Vplot(m,:) = abs(V(:,32))';
    VRes_1s = [VRes_1s; VRes];
    IRes = zeros(N-1,8);
    Loss = zeros(3,1);
    for k = 1:N-1
        IRes(k,:) = [Branch(k,2) Branch(k,4)
(abs(cell2mat(Iline(Branch(k,2),Branch(k,4)))))*Sb/Vb)'
(angle(cell2mat(Iline(Branch(k,2),Branch(k,4))))*180/pi)'];
        if k ~= N-2
            Loss = Loss +
real(cell2mat(Zline(Branch(k,2),Branch(k,4))))*((abs(cell2mat(Iline(Branch(k,
2),Branch(k,4))))).^2).*Sb;
        end
    end
    ILoss(m) = sum(Loss,1);
    Iplot(m,:) = Vb*IRes(size(IRes,1),3:5);
    IRes = {IRes};
    IRes_1s = [IRes_1s; IRes];
end
```

```
toc
plot(1:86400,Iplot(:,1)./1000)
hold on
plot(1:86400,WindGen(:,1),'b--')
hold on
plot(1:86400,Iplot(:,2)./1000,'r')
hold on
plot(1:86400,WindGen(:,2),'r--')
hold on
plot(1:86400,Iplot(:,3)./1000,'g')
hold on
plot(1:86400,WindGen(:,3),'g--')
title('Individual phase load demand and wind generation')
xlabel('Time in one second intervals')
ylabel('Load and wind generation kVA')
axis([0 90000 0 1600])
figure(2)
plot(1:86400,Vplot(:,1))
hold on
plot(1:86400,Vplot(:,2),'r')
hold on
plot(1:86400,Vplot(:,3),'g')
title('Individual phase voltage profile for wind & battery node')
xlabel('Time in one second intervals')
ylabel('Voltage in p.u.')
axis([0 90000 0.95 1.05])
figure(3)
bar(1:length(P_ess),P_ess)
title('Battery power charging and discharging')
xlabel('Time in one second intervals')
ylabel('Battery power -ve(charging) +ve(discharging) kW')
axis([0 90000 -P P])
figure(4)
plot(1:length(E_ess),E_ess)
hold on
plot(1:length(E_ess),Emin,'k')
title('Energy level of battery')
xlabel('Time in one second intervals')
ylabel('Battery energy level kWh')
axis([0 90000 0 Emax])
figure(5)
plot(1:length(ILoss),ILoss./1000)
title('Power loss of the feeder')
xlabel('Time in one second intervals')
ylabel('Power loss kW')
axis([0 90000 0 80])
F = sum(Iplot(:,1:3),2)./1000;
figure(6)
plot(1:86400,F)
title('Overall one second actual load of the feeder')
xlabel('Time in one second intervals')
ylabel('Three phase load kVA')
axis([0 90000 0 3500])
F_15 = [];
out = 0;
for i = 1:96
    out = out + 1;
    F_15 = [F_15;mean(F(out:i*900))./abs(sum(S_peak,1)./1000)];
```

```
    out = out + 900;
end
figure(7)
bar(1:96,F_15)
title('Overall 15 minute average normalized feeder load')
xlabel('Time in 15 min intervals')
ylabel('Normalized load factor Lf')
axis([0 100 0 1])
Avg_Dem = mean(F_15)
Peak_Dem = max(F_15)
Batt_util = max(E_ess)./Emax
```