Spatial Distribution of Wind Power Plants To Reduce Variability of Renewable Energy Generation

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Energy Systems

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Abstract

As the penetration of wind power into generation mix increases, the issue of its integration into the power grid becomes more and more important. The variability of wind power generation is a major concern as wind is highly intermittent. This may result in significant overproduction at times, followed by complete unavailability of wind power at other periods. This intermittency must be compensated for by other, conventional generation sources such as coal and gas fired power plants. This reduces the overall efficiency of the system, due to the need to run some generators as spinning reserves, and lowers the overall contribution of renewable generation to the mitigation of greenhouse gas emissions.

This thesis examines the possibility to optimize the spatial distribution of wind power plants over an extended area to decrease the overall variability of wind power generation in a system. A power exchange simulation model was developed to analyze the impacts of different realistic parameters of renewable resources on micro grids exchanging power among themselves and the national grid. The thesis then considers the integration of spatially distributed wind power generation in the wind-rich province of Alberta, Canada. The thesis is then extended to integrate the wind resources of Alberta and British Columbia together. The distribution of power plants is optimized using simulated annealing and quadratic programming. The results clearly show that the variability of wind power generation can be reduced if the wind resources are integrated over a wide geographic area. In this way, a steady average of wind power generation is possible that can reduce the base load requirements and spinning reserves which are necessary for integrating intermittent renewable wind power generation into the grid.

Acknowledgements

I appreciate the support of my supervisor, Dr. Petr Musilek for providing the guidance and tools required to obtain the goals of the thesis.

I am grateful to Dr. Andrew Knight, Dr. Amit Kumar, Dr. Yunwei (Ryan) Li, Dr. Mohammed Tarique and my teachers from whom I have learned a lot in different ways.

I acknowledge Mr. Sohel Bhuiyan, a former graduate from FACIA lab, for guiding me with my work and motivating & assisting me in many ways from the beginning till end.

I thank my lab mate and friend Asher Watts for supporting me throughout the period in my program and making it such an entertaining experience.

I thank my family for sharing this experience with me.

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List of Symbols and Acronyms

T_{init}	Initial local temperature for metropolis criteria
T_{local}	Local temperature for metropolis criteria
ΔE	Temporal variability of wind power generation
A.G.L.	Above Ground Level
AB	Alberta
AC	Alternating Current
AESO	Alberta Electric System Operator
AUC	Alberta Utilities Commission
BC	British Columbia
BPDB	Bangladesh Power Development Board
CCU	Central Control Unit
CHP	Combined Heat and Power
CV	Coefficient of variation
CWEC	Canadian Weather for Energy Calculations
CWEEDS	Canadian Weather Energy and Engineering Data Sets
DC	Direct Current
DESCO	Dhaka Electricity Supply Company Limited
DG	Distributed Generation
DPGS	Distributed Power Generation Systems
EPRI	Electric Power and Research Institute
GW	Giga Watt
HVDC	High Voltage DC Transmission

K	Kelvin
km	Kilo meter
Km^2	Square Kilo Meter
KV	Kilo Volt
m	Meter
MG	Micro Grid
MW	Mega Watt
MWh	Mega Watt Hour
n	Number of locations
N	Total Number
NARR	North American Regional Reanalysis
N_c	Number of iterations
NCAR	National Centers for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NetCDF	Network Common Data Form
NSRDB	National Solar Radiation Database
PCC	Point of Common Coupling
PV	Photo Voltaic
Quadprog	MATLAB Function block of Quadratic Programming
S.A.	Simulated Annealing
SCADA	Supervisory Control And Data Acquisition system
TMY3	Typical Meteorological Year
u	Wind speed component
v	Wind speed component
V	Wind speed

V_r	Wind speed at reference hub height
WT	Wind Turbine
Z	Hub height
Z_r	Reference height
V_z	Wind speed at hub height Z
p	Surface roughness factor

Chapter 1

Introduction

1.1 Introduction

The necessity of electric power in our day to day life has been increasing all over the world. The development of a country is closely related to the availability energy resources it can obtain to generate electricity. The developed countries of the world depend heavily on power generation to meet the everyday demand of common people. The industrial development greatly depends on power generation from several stable different power generation resources. The developing countries of the world are struggling to meet the everyday demand of electric power. They have limited power generation resources. The traditional power generation resources are used extensively to meet the demand of electricity as they are proven technology with a lower cost of conventional fuel. All over the world, the main resources for generating electric power are thermal power plants which are mostly run by fossil fuels. The conventional power plants heavily depend upon fossil fuels like coal to generate electricity. Natural gas is another form of fossil fuel which is used to generate electricity. Power generation from fossil fuels produce greenhouse gasses which is one of the main reasons of global warming. Carbon-di-oxide is one of the main greenhouse gasses which traps the heat in the atmosphere and increases the temperature of the atmosphere. As the necessity of electricity is increasing all over the world, the electrical power generation from fossil fuels is also increasing everyday which is worsening the global warming scenario. The ice caps in polar area are melting. This is causing the sea levels to rise. A lot of the low lying countries, like Bangladesh, are in danger of losing a huge amount of land due to the rise of sea levels which is caused by global warming. The global warming is also causing the climate to change all over the world. The change of climate is quite obvious in different parts of the world with visible deviations in different seasons and climatic events. The impact of climate change is huge. There have been a lot of climatic catastrophic events in recent years. The change in climate also has a mammoth impact on the ecosystem. Different species all over the world are becoming extinct due to the impact of climate change. The dependency of electric power generation from conventional fossil fuels which produces greenhouse gas emissions and causes global warming is one of the main reasons behind this. Still, the ever growing population of the world comprehensively relies on fossil fuels for electric power generation as the fossil fuels are easily available and the technology associated with it has been there for ages. This is also a very inexpensive and easy way of generating electricity which is an imminent requirement in everyday life. The fossil fuels are non-renewable energy resources which means there is a finite amount of fossil fuels available. The search for renewable energy resources to generate electricity is one of the most important issues of today's world.

The renewable energy resources are abundant. They do not produce greenhouse gasses. Even though the power generation from renewable resources can have an impact on nature, it can assists in improving the global warming scenario. Electric power generation from renewable resources like wind and solar are quite popular. There is a growing demand for power generation from renewable resources. Compared to the conventional power generating plants, the power generation from renewable resources are more expensive. The technology associated with it is comparatively new and more complicated. There are a lot of issues that need to be dealt with while generating power from renewable resources. The renewable energy resources like solar and wind are inherently intermittent. It is difficult to have a perfect forecast of the availability of wind or solar radiation for a given period. Wind and solar radiation are also quite variable compared to fossil fuels as the availability of fossil fuels is easier to predict. As a result, even though power generation from renewable resources can be included in the power system to reduce the base load of power generation from fossil fuels, the integration of power generation from renewable resources can also increase the quickly dispatchable reserve capacity of power generation from readily available fuel resources to cope up with the inherently intermittent nature of renewable resources. It would be very helpful if the variable nature of power generation from renewable resources like wind can be reduced. This will significantly assist the power system to integrate more power generation from renewable resources. There are several other technical and financial challenges of including renewable power generation. There have been a lot of research and development going on the technologies of renewable power generation to make it easily deployable and to reduce the cost and complexity of the technology. The scheduling of renewable power generation with system demand is also very important. As renewable resources generate electricity when they are available, the energy storage becomes a big issue so that this power can be used during peak demand even though if the power generation was during off-peak hours. Renewable resources are widely distributed. They may not be available near the load centers. As a result, the transmission of generated renewable power to the load centers is a big issue. There are several technics under research to optimize the performance of renewable power generation. Integrating renewable resources over a spatially distributed wide area to reduce the variability of renewable power generation can be one of the technics.

Canada is a country with the largest area in America. It has a huge area with ten provinces and three territories. Alberta is one of the provinces in Canada. According to Wikipedia, it is Canada’s fourth most populous province and the most populous province among the three prairie province. It shares its border with British Columbia to the west. There is the Rocky Mountain Range in between Alberta and British Columbia which creates an interesting wind profile. Other than the Rockies in the west, the rest of Alberta is quite flat. Alberta is a province with a lot of industrial growth. It has the oil sands industry in the north east side of the province. The southern part of the Alberta province is the place with more population.

There has been a steady growth in installed generation capacity in Alberta. Since 1998, over 7,400 MW of new generation capacity have been installed in Alberta [1-4]. At present, the installed generation capacity of Alberta is 14,003 MW [1-4]. The installed generation capacity is mainly made up of coal and gas power generation plants. There is 5,690 MW of coal and 5,784 MW of gas power plants in the province [1-4]. So, coal power plants is about 40.63% of total installed capacity whereas gas power plants are of 41.31% of installed capacity. As of November 2013, wind power plants are the third major player in installed capacity in Alberta with 1,113 MW of installed capacity which is about 8% of total installed capacity [1-4]. The rest of the installed generation capacity are mainly composed of hydro with 900 MW and biomass with 418 MW which is about 6.5% and 3% of installed capacity for hydro and biomass respectively [1-4].

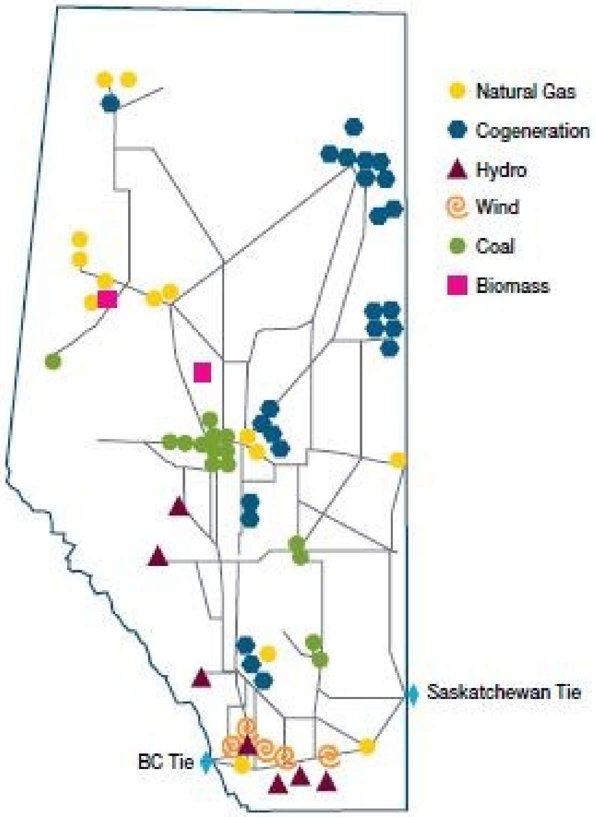

Figure 1-1: Alberta's Electric System: Generation and Transmission [5]

The British Columbia and Saskatchewan are the two provinces on the west and east side of Alberta respectively. Alberta has a total 900 MW of interconnections capacity with these two provinces as well [3]. 83% of the interconnection capacity, which is 750 MW, is with British Columbia. There is a 500 KV tie line and a 138 KV AC tie line between Alberta and British Columbia [6]. There is 150 MW of interconnection capacity which is 17% of total interconnection capacity of Alberta with British Columbia and Saskatchewan [3]. Alberta is connected to Saskatchewan with a back-to-back HVDC tie line [7].

The power flow in Alberta can be narrowed down to four main pathways using figure 1.1. The central part of Alberta near its capital Edmonton has lots of coal power plants and the southern part, the industrial capital is Calgary with huge population. There is a major power flow from these coal fired power plants situated in the center of Alberta to the southern part of Alberta. The power flows from the central coal power plants of Alberta to the northwest part of Alberta as well. The oil sands industry is situated in the northeast part of Alberta. There are lots of cogeneration power plants there which transports power to the north central part of Alberta. The southern part of Alberta has lots of wind power plants which provide power to the southern part of the province. Using the transmission ties with British Columbia and Saskatchewan provinces, Alberta is the net importer of electrical energy [6]. The industrial capital Calgary imports electrical power from the British Columbia during peak hours and exports power to British Columbia during off-peak hours [6].

Alberta province had a peak demand of 10,599 MW in year 2012. This is 10 MW less than the peak demand in year 2011. The average pool price was $ 64.32 per MWh in year 2012. This is $11.9 lower compared to the average pool price of year 2011 [1-4]. The peak demand usually occurs during winter in Alberta. There are a number of proposed generation projects. There are 29 projects with renewable energy resources which would have a capacity of about 3,000 MW [1-4]. The thermal and other power generation plants have 43 proposed projects which results to a total capacity of about 9,400 MW [3, 9]. Wind power plants consist most of the renewable power generation projects. There have been an intense interest regarding wind power in Alberta. The southern part of the province of Alberta has very good wind resources and most of the wind farms are situated there. In 2011, there have been 15 wind power farms which were connected to the grid of Alberta [10]. More wind farms are proposed to be installed which means an increased percentage of total power of grid will be supplied by wind power. Micro generation from renewable resources which generates power in the range of 1 MW or less, are also becoming very popular in Alberta [10]. Alberta Utilities Commission reported that in year 2009, the installed capacity of micro generation was 428 KW which increased to 1,318 KW in 2011. The number increased to 2,325 KW by June 2012. So, in less than three years, there have been 1,897 KW of additional installed capacity of micro generation [10]. So, there can be a good prospect for integration of power generation to the grid from distributed small scale renewable resources in Alberta.

1.2 Objective of the Thesis

Conventional power generation from fossil fuels is causing global warming and climate change. Renewable power generation assists to reduce these catastrophic long term effects as well as help the power grid to meet the ever increasing demand. However, the integration of renewable power generation to the existing grid has to meet different challenges. This thesis provides a brief overview on some of the challenges of integrating renewable power generation to the existing power system. The thesis then presents a method of power exchange algorithm. With this method, the advantages of exchanging generated power among the micro grids will be observed. The goal of this work is to find out whether exchanging power among micro grids and the national grid reduces the base load requirement of the national grid. It will be also observed whether generated power from micro grids are utilized to its maximum potential by sharing the generated power among the group of micro grids. The thesis will then focus on wind as renewable resources of energy and observe the variability of wind. The climatological data and yearly weather data will be used to observe the variation of wind power of one location in different time periods. Then the thesis will focus on reducing the variation of wind power generation by distributing wind resources over the province of Alberta as well as over the province of Alberta and British Columbia together. To observe the impact of integrating wind resources over a spatially distributed wide area on reducing the variability of wind power generation is the main focus of the thesis. It will be observed whether this type of integration of spatially distributed wind resources can generate a less variable wind power which can assist the grid to reduce its base load requirement by consuming more power from wind resources. In this way, base load power generation from fossil fuels as well as the reserve capacity which is required for inherently intermittent renewable power generation can be reduced and conventional power generation can be assisted more with renewable power generation to meet the ever increasing demand. By this way, the greenhouse gas emission can be reduced which can significantly improve the global warming and catastrophic climate change scenario.

1.3 Methodology

To discuss the challenges of integrating renewable energy resources, several journals papers, conference papers, articles etc. are required to be reviewed. The technical issues like forecasting, energy storage, transmission of power etc. as well as the financial issues are needed to be discussed.

A brief overview on distributed generation is also provided in the thesis before proposing the power exchange system for micro grids. The power exchange algorithm follows the basic principle of exchanging the micro grid generated power among the group of micro grids first before exporting the excess power to the national grid. The power generation and internal load data of Alberta is used for this algorithm. Using the power generation and internal load data of Alberta from Alberta Electric System Operator (AESO), user provided number of representative sample micro grids with generation and demand data is created using a MATLAB simulation model. When a micro grid generates more power than its demand, it will provide the excess power to all other micro grids in the group which need power and then export the rest of the excess power to the national grid. The micro grids that cannot meet their demand by their own generation will import power from all the micro grids in the group which are generating more power than their own demand before importing power from national grid. The impact of increasing number of micro grids, variable capacity of demand and generation, intermittency of renewable power generation etc. on the power exchange system has been observed. The results are analysed in terms of capability of reducing base load, maximizing the usage of generated power among the group of micro grids and in terms of economic loss. The power exchange system model is designed to observe the advantages of sharing the micro grid generated power which can reduce the dependency on national grid.

Wind is a renewable energy resource which is inherently intermittent. As a result, the wind power generation can be highly variable as well. The variability of wind power in same location in different time periods have been observed using the climatological data and yearly weather data. Climatological data is based on historical data which provides a rough idea on the different aspects of weather conditions for one location for one year. The weather data is the actual observations of different weather conditions for a location for a given period. At first, the data is pre-processed to the required format and wind speed is calculated. Then the wind speed in the required hub height region is calculated. Then using Vestas V90 3 MW VAS wind turbine model, the wind speed is converted to wind power. The climatological data and the weather data is compared. The results are represented with graphs and box plots to show the variability of wind resources of same area in different years compared to the climatological data.

The possibility of reducing the variability of wind power generation and reducing the base load requirement from national grid by integrating wind resources over spatially distributed wide area is analysed. The North American Regional Reanalysis database is used here. The data of Alberta and British Columbia wind resources are collected and pre-processed to calculate wind speed at the 80 m above ground level (a.g.l.) as the hub height of Vestas V90 3 MW VAS wind turbine is 80 m. The wind power is generated using this model. To reduce the variability of wind power generation, the locations of Alberta are considered first. Two optimization techniques are followed here. The location optimization is used to find out location that produces the wind power with least temporal variability. The simulated annealing (S.A.) algorithm is used. At the same time, the optimization of turbine allocation with quadratic programming function block of MATLAB is used for the optimized distribution of turbines in the locations to generate wind power with least temporal variability. The balance of exploration and exploitation is ensured with metropolis criterion. The results are compared with uniform distribution of turbines. Similar simulations are performed by taking the wind resources of Alberta and British Columbia together. The results are evaluated using several evaluation parameters. The focus of the work was to observe whether integration of wind resources over a distributed area can reduce the inherent intermittency of wind resources and generate wind power at a lower variability which will ensure more wind power consumption by the grid with reduced reserve capacity which is required for variable renewable generation and hence the base load requirement of national grid is reduced or not.

1.4 Structure of Thesis

The first chapter introduces the thesis with general information, objective and the methodology of the thesis.

The second chapter provides a brief overview of challenges of integrating renewable energy resources with the existing power system.

The third chapter proposes a power exchange system model to observe the impact of several practical parameters on the power exchange model in a realistic environment which can be used to represent the advantages of exchanging generated power by micro grids within the group of micro grids.

The fourth chapter represents the variability of wind power with climatological data and yearly weather data with graphs and box plots.

The fifth chapter discusses the ability of integrating spatially distributed wind resources over a wide area to reduce the temporal variability of wind power generation as well as reducing the base load requirement of national grid.

The sixth chapter provides the conclusion of the thesis with contribution and future recommendations of the work.

Chapter 2

Challenges of Integrating Renewable Resources to Existing Grid

2.1 Introduction

The increasing demand of electricity along with the growing demand of environment friendly power generation is encouraging the growth of power generation from renewable resources. As different generation resources and technologies need to be integrated in the electric power grid in order to transmit electricity to the users in an efficient and safe method, many aspects need to be considered. This chapter describes the different challenges of integrating renewable resources into existing power grid.

The growing demand for energy and efforts to restrict environmental pollution are some important reasons that triggered intense worldwide searches for renewable and green energy sources as they provide lower emissions of environmentally harmful substances. The necessity and importance of an energy market that consists of diversified generation sources and efficient delivery mechanism has been realized by leaders in industry, government and academic world. As diversified generation ensures the safety and freedom of energy supply, the optimal, safe, and reliable delivery of power is ensured by diversified transmission technologies [11]. The integration of renewable resources (like solar and wind) into traditional electric power grid can bring a number of technological challenges in the current system design and operation practices [12]. The focus of this chapter is to identify the issues of integrating renewable power into an existing grid.

2.2 Renewable Energy Resources

The term renewable energy usually refers to the generation of electricity from natural sources such as sunlight, wind, geo-thermal heat, wave or tidal energy, running water etc. The Pembina Institute reports that renewable energy usually has two common characteristics. The first characteristic is to ensure that the power generation from renewable resources does not affect the ability of future generations to access efficient and affordable electricity. The second characteristic is to ensure the protection of human health and environmental quality [13]. The renewable generation resources can be categorized into two types: non-dispatchable generation resources and turbine-based generation resources. When the fuel source is naturally variable by nature (like wind, solar, wave, tidal power etc.), it can be termed as non-dispatchable generation source. When resources use different means to rotate turbine based generators, they are termed as turbine-based generation sources [14]. Renewable resources can represent a solution for energy poverty and a feasible model for sustainable energy strategies that enables reduction of carbon dioxide emissions and thus contribute to the slowing down of the global temperature rise.

2.3 Issues with Traditional Power Grid

The traditional power grid is a rigid system that lacks flexibility in power source and transmission. A real time configuration is very difficult to implement in the existing system. The SCADA (Supervisory Control And Data Acquisition system) is used in traditional system which takes samples in every 2 to 4 seconds [11]. Sometimes it includes stain data which may lead to an error in state estimation. This causes poor visibility of traditional systems [11]. As there are high intermittency and uncertainty associated with renewable resources like wind and solar power, the integration of large-scale stochastic renewable resources would increase the uncertainty of existing grid system. This would make a risk assessment process more complicated. Self-healing and self-recovery capabilities of the traditional grid are also weak. It does not have two way interactive communications and thus does not allow the user to be an active part of the system. Hence many potential benefits of optimized power operation, such as price responsive demand reducing program, faster protection technology etc., cannot be fully utilized [11].

2.4 Challenges of Integrating Renewable Resources within Existing Grid

There are some challenges of integrating renewable resources within an existing power grid. The main challenges include location of renewable energy resources, fluctuation and variation in their availability, difficulty of forecasting, confidence level in the forecast, storage of energy, long distance transmission, security and safety issues, different policy proposals reflecting regional issues and concerns.

2.4.1 Forecast

While discussing the planning and operation of power grid, the difference between variability and uncertainty should be distinguished first. The variability means the change of generation output due to fluctuation of wind or sun. Uncertainty is the inability to predict the timing and magnitude of the changes in the generation output in advance. Forecasting actually targets to accommodate the variability more accurately by reducing the uncertainty of generation output [15].

The variability of power demand is comparatively easier to predict as it can be estimated based on weather forecasts, historical data, major events etc. However, the renewable generation usually do not follow any regular or daily pattern [16]. For solar power, there is around 70% variability due to passing clouds whereas, for wind, variability becomes 100% in calm days [16]. The forecasting accuracy is also at immature state [16]. Figure 2.1 shows three forecasts for wind power in Alberta Electric System Operator (AESO) wind generation system. Forecast one predicted the evening high wind power generation whereas forecast three predicted the very early low wind power generation to some degree of accuracy. Forecast two predicted very early morning low generation and late night high generation. Only one of the three forecasts, which is forecast three, predicted the four hour morning lull. However, none was able to predict the total range of variability [16]. So, there can be a significant difference in the amplitude and phase (timing) of the actual and forecasted wind power generation.

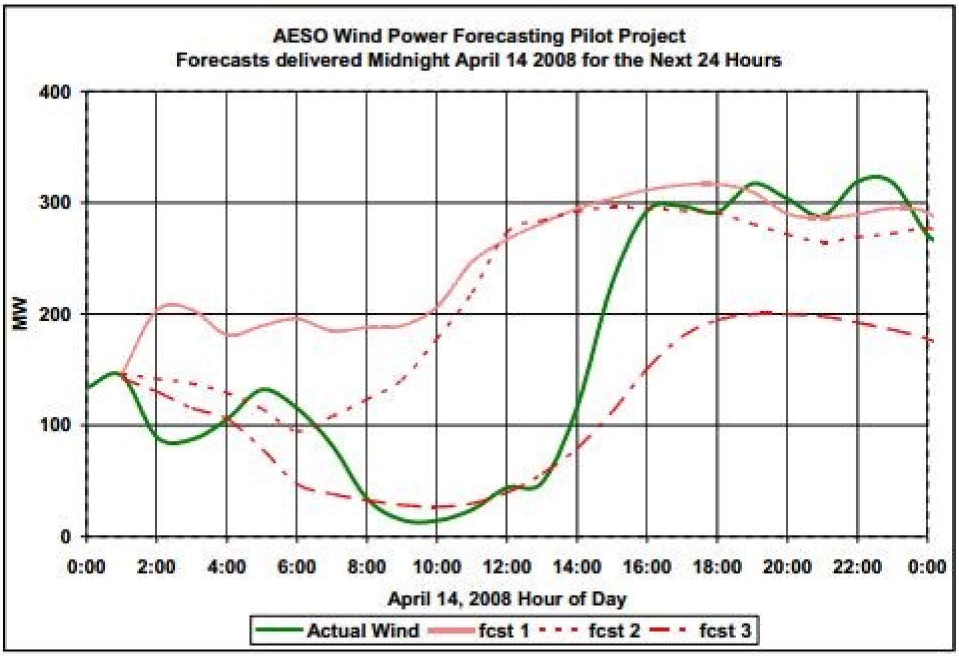

Figure 2-1: AESO wind power forecasting pilot project [16]

Integrating this variability of renewable resources on the grid is highly challenging. To accommodate this variability and to maintain the reliability of grid, the system operators quickly ramp reserves of dispatchable resources like natural gas turbines or hydroelectric power plants [15]. Increased quality of forecast means reduced reserve capacity requirement and costs. A study shows that it was necessary to add 9% reserve requirement to accommodate a 15% wind penetration [17]. Figure 2.2 shows the required ramping capacity for different systems. With red, it is assumed that all the load is supplied using conventional fuel sources. When all the demand is met using only conventional load, the daily ramping capacity required is around 4,500 MW (ramping required from 9,600 MW to 14,100 MW). When wind is integrated in the system, the required ramping capacity is shown with blue. When the wind is integrated in the system, the ramping is required from 7,000 MW to 13,600 MW. This happens as wind power generation increases during off-peak hours rather than peak hours. So the required ramping capacity is 6,600 MW when wind power generation is added to the system. This means that the ramping capabilities need to be increased by 46% when wind generation is introduced, compared to the normal capability [16].

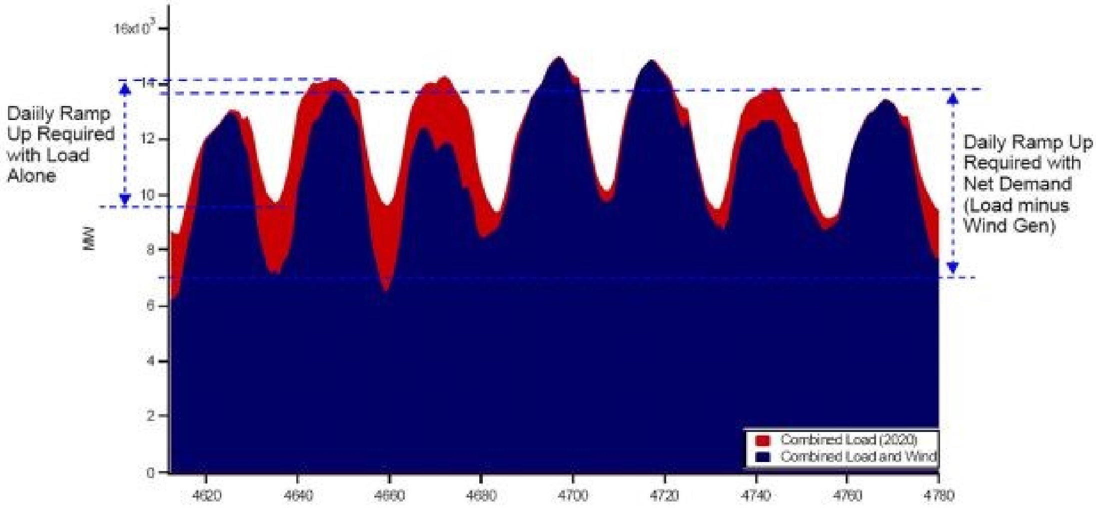

Figure 2-2: Variable generation can increase system flexibility needs [16]

Due to generation variability, two major scenarios occur which are needed to be handled very carefully. These are the up ramp of renewable generation at times of low demand and down ramp of renewable generation at times of high demand. For the first case, renewable generation might be high when there is a low demand. So, there is higher power generation compared to the demand. At this scenario, the base load from conventional or renewable generation needs to be turned off to accommodate the low demand. This is inefficient, costly and causes reliability issues. For the second case, there may not be enough power generation from renewable resources during high demand. In this scenario, most of the traditional generations may already be turned on to meet the high demand. So it leaves few options to compensate the power lost due to renewable down ramps. So the accuracy of the forecast of renewable generation is very important to maintain an efficient scheduling of power generation resources [15].

The confidence level of an operator about a forecast is as important as forecast accuracy. Lower confidence level requires the operator to maintain a higher reserve even if the forecast is for steady output.

The accuracy and confidence level, as well as maintaining the equilibrium between generation and load, can be improved by aggregation of renewable resources over a wider area. An analysis shows that the forecasting error can be reduced by 42% for a typical German forecast over around 1,000 km distance [18]. The difference in local demand and supply can be balanced by a distant renewable resource which can be located in another region. As a result, the cost of using the conventional reserve can be reduced [15]. This key finding is one of the motivations for this thesis which will be discussed in chapter 5. When power generation is integrated from distant renewable resources, long transmission lines become a key feature. Long transmission lines are required to implement interconnection among distant renewable resources. Along with it, correlated and accurate forecasts need to be coordinated by a governing body. Such coordination is not currently in place [15].

Weather forecast needs to be converted into the forecast of power generation. By achieving an improved forecast with higher degree of confidence, the system operators will be able to manage the power generation scheduling more precisely. Better forecast of renewable power generation can reduce the base load requirement as well as it can assist to reduce the operating reserve from conventional fuel. This can be done using complex combinations of a physical model, statistical analysis, artificial intelligence based learning system and other components. Human forecaster can sometimes add more value in forecasting events based on pattern and features. So, the experience of the operator in analyzing the risks and uncertainty and taking mitigating actions based on these is also an important challenge of integrating renewable energy in the grid [15].

2.4.2 Issues Related to Dispatch of Generation Resources

Issues with voltage instability and voltage flicker need to be taken care of while dispatching generation resources. Voltage instability is a main concern for dispatching generation resources. The output voltage of the generation resources must be equal to the grid operating voltage while interconnecting renewable resources at the point of common coupling (PCC). Instability in the grid can be caused if there is a difference between these two voltages [12].

Voltage flicker is the sudden fluctuation of voltage which can cause noticeable inconvenience for the grid. For wind power, it can be observed when wind turbines are switched on or off. This happens due to changes of wind speed outside the operating range [12].

2.4.3 Issues Related to Wind Turbines

Voltage sags can be produced by wind turbines as they draw a large amount of inrush current while they start to rotate. This current is drawn from grid and can be 2 to 3 times larger than the machine rated current which causes voltage sags [12].

Tripping of turbines can have a direct impact on stability. There can be a sudden generation loss due to tripping of turbines. This might start a major cascading outage event [12].

2.4.4 Energy Storage

The variability of renewable resources is currently compensated by dispatchable conventional fuel sources. But as the penetration of renewable resources grows, the necessity to balance the mismatch between variation of renewable generation and power demand also increases. Thus, the energy generated from renewable resources needs to be captured and stored for future use. Storage helps smoothing the fluctuations of renewable resources like solar and wind which are inherently intermittent [19].

Grid level storage or utility level storage includes different technologies like batteries, pumped storage hydroelectric power, compressed air electric storage, flywheels etc. Such technologies store energy on the grid so that it can be dispatched when needed. The storage improves the reliability and resilience of grid. Short term storage is used for peak shaving while long term storage is used for load shifting [19].

The grid storage requires high capacity and longer lifetime. Also, the grid storage lacks sufficient regulatory history. The utility-scale basis storage is also very uncommon. It is usually limited to site-specific projects except for pumped hydroelectric storage. A lot of research and development is needed to make these technologies more efficient, cost effective and widely accepted. Currently there is no widely accepted policy guiding how investments in storage will be treated and how the costs will be recovered. Due to these uncertainties, there is a lack of interest in investing in grid-scale storage. This hampers the development of the entire energy storage field [19].

Plug in hybrid vehicles is a storage concept where energy is stored on board of electric or hybrid vehicles. These vehicles are distributed storage options that will be available to grid while they are plugged in and recharging. The capability of discharging energy back to the grid by these vehicles improves the grid utilization, reliability and levels the energy demand.

The challenge is how to synchronize the period when vehicles should be charged, while there is available generation from renewable resources. For example, plug in vehicles can be used in areas where there is strong wind power available during night time so that vehicles can be plugged in to be charged. During peak load, the owners of the vehicles can plug in the vehicles so that energy can be discharged to the grid. But if the vehicle charging schedule does not match the daily renewable generation cycle, the mismatch can create even more problems [15].

2.4.5 Issues Related to Transmission

Conventional power grids are usually designed to serve the local and regional customers with local and regional generation. The renewable resources are, on the other hand, usually distributed over a wide area. Most of the times, the large-scale renewable resources are located in remote areas, away from the load centers. Aggregation of renewable resources over a large area can improve the quality of forecasts thus ensuring better stability of renewable generation [17]. As a result, the need for long distance transmission lines increases. Transmission systems can capture renewable generation from distant locations and deliver generated energy to load centers that may be also situated far apart. This way, long distance transmission lines actually provide the interconnection among different resources across the country [20]. The challenges associated with their use for renewables integration is exacerbated by a historically low investment in the transmission. From 1988 to 1998, electricity demand increased by 30% in the USA alone, while transmission grew only by 15%. From 1999 to 2009, demand increased by 20% while transmission grew only 3% [15].

There are many challenges that system planners are facing while expanding the transmission lines to integrate different type of resources to the grid. There is a lack of comprehensive regional planning to interconnect different regions with the transmission lines. Cost allocation rules for transmission investment is also very complex. There are not sufficient financial incentives for transmission developers. In addition, there is uncertainty about when and how the cost can be recovered in wholesale and retail rates [21]. Due to the expansion of urbanization, cities are getting more congested and this makes it more difficult to install new overhead transmission lines to carry the generated power to the end user.

Electric power is proportional to the product of voltage and current whereas, power loss is proportional to square of current. So, common practice is to increase the voltage to reduce the amount of current in transmission lines to reduce losses. Different technologies exist for long distance transmission to provide better efficiency. The High Voltage DC Transmission (HVDC) is one such technology that is at a stage of maturity. The largest HVDC project, the Xiangjiaba line terminating in Shanghai, China, operates at 800KV and delivers 6GW power over 2,000 km [22]. The problem of HVDC transmission is that it requires single point of origin and termination. So collecting power from wide area becomes difficult. Losses in these transmission lines can be as high as 10% [12]. It requires expensive and complicated technology for AC-DC-AC conversion. In addition, such systems requires large towers which reduces their aesthetic appeal and thus acceptability by the public. It also requires a long time to get permission from all the relevant regulation zones [22].

Another new technology is underground super conducting DC transmission lines which can carry almost 5 times more current [15]. There are almost no losses as the lines operate close to zero resistance [15]. These lines require no conversion, maintain transient and short term voltage stability, and their multi-terminal entrance and exit ramps can collect power from different renewable resources and deliver it to different locations.

Recent feasibility studies by EPRI (Electric Power and Research Institute) shows that superconducting DC transmission lines can carry10 GW power over 1600 km [15]. The problem of this technology is that the transmission lines need to be refrigerated to 72K to maintain superconductivity [15]. Technological development is required to maintain such temperature as well as to reduce associated costs.

Long transmission lines improve the reliability of renewable generation in terms of variability and fluctuations by providing opportunity to accommodate different types of resources and loads to be connected over a wide area. This way, generation excesses and deficits across the country can be anticipated by forecasting and matched over long distance to balance the system. It also reduces the cost of conventional reserves. But complexity of many generation resources and load centers eventually limits the size of balancing area [15]. The distributed generation (DG) and Micro-Grids concepts require better transmission facilities to be implemented. The challenges of including these small scale renewable resources into grid using transmission lines are numerous. Existing transmission lines may be inaccessible or of insufficient capacity to carry the excess electricity. The different pricing mechanism over different regions and utilities can also hamper power transmission over longer distances. High infrastructure cost is a major issue. The difficulty in scheduling accuracy also puts renewable resources in a disadvantage [21].

2.4.6 Issues with Communication

The existing power systems mostly use only one way communication. It lacks the interaction with the user. Here, the generation, transmission and user sides are only concern with their own bodies. Power generation is concerned with power plant safety and operation. Transmission operators emphasize the stability of the power grid. Users are concerned with their own power stability. But if all these players worked together, the risks would be reduced and outages could be prevented [11]. For this to happen, two way communications is required. With this two-way communication, the demand side information can be updated real time which will allow the control center to have updated information about the load. Control center can predict demand with higher accuracy and hence schedule the generating units to reduce loss. It will also allow the protection schemes to work faster and help the grid become self-healing. With better measurement tools and two way communication, user can interact with the grid more and help to reduce the peak demand with the help of dynamic pricing. This way, user becomes an integral part of the system. As the renewable resources can be small scale and highly diversified, this type of communication system will allow more information about these resources to the grid. This will increase the stability of the overall system [23]. To implement this two way communication, a communication link has to collocate with the power line. This is a new technology which needs to be implemented on a wide scale. More research and development is required to increase the efficiency of the system and to make it cost effective [23].

2.4.7 Issues with Security

While integrating the renewable resources with the grid, important parameters of the grid must be maintained, such as voltage, frequency, waveform purity, equipment fault isolation etc. Due to the small size of renewable generators, there might be many owners. A well-accepted policy and regulation is required for maintaining these technical parameters and grid stability [14]. Due to the dynamic performance of the power system, security issues are also a major concern for integration of renewable energy into grid. The renewable energy generators have to ride through disturbances caused by power system to prevent major outages.

They have to adjust their output to avoid overloading or insecure power system operation. Following a disturbance, they must help stabilizing the system operation through voltage and frequency control [24].

2.4.8 Financial Issues

The assessment of utility renewable energy investments is typically done based on regulatory, project finance and technical perspective. Even though these views are important for investors, utilities, regulators and rate payers, these views do not fully capture the benefits of investments in renewable energy [15]. Challenges regarding the realization of value of integrating renewable resources into grid are discussed below.

Renewable projects are typically considered as generation projects. So their value to the grid is not observed as primary benefit. To estimate the benefits that renewable resources bring to the grid, complicated engineering and financial analysis related to power market, storage capacity, demand scheduling, peak consumption reduction and realization of consequences of prices paid is required. Huge initial capital cost, transmission cost, long payback period, small or no earnings at all during construction period, research and development cost, etc. are among the common financial challenges for renewable resources. Also, as the technologies are still developing and industry experience is limited, the benefits of renewable resources are considered too theoretical. As a result, the focus is to run these projects operationally rather than to their full potential. These projects require government subsidy, more time and research to make them feasible on a wider scale, and to reduce cost. These challenges are preventing the inclusion of the value that could be generated by integrating renewable resources into grid [15].

2.5 Conclusion

The necessity of environmentally friendly power generation and the increasing demand for electricity are the main reasons for the growth of power generation from renewable resources. There are many challenges of integrating renewable resources to the existing grid. The variability and uncertainty of renewable resources, forecasting with accuracy and confidence level on the forecast of renewable resources are major issues. Based on these, the dependency on conventional reserves and how the resources will be dispatched efficiently are determined. Due to increasing penetration of renewable resources, the demand for energy storage is also increasing. As most renewable resources are intermittent by nature, accommodating distributed renewable resources over a wide area can provide less variability in terms of renewable power generation. It will also ensure better forecast for scheduling conventional fuel resources. Even though renewable power may not be sufficient in one location to meet the demand of that location, the distributed renewable power generation from a different location can provide the option to system operators to meet the demand. By integrating renewable resources over a distributed area, the load on conventional fuel can be reduced. To accommodate renewable resources over a larger area and match the supply and demand all over the country, long transmission lines are required. As renewable resources of different scales along with conventional resources are integrated with existing grid, the security parameters need to be maintained. Strong uniform policy based on technological aspects, financial support, and market analysis is also a major concern of integrating renewable resources into existing grid.

Chapter 3

The Impact of Power Exchange System on Distribution Micro Grids

3.1 Introduction

The electricity generation capacity is one of the main driving forces for the socio-economic development of any country. Energy demands on traditional power systems are increasing all over the world due to the growing load and the necessity for geographically distributed power sources for dispersed populations. Studies show that if the energy generation structure was modified, 3,240 million tons (about 35%) of carbon emissions could be reduced [25]. This can significantly improve the global warming scenario. Thus, the growing demand for energy and efforts to restrict environmental pollution are leading the developing as well as the developed countries of the world towards alternative sources of energy. For most of the developing countries, the electricity demand has already surpassed the capacity of electricity generating power plants from conventional fossil fuel sources [26-27]. To meet the ever increasing electricity demand, more attention has been placed on generating electricity from renewable energy sources [28]. The rural and the remote areas of developing countries usually do not have much access to the supply of electricity from national grid [29]. Even in the places of rural areas that have electricity connection, there is a lot of power shortage [29]. The solar photo-voltaic (PV) systems are among the renewable energy systems which are widely implemented in these rural and remote areas [29]. This is not only the picture of a developing country. For a developed country like Canada, there is a record breaking development in wind energy [30]. In year 2013 about 1,600 MW of new wind power capacity was installed which ranks 5th globally for new installed capacity of wind power [30]. Currently, there is 8,517 MW of total installed capacity of wind power in Canada [30]. This supplies about 3% of Canada's overall electricity demand [30].

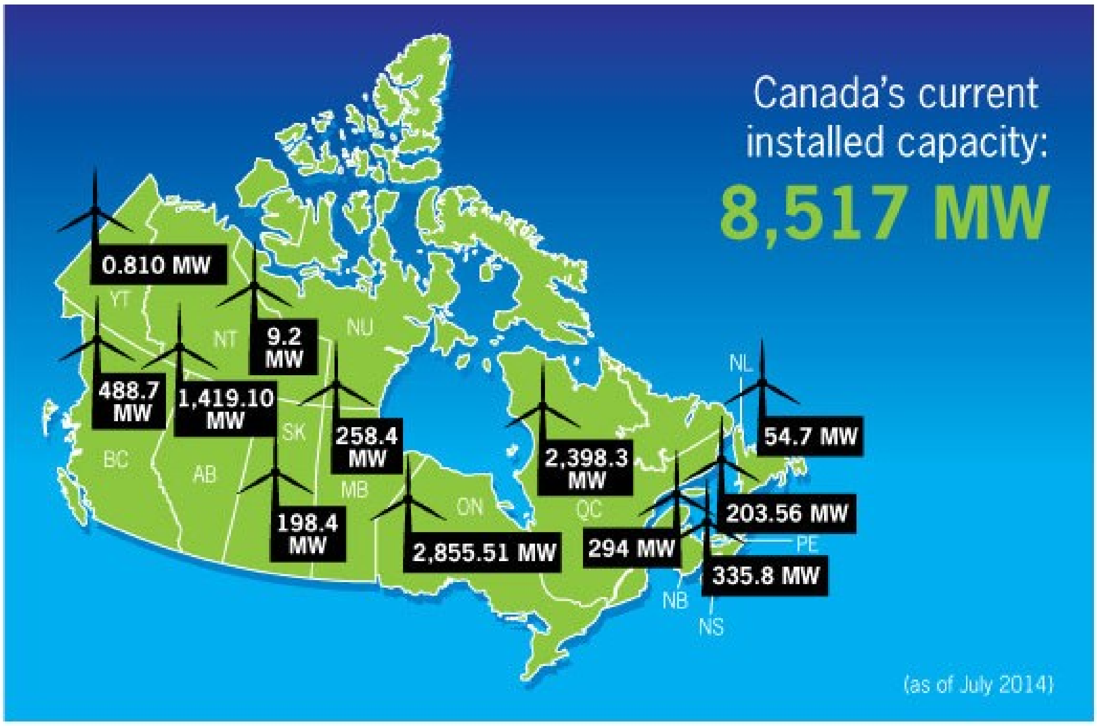

Figure 3-1 : Canada's installed wind capacity as of July 2014 [30]

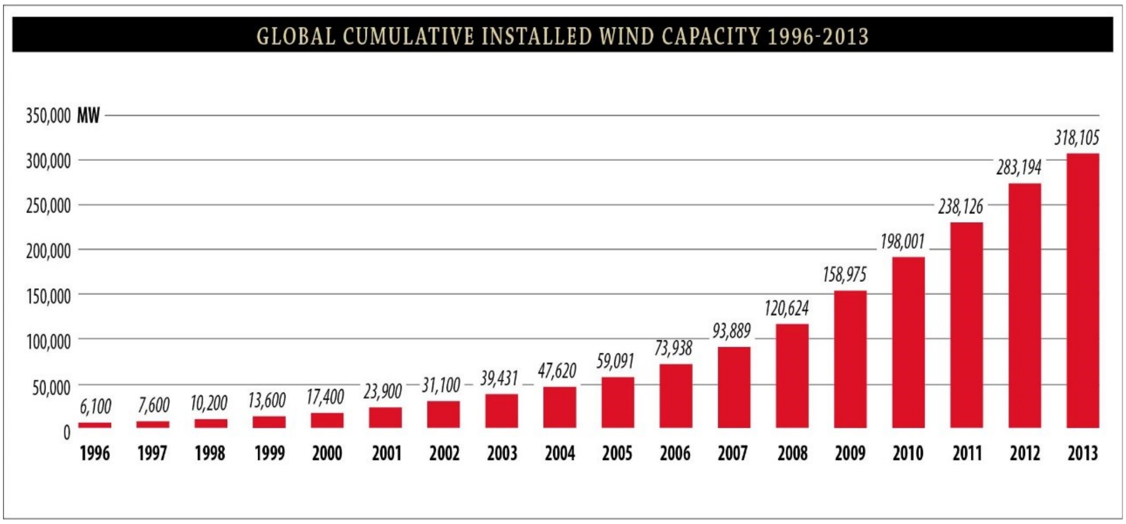

Figure 3-2 : Global cumulative installed wind capacity from 1996 to 2013 [31]

There has been a gradual increase in installation of wind resources all over the world. Figure 3.2 represents the cumulative installed wind capacity from 1996 to 2013.

Most of the time, the locally available renewable resources are of small scale [32] and are widely distributed. Distributed Generation (DG) utilizes majority of renewable resources with smaller generation capacity. It is more economical to connect them at lower voltages in power system through DG as well [32].

A Micro Grid (MG) is a systematic organization of DG systems. It is a cluster of loads and power generation units under a unified controller within a local area [33-35]. If DG sources in a MG can exchange power among themselves, the overall performance of the system may improve. In rural and remote areas with limited access to reliable and uninterruptible sources of energy, these DG or MG can be very advantageous. They can help support the traditional power system by providing power during periods of peak demand as well [33-35].

In this section, different aspects of DG as well as MG will be discussed. A power exchange simulation model will be used to capture exchange of power among different MG's and a national grid. The impact of different practical parameters on the power exchange system will also be examined. These parameters will be set to create a realistic environment. The power exchange model will be used to observe the performance of the model in a practical environment. Based on the performances of the evaluation parameters of the model, the benefits of power exchange system will be discussed.

3.2 The Conventional System

In a conventional power system, power is generated from a relatively small number of large power plants. These are usually located far away from the consumers. The generators operate at a fixed speed and fixed grid frequency. Then, the generating voltage is stepped up to a high voltage level. Power is then transferred over high-voltage long distance transmission lines. In the distribution network, voltage is then stepped down to medium or low voltage. Power is finally distributed through the unidirectional (radial) distribution network to the consumers. Power grids centrally monitor and control the power quality. Figure 3.3 shows a conventional power system.

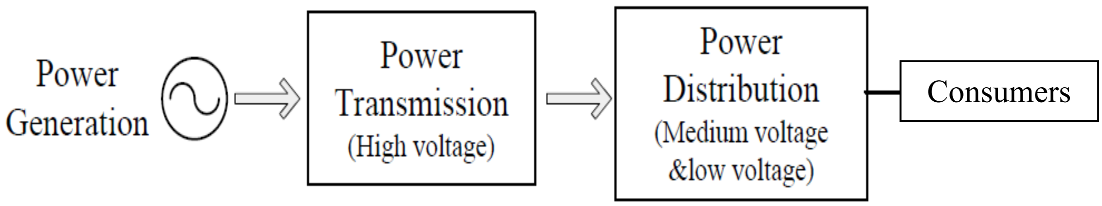

Figure 3-3 : Conventional power system [34]

Conventional power systems supplies power in most parts of the world. But it has some issues as well. There are system losses in terms of line and heat losses. In developing countries, the losses also include unaccounted energy usage and electricity theft. In Bangladesh, according to Bangladesh Power Development Board (BPDB), the overall system loss was 6.58% of net generation in 2008- 2009 [26]. Based on the website of Dhaka Electricity Supply Company Limited (DESCO), the monthly system loss in percentage for the year of 2011 in Dhaka, the capital of Bangladesh [27] is shown in Figure 3.4.

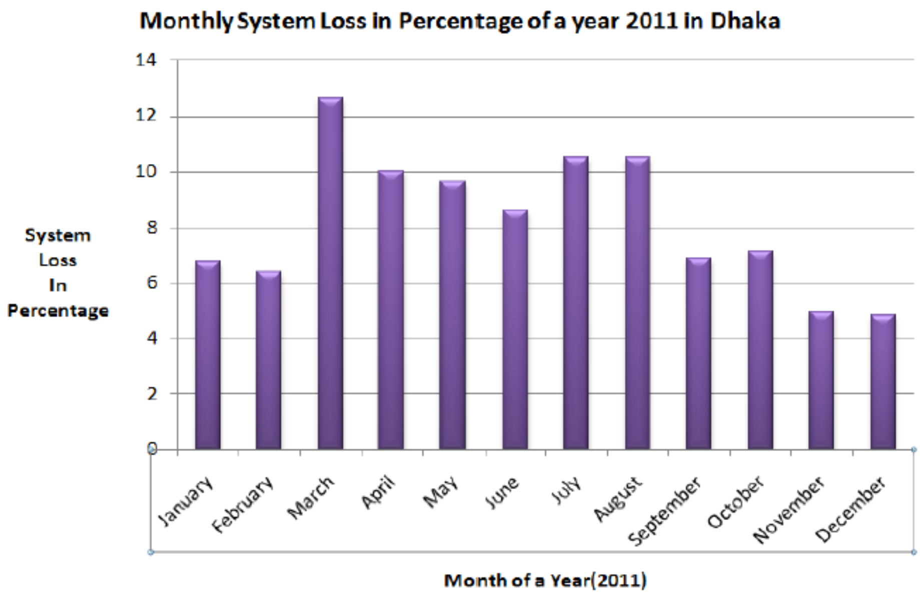

Figure 3-4 : The monthly system loss in % for year 2011 in Dhaka [27]

3.3 The Distributed Generation

In Distributed Generation (DG), an electric power generation source can be connected directly to the distribution network [35]. Small DG systems, also known as Distributed Power Generation Systems (DPGS), are mainly based on micro power generation sources. These small scale energy sources can be both renewable resources and non-renewable resources. Small scale PV, wind turbines (WT), biogas etc. are some example of renewable resources. Small scale gas turbine, small diesel engines etc. are the example of non-renewable resources. All small scale DG systems require power electronic interfaces [33-35]. The energy sources can produce DC or AC power, processed through power electronic interfaces and finally connected to an AC utility system [33-35].

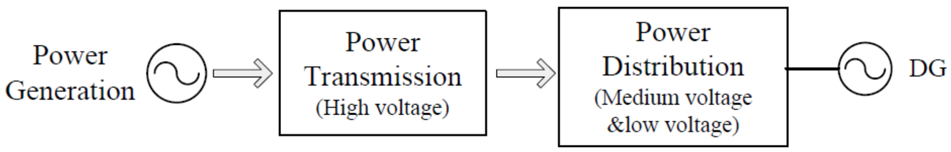

Figure 3-5: Distributed generation (DG) system

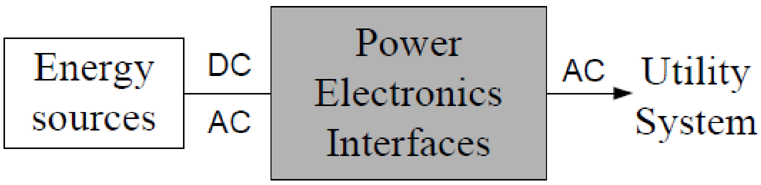

Figure 3-6: The DG System with power electronic interfaces

From the customer point of view, there are several advantages of DG applications [34]

- It ensures reliability of energy supply and can provide uninterrupted power.
- Due to shorter transmission paths, the line losses can be reduced.
- Combined Heat and Power (CHP) applications can improve the efficiency of the overall system.

- Energy savings on electricity rates can be achieved by self-generation during peak hours when electricity price is higher.
- Through the utilization of renewable resources, the environmental pollution can be reduced.

From the utility point of view, the advantages of DG applications include [34]:

- It provides limited capital risk because of the smaller size, flexibility in choice of sites and rapid installation time.
- Major investments in transmission and distribution system upgrading can be avoided.
- It can offer relatively low cost entry point into a competitive market.

There are also some issues associated with DG [34]:

- Due to sudden connection or disconnection of DG, steady state or transient over/under voltages can be produced at the point of connection.
- Malfunctions in protection schemes can increase due to breaker reclosing problem, over current protection relying interference etc.
- It can also produce power quality problems such as voltage harmonics, flicker, voltage fluctuations etc.
- There are safety concerns for the public or for the utility personnel due to the islanding operation of a single DG.

3.4 Micro Grids

Micro Grids (MG) provide a new concept for more efficient use of the DG system. A Micro Grid is a community level power generation and supply system that produces electrical energy at or near the load site from small sources. Figure 3.7 represents a small micro grid system. It can utilize the distributed nature of small scale renewable resources.

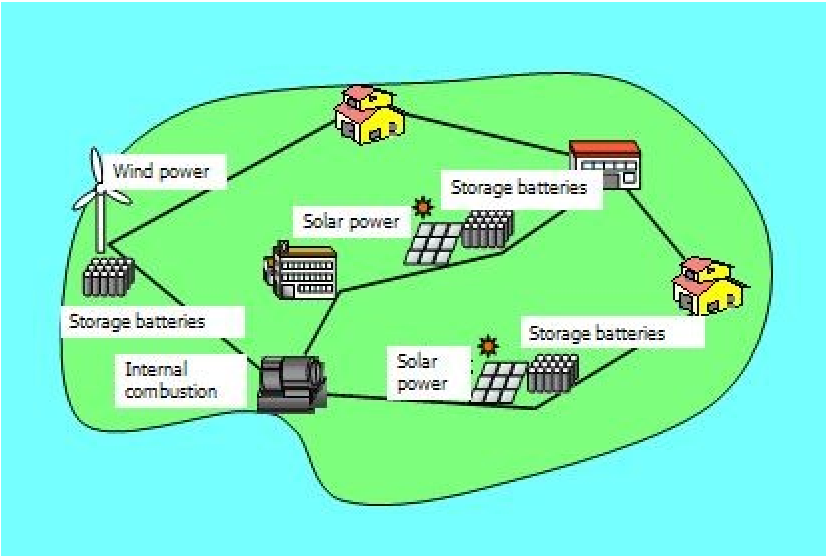

Figure 3-7: A micro grid system [56]

MG is basically a cluster of loads and power generation units under a unified controller within a certain local area [35]. It is a systematic organization of DG system. In a MG, a lot of power generation sources can be connected together. In other words, it can accommodate more than one DG. Thus, MG has larger power capacity and more control flexibility than a single DG [33-35]. MG can also minimize many potential problems caused by individual DG systems [33-35].

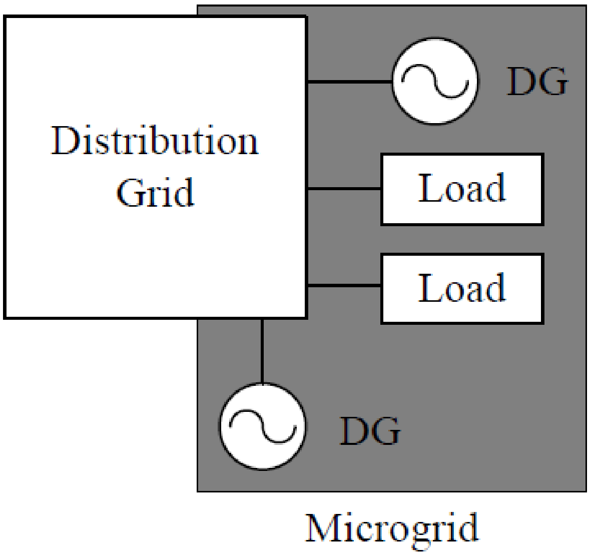

Figure 3-8: Micro grid (MG)

There are three main parts of the micro grid structure [35]. The DG controller is one of the main components. It realizes the operation of DG systems.

The micro grid Central Control Unit (CCU) is the most integral part of the micro grid systems. It can also be termed as the energy manager. It dispatches power to each DG controller, the loads etc. It can also optimize the organization of the DG system.

The third part of the micro grid structure is the protection scheme. The protection scheme has to be designed in such a way so that it responds quickly to both the main grid faults as well as the micro grid faults.

The benefits of optimizing the DG systems can be explained through an example shown in Figure 3.9 [33]. Here, a heat generating system and a power generating system provides energy separately at first. Then, combination of the heat generating system is put together with the power generating system. This is called Combined Heat and Power. The fuel consumption of the systems and the losses have been observed.

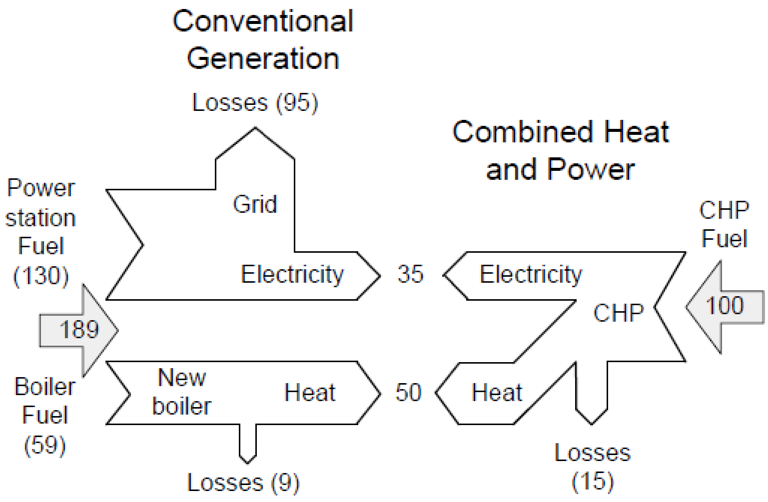

Figure 3-9: CHP versus separate heat and power energy flows [33]

The fuel consumption of the power station was taken as 130 units. The boiler fuel consumption was 59 units. The conventional generation losses of electricity through the grid were taken as 95 units whereas the heat losses were 9 units. This separated system provides 35 units of electrical energy and 50 units of heat energy [33].

When the power station and heat generating station (CHP) were combined and used together, for example, the exhaust heat of the heat generating station was provided to power station, or vice versa, the fuel consumption of the CHP system was 100 units. The CHP system was providing the same amount of 35 units of electrical energy and 50 units of heat energy as before. This is because the losses of the CHP system were reduced to only 15 units since the power station and heat generating station were working together [33].

It can be concluded that the micro grid system, composed of different DG systems, can provide improved performance. In this case, almost 90% improvement in efficiency has been achieved by using CHP system.

3.4.1 Operation Modes of Micro Grids

Grid connected and islanding are the two operation modes for micro grid operating systems. In grid connected operation, Micro Grids operate with a national grid. In islanding operation, Micro Grids provide power to the local load by themselves.

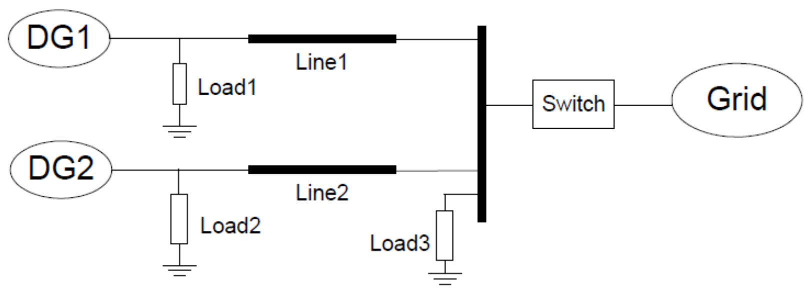

Figure 3-10: Operating modes of micro grid

Power flow control and voltage regulation are needed to be supervised while operating a micro grid. In Figure 3.10, two DG sources are operating in parallel. The system is also connected with a switch to the grid. This switch can be a mechanical or an electrical switch. The mechanical switches are used more widely. The electrical switches are usually implemented with power electronic devices like thyristor. When there is a fault, the mechanical switches may take 5 to 10 cycles to get opened and disconnect the system. On the other hand, the power electronic switches can be controlled by just providing a gate pulse. So, the switches can operate very fast, with half of a cycle to one cycle [34]. If the switch remains connected, then this system is a grid connected system. If the switch is disconnected, then the system would operate in the islanding mode. Here, the loads can be shared by the two DG sources since they are working in parallel. This is called the power sharing of micro grids. Synchronization and reconnection are also very important features of micro grid operation. Plug and Play of the DG sources can be achieved by micro grids [34].

3.4.1.1 Grid Connected Operation

If the switch in Figure 3.10 is closed, then micro grid is operating in grid connected mode. The different aspects of grid connected operation are explained below [34]:

- The DG systems are connected to the grid and they can provide heat and voltage support for the nearby loads.
- The DG systems in the micro grid should be able to regulate the local voltages.
- The DG systems should be able to accurately control the dispatched real and reactive power flows.
- The grid power quality problems can affect the micro grids and all the DG units due to the grid interfacing nature.
- In case of non-significant power quality events, the DG units should be able to cope up with them. This is called grid fault ride through capability. This improves the stability of the total system. Whenever a DG is connected with or disconnected from the system, it produces some disturbances. Now if the fault in the grid is far away from the micro grid, then the fault may become insignificant. Due to this insignificant fault, if the DG or the micro grids are disconnected from the system, it may produce a larger disturbance in the system. So, this fault-ride-through-capability is very important for the overall stability of the system.

3.4.1.2 Islanding Operation

If the switch in Figure 3.10 is opened, then micro grid is operating in islanding mode. The different aspects of islanding operation are explained below [34]:

- Even if a section of main grid is disconnected due to various reasons, the DG or the micro grid is still providing power to that section, then that is called islanding.

- Islanding can be of two types: unintentional islanding and intentional islanding.
- Unintentional islanding is when the disconnected section of the main grid is provided power unknowingly from the micro grid or DG. This can be dangerous to the public or utility personals and is a matter of major safety concern. Also, unintentional islanding can damage the equipment as well.
- Intentional islanding is when the disconnected section of the main grid is provided power knowingly from micro grid or DG. It provides increased reliability of the system. Uninterrupted power supply can be achieved using the islanding operation during main grid faults.
- When transition from grid connected mode to islanding mode occurs, the DG units must share the new power loads immediately. Otherwise, some of the DG would be damaged because they might be exceeding their rated demands.
- When the fault period is over and everything is stable, micro grid can be reconnected with the main grid through proper synchronization techniques. Voltage, phase, frequency, current etc. has to be matched with the system.

3.5 The Power Exchange System for Micro Grids

Micro Grids are composed of renewable and non-renewable resources. They can generate power using small gas turbines or other fossil fuel power generation sources. However, they are more popular for generating power from renewable power generation resources. Solar panels, PV cells, wind turbines etc. are more popular power generation resources for small scale micro grids. Micro Grids can be connected to a national grid. They attempt to meet their own demand using the power generation resources they have. If they are not able to meet the demand, they draw power from national grid. This way, micro grids have the ability to reduce the load of the national grid. In some cases, they are able to provide power to the national grid if they are generating more power than their own demand. However, they have to meet a number of system requirements before providing power to the national grid. Otherwise system instability may occur. Micro grids can form a group among themselves and exchange power to balance their generation and demand. This way, they may help the national grid to reduce base load requirement.

In this section of the thesis, a power exchange algorithm for sharing power among micro grids and national grid will be discussed, considering different parameters. The impact of these parameters on the power exchange system will be discussed as well. The goal of this experiment is to examine, using simulations, whether there are any advantages of exchanging power among micro grids as well as with the national grid.

3.5.1 Parameters Considered for the Power Exchange System

To create a practical environment, different parameters have been considered for this simulation model. The simulation environment was created in MATLAB. The focus of the model is to observe whether it is useful to exchange power among micro grids. The parameters considered are given below:

- The number of micro grids.
- The variability of generation and demand capacity of micro grids.
- The instrument malfunction probability of micro grids.
- Intermittency of renewable power generation.

3.5.2 Data Description for the Simulation Model

The data was collected from AESO website. The website provides information on power generation and Alberta Internal Load data. Due to lack of realistic micro grid data, this data was used for the simulation model. The hourly power generation and Alberta demand data for September 11, 2012 was selected for simulations. This hourly generation and demand is considered as the main feed data. This dataset will be used to generate several power generation and demand data for different number of micro grids.

The power generation data includes different types of power generation sources such as coal, gas, hydro, wind etc. The user has the capability to control the degree of variation for power generation and demand capacity for other micro grids. The power generation and demand data is provided in MW. Instead of hourly data for one day, the model can be redesigned for any period based on the availability of the data and its frequency. Hourly data for one day was considered for simplification of analysis.

3.5.3 Model Assumptions

This simulation model creates a group of virtual micro grids which will work together with the national grid. Since all the grids are virtual, no transmission losses are considered.

The average pool price of electricity provided by Alberta Energy for year 2012 ($64.32 per MWh) is considered as the national grid power generation price [3]. When the micro grids draw power from the national grid, they buy it from national grid at the price of $64.32 per MWh.

The power generation from renewable energy resources usually has a high installation cost. So it is usually more expensive. To provide more incentive, government usually provides subsidies for renewable power generation. Keeping this in mind, the price of power generated from micro grids is considered at 80% of the national grid price for this simulation model. So, micro grids trade power among themselves at $51.46 per MWh. These prices are kept same throughout the analysis.

It is considered that all the micro grids are generating power that meets the required technical parameters so that it will not cause any instability while power is exchanged among micro grids and national grid.

3.5.4 Algorithm for Power Exchange System

In this system, all the micro grids are assumed to be virtually connected with each other as well as with the national grid. The micro grids can trade power among themselves as well as with the national grid.

The micro grids will produce electricity by themselves. They will try to meet their own respective demand first. If any micro grid, suppose micro grid 'A' for example, do not have enough power to meet its demand, the micro grid 'A' will look to import power from other micro grids in the group which are producing more power than their respective demand. For example, if micro grid 'B' generates more power than its demand, then micro grid 'A' will import power from micro grid 'B'. If micro grid 'A' still could not have acquired enough power to meet its demand, it will import the rest amount from micro grid 'C' if micro grid 'C' generates more power than its demand. If micro grid 'A' still needs power that any other micro grid in the group cannot provide, then micro grid 'A' will import the rest of the amount from the national grid.

When a micro grid produces more power than its demand, it will look to export the excess power to other micro grids in the group. For example, if micro grid 'B' was generating more power than its demand and as micro grid 'A' needs power to meet its demand, micro grid 'B' will export power to micro grid 'A'. After meeting the requirements of its own demand and demand of the other micro grids in the group, if any micro grid has excess power, the micro grid will export the excess power to the national grid at the end of each hour. This is done every hour for 24 hours for this simulation model for all the micro grids.

The flow diagram for the algorithm is represented with figure 3.11. The power exchange system is explained below.

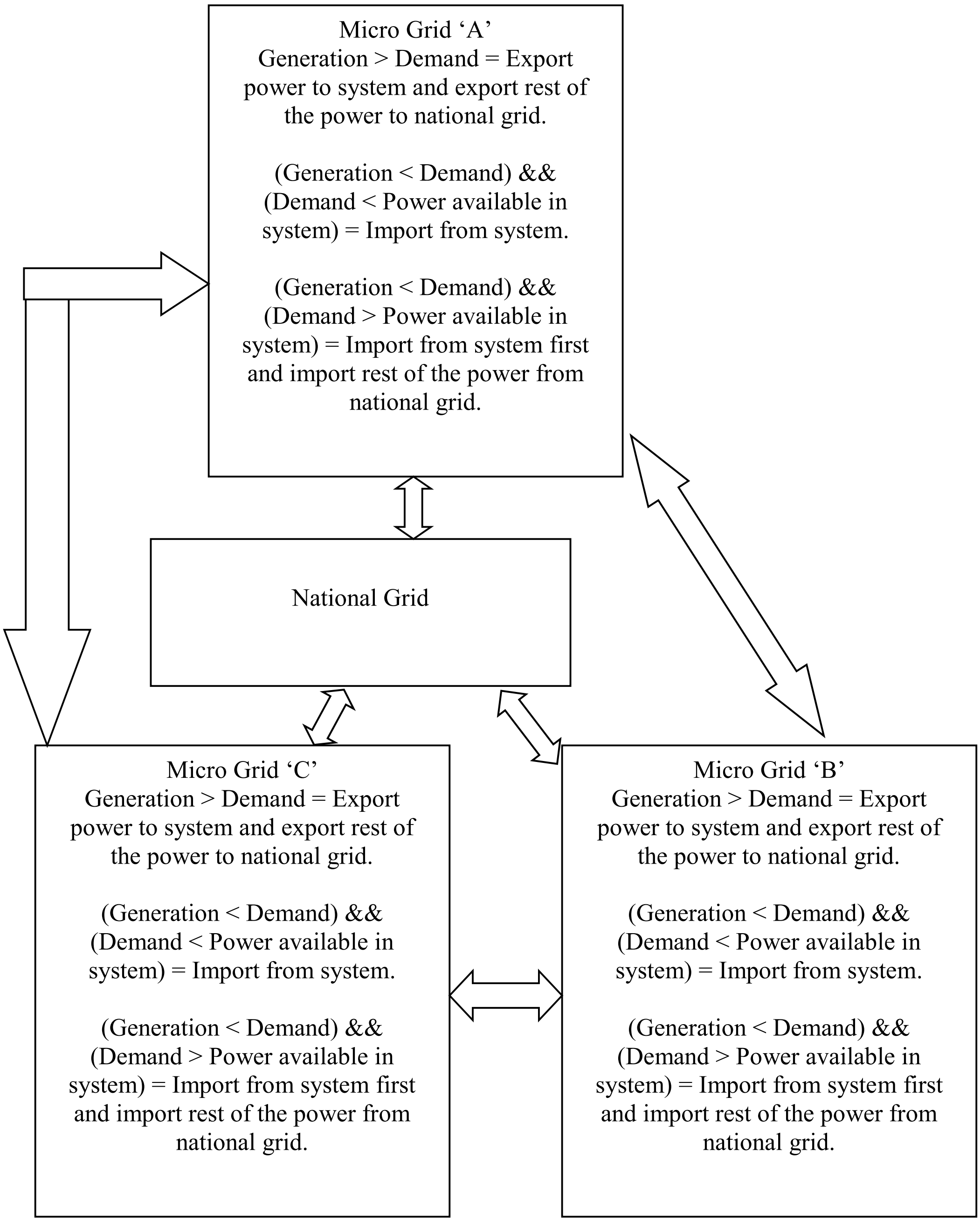

Figure 3-11: The flow diagram of power exchange algorithm

A. Micro grid data is generated based on user provided parameters.

For hour 1,

B. A micro grid first checks whether it generates enough power to meet its demand. It satisfies its own demand first.

C. The micro grid checks whether it generates more power than its demand.

- If yes, the concerned micro grid will provide as much as possible of the excess power to any other micro grid in the group that needs the power to meet its demand.
- If the concerned micro grid still has excess power, it will provide as much as possible of the excess power to all other micro grids in the group, one after another, that need the power to meet its demand. This process continues until all the micro grids can meet their respective demand.
- After meeting as much as possible of the demand of all the micro grids in the group, if the concerned micro grid still has excess power, it will provide the excess power to national grid.
- This process continues for all micro grids in the group for hour 1.

D. The micro grid checks whether it generates less power than its demand.

- If yes, the micro grid first consumes as much as possible of the required power from any other micro grid in the group that produces excess power than its demand.
- If the concerned micro grid still needs more power to meet its demand, it will consume as much as possible of the rest of the power from all other micro grids in the group, one after another, that produces excess power than its demand.
- After consuming as much as possible of the required power from the group of micro grids, if the concerned micro grid still requires more

power which no other micro grid can provide, then it consumes that rest of the required power from the national grid.

- This process continues for all the micro grids for hour 1.

From hour 2 to till hour 24, the process from **B** to **D** continues.

3.5.5 The Description of User Provided Parameters

To assess the different realistic environments of the power exchange system, the user provides different parameters in the beginning of the model. These parameters will be varied one at a time to observe their impact on the power exchange system. At last, all the parameters will be set in a way to accommodate the most possible realistic environment in the model.

3.5.5.1 Number of Micro Grids (N)

The user will provide the number of micro grids to be accommodated in the system. Based on this number, a dataset for N number of micro grids with hourly power generation and demand data for one day will be created. The Number of micro grids will be increased by 15 throughout the experiment to maintain equal conditions.

3.5.5.2 The Variability of Generation and Demand Capacity of Micro Grids

The model asks the user to provide three types of variability for the generation and demand capacity of the generated micro grids. Low, medium and high variability of the capacity can be provided by the user.

A low variability produces the generation and demand data of the generated micro grid within a range of 0.6 times of the original feed data to 1.5 times of the original feed data. For example, if the original demand data is 50 MW, the generated demand data for the micro grid can be in the range of 30 MW to 75 MW.

A medium variability produces the generation and demand data of the generated micro grid within a range of 0.4 times of the original feed data to 3 times of the original feed data. For example, if the original demand data is 50 MW, the generated generation data for the micro grid can be in the range of 20 MW to 150 MW.

A high variability produces the generation and demand data of the generated micro grid within a range of 0.1 times of the original feed data to 10 times of the original feed data. For example, if the original demand data is 50 MW, the generated generation data for the micro grid can be in the range of 5 MW to 500 MW.

This way, a large variety of the generation and demand capacity for micro grids can be generated. This will provide a more realistic environment for the simulation model.

3.5.5.3 The Instrument Malfunction Probability of Micro Grids

Any device is prone to malfunction. A micro grid has every chance to go out of order. In this case, the micro grid will not be able to generate any electricity, but it will still require power from other micro grids or the national grid to meet its demand. This feature provided by the user will create a realistic environment.

The model is designed in a way that the chances of the micro grid malfunctioning is very low. If the user chooses to include instrument malfunction in the model, a very low probability is set so that very few of the micro grids will be out of order. When user chooses this option, the model generates a random number in the range of 0 to 1 which follows the uniform distribution. If the generated number is below 0.005, then one micro grid will malfunction. As a result, that micro grid will not generate any power, but it will still consume power from other resources to meet its demand. If this option is not chosen, then all the micro grids will function properly.

3.5.5.4 The Intermittency of Renewable Power Generation

The most important feature while dealing with renewable power generation is the intermittency of the renewable resources. Hydro power is the least variable renewable power resource and the easiest to forecast. The wind resource is one of the most variable renewable resources. It is highly intermittent. There are several models which provide the forecast for wind, but it is still highly intermittent. Also, sometimes there may not be any wind resource available for power generation. The solar power is comparatively less variable, but the passing clouds create intermittency as well. For all these reasons, it is very important to include a factor that includes the intermittency of the renewable resources in the system. Studies show that solar and wind power can vary up to 70% and 100% respectively in a given period [16]. As a result, the simulation model is designed in a way that if the user chooses to include the intermittency factor, the model will randomly assign within a range of 70% to 100% intermittency of renewable power generation for each micro grid. If the user does not choose to include it, then the model will not assign any intermittency factor to power generation. As a result, the power generation data from the original feed data will not vary for this factor.

3.5.6 Sample Simulation Results:

In this section, a sample analysis will be provided to explain the model with example scenarios. At first, an original feed data for power generation and demand for micro grid 'A' will be set. Based on the user provided parameters, constant values for the parameters will be assigned to produce power generation and demand data for micro grid 'B' and micro grid 'C'. An example will show the process of producing sample micro grid data. After this, three scenarios will be discussed to explain model algorithm of the power exchange system with simplistic data.

3.5.6.1 Producing Sample Micro Grid Data

The original feed data for power generation and demand for micro grid 'A' is taken as 7,420.44 MW and 7,501.33 MW respectively. The power generation and demand data is taken from the AESO website for September 11, 2012.

Let's assume that only one micro grid data will be generated, that is $N = 1$. Assuming user chooses a medium variability for generation and demand capacity of micro grids, the value should be within 0.4 times of the feed data to 3 times of the feed data. Let's assume this value is taken as a constant 1.5 for this example.

The instrument malfunction probability is not chosen so that there must a valid power generation and demand data for micro grid 'B'.

The intermittency of renewable energy is considered for this scenario to create a realistic environment. Since the range of intermittency is considered within 70% to 100% for the model, for this scenario it is taken constant as 85%.

So, for the Power generation data for micro grid 'B', the feed generation data (7,420.44) should be multiplied by the variable capacity factor of micro grid (1.5) and the intermittency factor (0.85).

Generation Data = Feed Generation Data * Capacity Factor * Intermittency Factor…… … (3.1)

This calculates the generation data for micro grid 'B' as 9,461.06 MW.

The intermittency factors will only have an impact on power generation. It is not supposed to impact the demand of micro grid. So, for the demand data of micro grid 'B', the feed demand data will be multiplied by variable capacity factor of micro grids (1.5) only.

Demand Data = Feed Demand Data * Capacity Factor … … … (3.2)

This calculates the demand data for micro grid 'B' as 11,251.99 MW.

3.5.6.2 Scenario 1: Group of Micro Grids Generates More Power than Demand

Let's assume that there are three micro grids in the system. Their respective generation and demand data are provided below.

Table 3-1 : Sample data for simulation scenario 1

	Micro grid 'A'	Micro grid 'B'	Micro grid 'C'
Generation at hour 1	15	18	16
Demand at hour 1	12	14	21

In this scenario, micro grid 'A' and 'B' produces 3 and 4 units of excess power whereas micro grid 'C' has a demand of 5 units more than its generation. So in the power exchange system, micro grid 'A' and 'B' will provide 5 units of power to micro grid 'C' to help meet its demand. The excess 2 units of power will be sold to national grid.

In the absence of power exchange system, micro grid 'A' and 'B' will sell 3 and 4 units of power to national grid whereas micro grid 'C' has to consume the total excess amount of demand, which is 5 units, from the national grid.

Table 3-2 : Analysis parameter values for simulation scenario 1

	Export to System	Export to Grid	Import from System	Import From National Grid	Export To Grid Without Exchange	Import From National Grid Without Exchange
Amount in units	7	2	5	0	7	5

So, by deploying power exchange system, a group of micro grids exchanged their power among themselves to reduce power consumption from national grid by 5 units.

3.5.6.3 Scenario 2: Group of Micro Grids Power Generation and Demand is Equal

Let's assume that there are three micro grids in the system. Their respective generation and demand data are provided below.

Table 3-3 : Sample data for simulation scenario 2

	Micro grid 'A'	Micro grid 'B'	Micro grid 'C'
Generation at hour 1	21	11	20
Demand at hour 1	17	20	15

In this scenario, micro grid 'A' and 'C' produces 4 and 5 units of excess power whereas micro grid 'B' has a demand of 9 units more than its generation. So in the power exchange system, micro grid 'A' and 'C' will provide the 9 units of excess power to micro grid 'C' to help meet its demand. In this scenario, the group of micro grids does not have any power to sell to national grid, neither does it require t import power from national grid.

In the absence of power exchange system, micro grid 'A' and 'C' will sell 4 and 5 units of power to national grid whereas micro grid 'B' has to consume the total excess amount of demand, which is 9 units, from the national grid.

Table 3-4: Analysis parameter values for simulation scenario 2

	Export to System	Export to Grid	Import from System	Import From National Grid	Export To Grid Without Exchange	Import From National Grid Without Exchange
Amount in units	9	0	9	0	9	9

So, by deploying power exchange system, a group of micro grids were able to meet their group demand by their group generation.

3.5.6.4 Scenario 3: Group of Micro Grids Generates Less Power than Demand

Let's assume that there are three micro grids in the system. Their respective generation and demand data are provided below.

Table 3-5: Sample data for simulation scenario 3

	Micro grid 'A'	Micro grid 'B'	Micro grid 'C'
Generation at hour 1	15	18	17
Demand at hour 1	18	20	18

In this scenario, micro grid 'B' produces 2 units of excess power whereas micro grid 'A' and micro grid 'C' has a demand of 3 and 1 units more than its respective generation. So in the power exchange system, micro grid 'B' will provide the 2 units of excess power to Micro grid 'A' and 'C' to help them meet their demand. The rest of micro grid 'A' and C's demand will be met by consuming power from national grid.

In the absence of power exchange system, micro grid 'B' will sell 2 units of power to national grid whereas micro grid 'A' and 'C' has to consume the total excess amount of demand, which is 4 units, from the national grid.

Table 3-6: Analysis parameter values for simulation scenario 3

	Export to System	Export to Grid	Import from System	Import From National Grid	Export To Grid Without Exchange	Import From National Grid Without Exchange
Amount in units	2	0	2	2	2	4

So, by deploying power exchange system, a group of micro grids exchanged their power among themselves to reduce power consumption from national grid by 2 units.

3.5.7 Evaluation Parameters

There can be lots of benefits of micro grids exchanging power among them. Evaluation parameters will help to quantify the advantages of power exchange. At the same time, the impacts of different user provided parameters can also be analyzed using the evaluation parameters. For this project, three parameters will be considered.

3.5.7.1 Base Load Reduction

The base load reduction of national grid is the main focus of this project. If micro grids can share the power generated by them, they will depend less on the nation grid for their excess demand. It will also allow the national grid to reduce the base load as well as to reduce the reserve capacity. The focus of this project is to observe the impacts of different parameters on maximizing the reduction of base load requirement by national grid.

With this evaluation parameter, the amount of power imported by the group of micro grid system from the national grid with and without the power exchange system will be used. It is the ratio of the difference between imported power from national grid with and without the power exchange system to imported power from national grid without the power exchange system.

$$Base\ Load\ Reduction = \left[\frac{(Total\ import\ from\ national\ grid\ without\ exchange - Total\ import\ from\ national\ grid\ with\ exchange)}{Total\ import\ from\ national\ grid\ without\ exchange}\right] * 100$$

… … … (3.3)

3.5.7.2 Excess Power of Group of Micro Grid

Micro grids generate power and try to meet their demand with the generated power. In a group, some of the micro grids will have excess power where some of them would need power from other micro grids and sometimes from the national grid to meet their demand. If the micro grids can work together and meet all their required demand from the group, then they would be maximizing their usage of generated power and depend less on the national grid. The excess power can be sold to national grid. It can also be stored so that it can be used later on when demand is higher. The energy storage will need further studies and a lot of the technical issues are needed to be considered. The focus of this project is to observe the impacts of different parameters on reducing the excess power of the group of micro grids which can represent the maximization of the generated power by the group of micro grids to reduce their dependency on the national grid.

With this evaluation parameter, the amount of power imported by the group of micro grids from the other micro grids of the group and the amount of power exported by the group of micro grids to other micro grids of the group will be used. It is the ratio of the difference between exported and imported power by the group of micro grids within the power exchange group system to the amount of power exported by the group of micro grids to other micro grids of the group.

$$Excess\ Power = \left[\frac{Export\ to\ system - Import\ from\ system}{Export\ to\ system}\right] * 100 \ \ldots\ \ldots\ \ldots\ (3.4)$$

3.5.7.3 Economic Loss

The focus of this parameter is to quantify the monetary advantage of using the power exchange system. It will compare the income of the group of micro grids with and without the power exchange system. Since micro grids depend on consuming power from national grid most of the time, the parameter is termed as economic loss. The focus of this project is to observe the impacts of different parameters on minimizing the economic loss of the group of micro grids by using the power exchange system.

$$Economic\ Loss = \left[1 - \frac{Income\ without\ exchange - Income\ with\ exchange}{Income\ without\ exchange}\right] * 100 \ \ldots\ \ldots\ \ldots\ (3.5)$$

3.5.8 Result Analysis

In this section, the impact of different user provided parameters on the group of micro grids with the power exchange system will be observed and analyzed. Based on the observation, the performance of the group of micro grids using the power exchange system in a realistic simulation environment will be analyzed.

3.5.8.1 The Impact of Number of Grids (N)

In this simulation, the number of micro grids in the system will be gradually increased. The simulation process starts with 5 micro grids in the system. Then the number of micro grids will increase by 15 each time. The impact of increasing number of grids on based load reduction, excess power and economic loss will be observed.

For these sets of simulations, only the number of grids will be varied. The variability of generation and demand capacity of micro grids are taken as medium. The instrument malfunction probability of micro grids and the intermittency of renewable power generation are not considered for these sets of simulations.

Table 3-7: Simulation parameters

Number of Grids	Variable
The variability of generation and demand capacity of micro grids	Medium
The instrument malfunction probability of micro grids	Not considered
The intermittency of renewable power generation	Not considered

The results of these sets of simulations are discussed in below.

Table 3-8: The impact of number of micro grids in the system

Number of Grid	Base Load Reduction (%)	Excess Power (%)	Economic Loss (%)
5	35.4	54.57	81.22
20	52.84	33.83	70.76
35	62.13	37.06	40.95
50	71.28	18.98	51.88
65	72.37	20.85	46.12
80	74.09	16.83	48.44

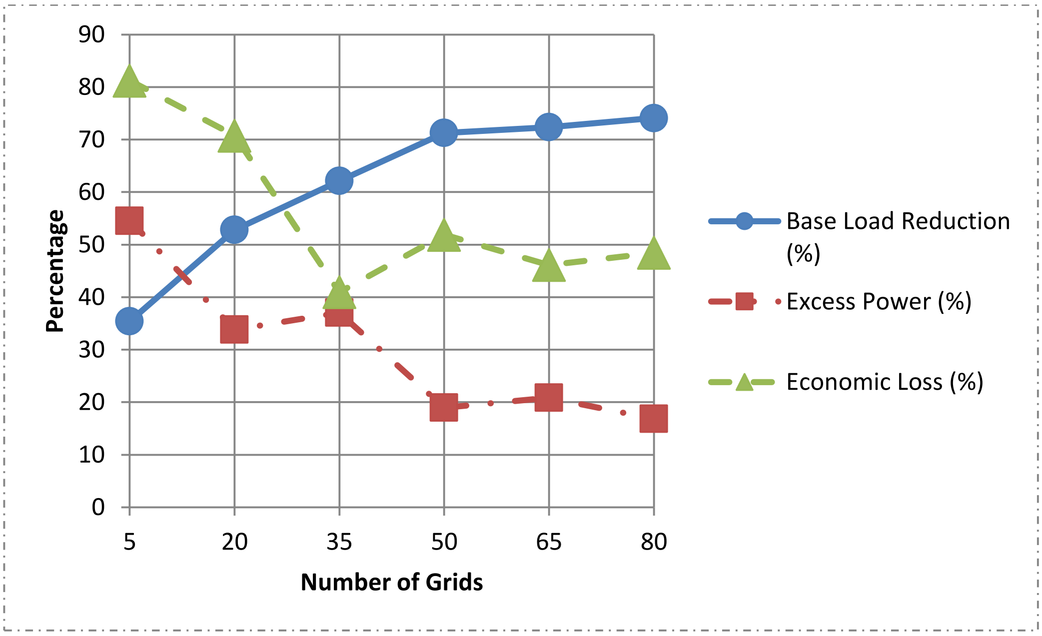

Figure 3-12: The impact of number of micro grids in the system

It can be observed that there is a steady increase in base load reduction for number of grids up to 50 with71.28% reduction in base load. After that, the impact of increasing number of grids on the system is not that significant. For 65 and 80 micro grids, the base load reduction is 72.37% and 74.09% respectively. There is a gradual decrease in the amount of excess power in the system for gradual increase in number of grids. For number of micro grids 5 to 80, the excess power is reduced from 54.57% to 16.83%. The economic loss is the minimum at 40.95% for 35 micro grids.

As the number of grids increases, there are more probability of micro grids with different generation and demand capacity. So, there is more opportunity for micro grids to exchange power among themselves. As a result, the amount of power exchanged among the micro grids increases which reduce the dependency on national grid. So the base load reduction increases. It also ensures that generated power from the group of micro grids are consumed more by the group of micro grids. So, the amount of excess power also reduces. Since, the dependency on the national grid reduces and the micro grids are consuming more power from their generated power, the economic loss factor also decreases. This means, the group of micro grids will be paying less if they are using the power exchange system compared to not using the power exchange system.

Table 3-9: Percentage of improvement in terms of 5 micro grids system

% of increase for Number of Grid	% of Base Load Reduction	% of Excess Power	% of Economic Loss
5 to 20, 300%	49.26553672	38.00623053	12.87860133
5 to 35, 600%	75.50847458	32.08722741	49.5813839
5 to 50, 900%	101.3559322	65.21898479	36.12410736
5 to 65, 1200%	104.4350282	61.79219351	43.21595666
5 to 80, 1500%	109.2937853	69.1588785	40.35951736

Table 3.9 and figure 3.13 represents the percentage of improvement in evaluation parameter in terms of the 5 micro grid system is provided.

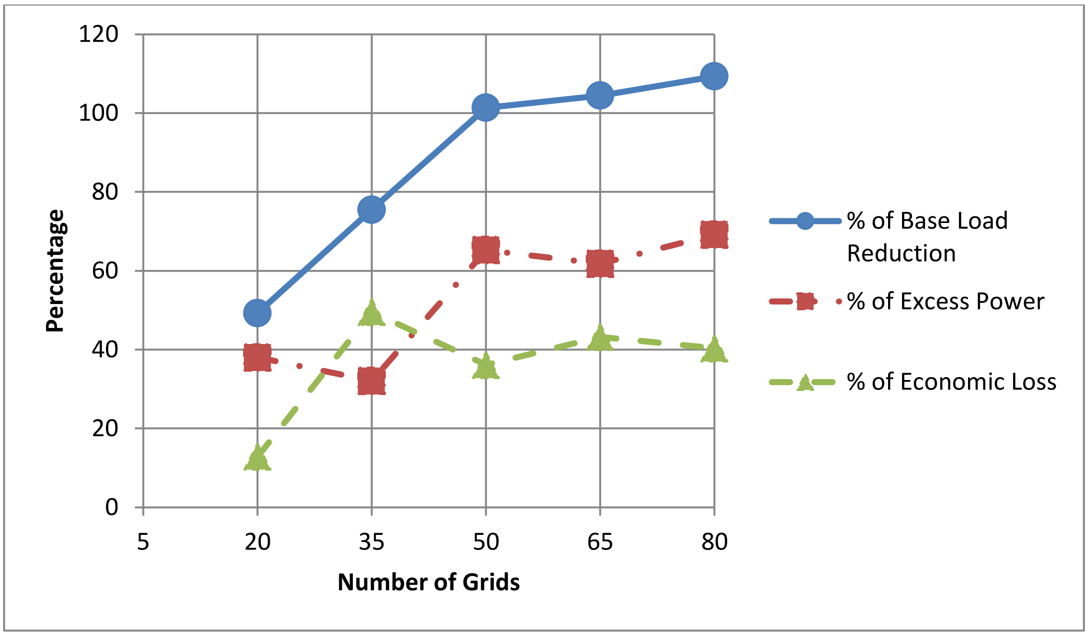

Figure 3-13: Percentage of improvement in terms of 5 micro grids system

In this simulation, it is assumed that all the micro grids will have the equal installation cost. So, the advantage of increasing number of grids will be compared with 5 micro grid systems so that the payoff advantage can be assessed. From figure 3.13, it can be observed that there is a steady increase for base load reduction up to 50 micro grids compared to 5 micro grids system. After that, there is not significant payoff in terms of base load reduction. In terms of excess power, there is a significant payoff till 50 micro grids. For economic loss, there is a significant payoff till 35 grids.

3.5.8.2 The Impact of Variable Generation and Demand Capacity of Micro Grids

In this simulation, the variability of generation and demand capacity of micro grids in the system will be varied. The simulation process starts with a low variability of generation and demand capacity of micro grids in the system. Then medium and high variability will be introduced. The impact of generation and demand capacity of micro grids on based load reduction, excess power and economic loss will be observed.

For these sets of simulations, only the generation and demand capacity of grids will be varied. The number of micro grids used for these sets of simulation is taken as 35. The instrument malfunction probability of micro grids and the intermittency of renewable power generation are not considered for these sets of simulations.

Table 3-10: Simulation parameters

Number of Grids	35
The variability of generation and demand capacity of micro grids	Variable
The instrument malfunction probability of micro grids	Not considered
The intermittency of renewable power generation	Not considered

The results of these sets of simulations are discussed in below.

Table 3-11: The impact of variable generation and demand capacity of micro grids

Variable Capacity	Base Load Reduction (%)	Excess Power (%)	Economic Loss (%)
Low	59.69	33.93	56.95
Medium	64.38	32.72	45.1
High	74.57	27.29	16.92

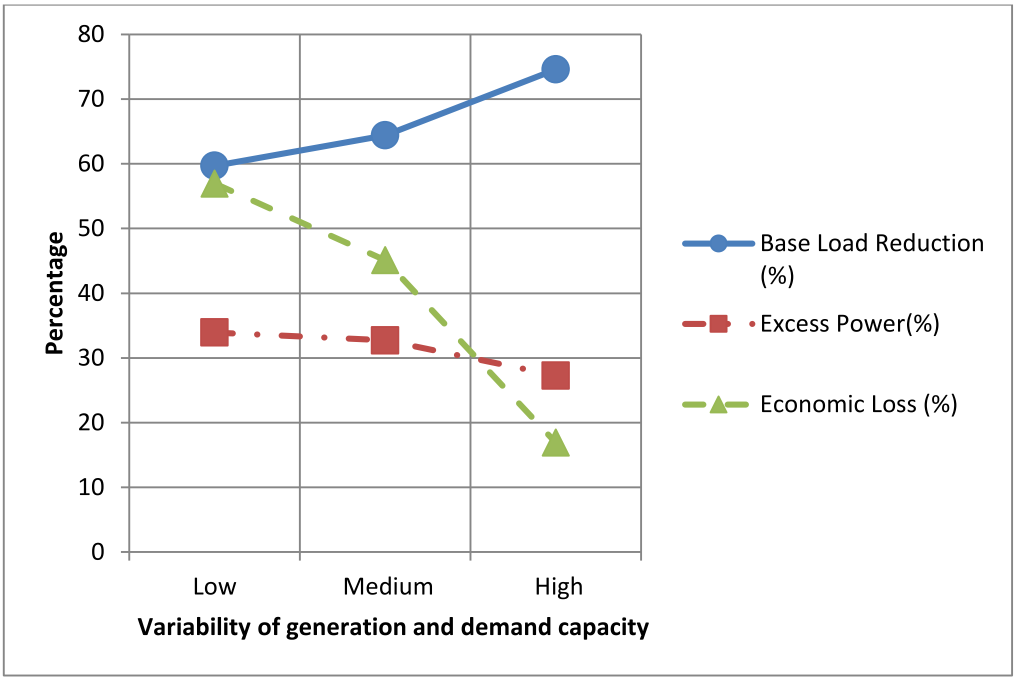

Figure 3-14: The impact of variable generation and demand capacity of micro grids

It can be observed that there is an increase in base load reduction for increasing variability in capacity. For low, medium and high variability, the base load reduction is 59.69%, 64.38% and 74.57% respectively. There is a slight decrease in the amount of excess power in the system for increasing variability of capacity of grids. For low, medium and high variability, the excess power is 33.93%, 32.72% and 27.29% respectively. The economic loss drops significantly for increasing variability of capacity.

As the variability of capacity of grids increases, there are more probability of micro grids with a much wider range of generation and demand capacity. So, there is more opportunity for micro grids to have equilibrium between their generation and demand within the group of micro grids. This ensures the increased power exchange among micro grids which ensures the decreased dependency on national grid. As a result, the base load reduction increases. The wider range of variable generation and demand capacity also increases the power consumption from the generated power within the grid. This is why the excess power is reduced for high variable generation and demand capacity. The economic loss decreases because the reduction of base load and increased consumption of group generated power.

In the following table and graph, the percentage of improvement in evaluation parameter in terms of the low variable generation and demand capacity of micro grid system is observed.

Table 3-12: Percentage of improvement in terms of Low variable capacity

Increased Variable Capacity	% of Base Load Reduction	% of Excess Power	% of Economic Loss
Low to Medium	7.86	3.57	20.81
Low to High	24.93	19.57	70.29

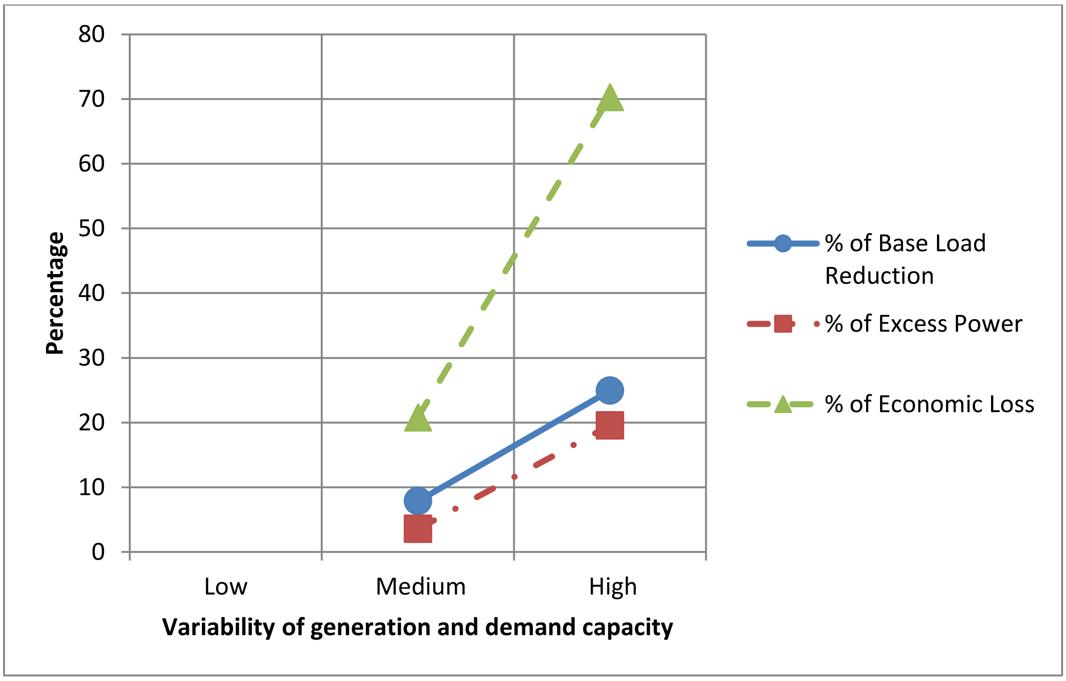

Figure 3-15: Percentage of improvement in terms of Low variable capacity

From table 3.12 and figure 3.15, it can be observed that there is a significant improvement for economic loss for high variable capacity in terms of low variable capacity compared to medium variable capacity in terms of low variable capacity. For base load reduction and excess power, a similar pattern is observed.

3.5.8.3 The Impact of Instrument Malfunction Probability of Micro Grids

In this simulation, the instrument malfunction probability of micro grids will be introduced. When chosen, this will ensure a very low probability for micro grids not being able to generate power. The impact of instrument malfunction on based load reduction, excess power and economic loss will be observed.

For these sets of simulations, only the instrument malfunction probability of grids will be varied. The number of micro grids used for these sets of simulation is taken as 35. The variability of generation and demand capacity of micro grids is set as medium. The intermittency of renewable power generation is not considered for these sets of simulations.

Table 3-13: Simulation parameters

Number of Grids	35
The variability of generation and demand capacity of micro grids	Medium.
The instrument malfunction probability of micro grids	Variable.
The intermittency of renewable power generation	Not considered

The results of these sets of simulations are discussed in below.

Table 3-14: The impact of instrument malfunction probability of micro grids

Is instrument malfunction probability considered?	Base Load Reduction (%)	Excess Power (%)	Economic Loss (%)
Yes	65.55	27.38	52.82
No	67.03	30.61	41.01

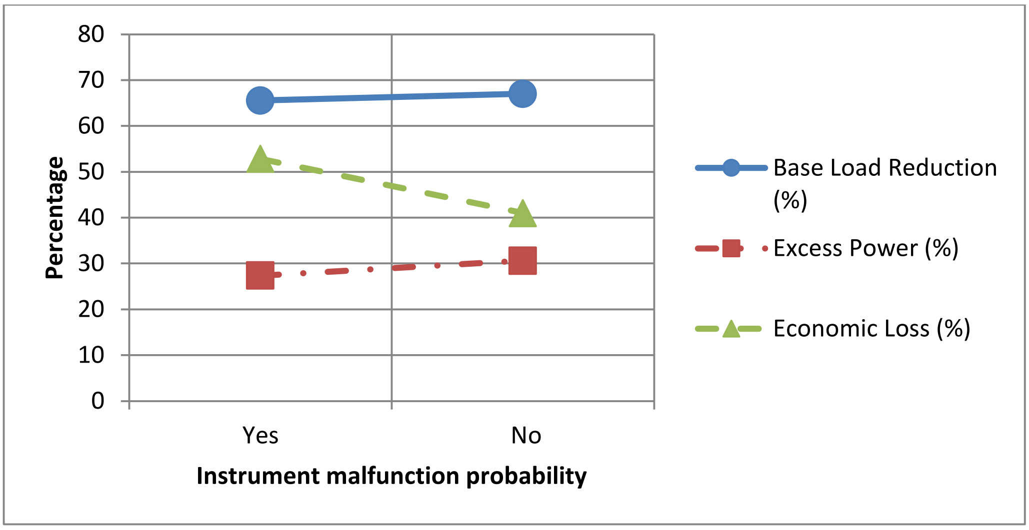

Figure 3-16: The impact of instrument malfunction probability of micro grids

From the above table and figure, it was observed the introduction of instrument malfunction probability has minimal impact on base load reduction. When the instrument malfunction is not considered, the base load reduction is slightly higher (67.03%) compared to when the instrument malfunction is considered (65.55%). Similarly, when instrument malfunction is not considered, the excess power is also slightly higher (30.61%) compared to when the instrument malfunction is considered (27.38%). However, there is 52.82% economic loss when instrument malfunction is considered. When instrument malfunction is not considered, the loss reduces to 41.01%.

The instrument malfunction affects the generation capacity of the micro grids. It does not have any impact on the demand. So, when the instrument malfunction factor is introduced, the generation capacity of the micro girds gets affected. So the micro grids generate less power and depend more on national grid. However, since the probability of instruments malfunctioning is very low, the national grid does not require increasing its base load significantly. There is about 2.26% increase in base load required from national grids perspective. This also ensures that group of micro grids will have less excess power in the system. There is about 11.80% less excess power available in the system when instrument malfunction is introduced. Similarly, since group of micro grids are consuming more power from national grid and have less excess power available to sell to national grid, there is about 22.36% increase in economic loss when instrument malfunction is considered.

3.5.8.4 The Impact of Intermittency of Renewable Power Generation

In this simulation, the intermittency of renewable power generationwill be introduced. The model is designed in such a way that it will introduce variability within a range of 70% to 100% in terms of power generation when this factor is chosen. The impact of the intermittency of renewable power generationon based load reduction, excess power and economic loss will be observed.

For these sets of simulations, only the intermittency of renewable power generationwill be varied. The number of micro grids used for these sets of simulation is taken as 35. The variability of generation and demand capacity of micro grids is set as medium. The instrument malfunction probability of micro grids is not considered for these sets of simulations.

Table 3-15: Simulation parameters

Number of Grids	35
The variability of generation and demand capacity of micro grids	Medium.
The instrument malfunction probability of micro grids	Not considered.
The intermittency of renewable power generation	Variable.

The results of these sets of simulations are discussed in below.

Table 3-16: The impact of intermittency of renewable power generation

Is intermittency considered?	Base Load Reduction (%)	Excess Power (%)	Economic Loss (%)
Yes	50.18	19.51	79.98
No	65.51	31.27	44.84

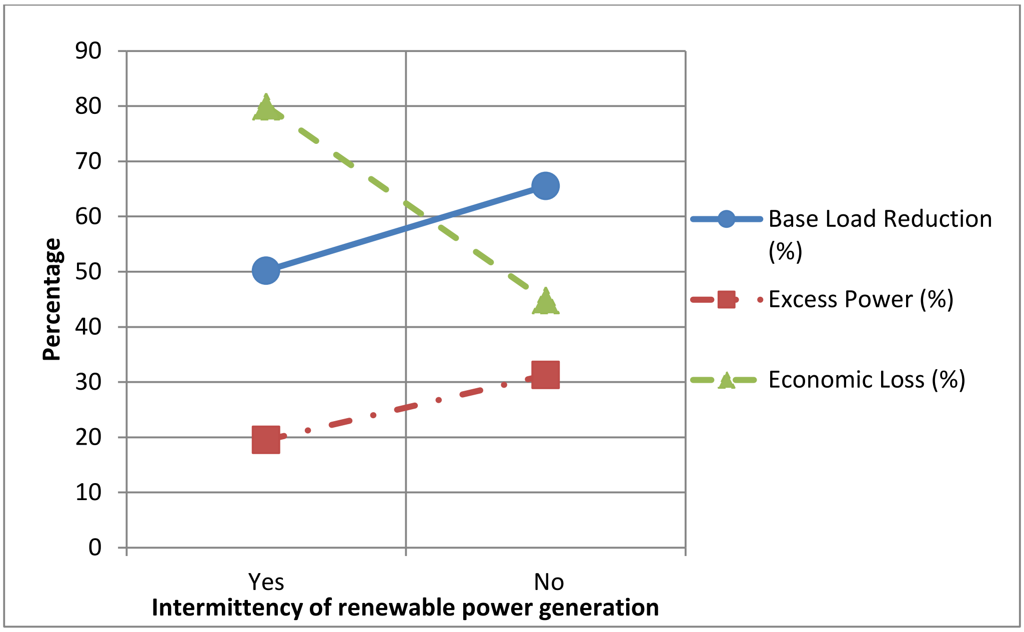

Figure 3-17: The impact of intermittency of renewable power generation

From the above table and figure, it was observed the introduction of intermittency of renewable power generationhas a significant impact on base load reduction. When the intermittency of power generation is not considered, the base load reduction is much higher (65.51%) compared to when the intermittency of power generation is considered (50.18%). Similarly, when intermittency of power generation is not considered, the excess power is also higher (31.27%) compared to when the intermittency of power generation is considered (19.51%). The economic loss is 44.84% when intermittency of power generation is not considered. When intermittency of power generation is considered, the loss increases to 79.98%.

The intermittency of power generation affects the generation capacity of the micro grids. It does not have any impact on the demand. So, when the intermittency of power generation factor is introduced, the generation capacity of the micro girds gets affected. So the micro grids generate less power and depend more on national grid. There is about 30.55% increase in base load required from national grids perspective when the intermittency of renewable power generation is considered. This also ensures that group of micro grids will have less excess power in the system. There is about 32.58% less excess power available in the system when intermittency of power generation is introduced. Similarly, since group of micro grids are consuming more power from national grid and have less excess power available to sell to national grid, there is about 42.89% increase in economic loss when intermittency of power generation is considered.

3.5.8.5 The Performance of the Power Exchange Model in a Realistic Environment

Different parameters of the model have been varied to observe the impact of these parameters in the power exchange system. The impact of the parameters on the power exchange system is logical and follows common sense. This ensures that the power exchange model is performing properly. In this section, the parameters will be set in a way to create a realistic environment. Then the result of model can be used to analyze the performance of the power exchange system in a realistic practical environment.

For these sets of simulations, only the number of grids will be varied. Other parameters will be set based upon the previous results. The variability of generation and demand capacity of micro grids are taken as high. The instrument malfunction probability of micro grids and the intermittency of renewable power generation are considered for these sets of simulations. In this simulation, the number of micro grids in the system will be gradually increased. The simulation process starts with 5 micro grids in the system. Then the number of micro grids will increase by 15 each time. The impact of increasing number of grids on based load reduction, excess power and economic loss will be observed.

Table 3-17: Simulation parameters

Number of Grids	Variable.
The variability of generation and demand capacity of micro grids	High.
The instrument malfunction probability of micro grids	Considered.
The intermittency of renewable power generation	Considered.

The results of these sets of simulations are discussed in below.

Table 3-18: The performance of power exchange model in a realistic environment

Number of Grid	Base Load Reduction (%)	Excess Power (%)	Economic Loss (%)
5	33.7334	55.1944	83.0387
20	46.9847	23.3097	81.5745
35	54.3984	11.6828	78.5565
50	57.2915	9.7741	76.717
65	57.69	8.4546	76.7366
80	58.1532	8.3043	76.3967

In these sets of simulation, it was observed that there is a gradual change in all of the evaluation parameters. As Number of grids increases, the base load reduction also increases. The amount of excess power in the realistic environment of power exchange system of the micro grid also decreases when the number of grid increases. In terms of economic loss, even though there is not a significant decrease, but there is a gradual decrease with increased number of grids.

In these sets of simulation, the micro grids generation and demand capacity is set as high. This ensures that the generation and demand of each micro grid will vary in a wide range. So, the system of micro grids will have a wide range of generation and demand capacity. In the practical environment, different sizes of micro grids are available. The instrument malfunction probability factor ensures that some micro grids may go under maintenance and will not be able to generate power. The intermittency factor includes the most important factor while dealing with renewable energy. As a result, this model is now set up to handle a realistic environment.

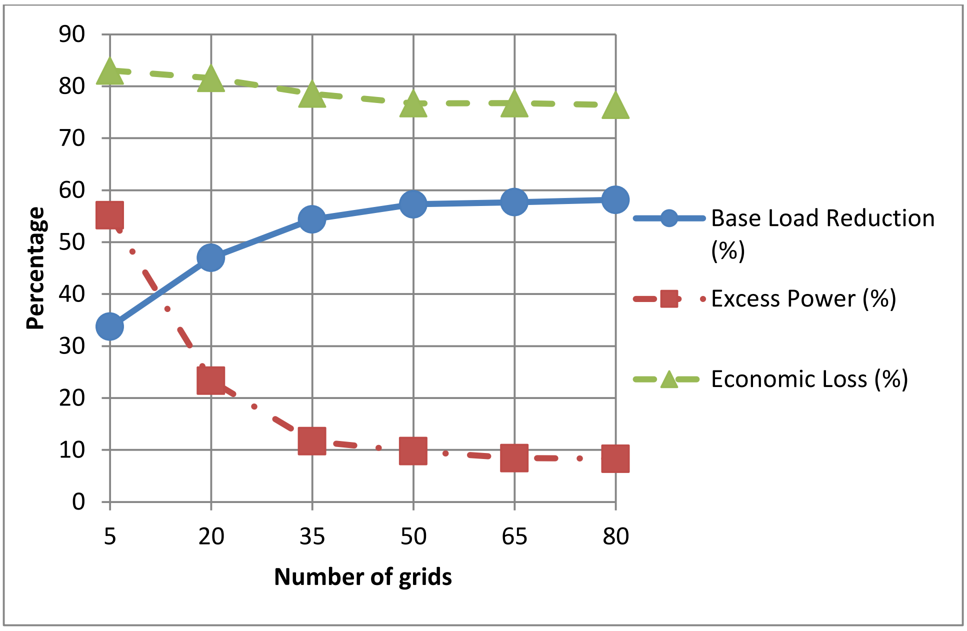

Figure 3-18: The performance of power exchange model in a realistic environment

Table 3-19: Percentage of improvement in terms of 5 micro grids in a realistic environment

% of increase for Number of Grid	% of Base Load Reduction	% of Excess Power	% of Economic Loss
5 to 20, 300%	39.28243225	57.7679982	1.763274232
5 to 35, 600%	61.25976036	78.83335991	5.397724194
5 to 50, 900%	69.83612681	82.29150059	7.612956369
5 to 65, 1200%	71.01744858	84.68214167	7.589352916
5 to 80, 1500%	72.3905684	84.9544519	7.998680133

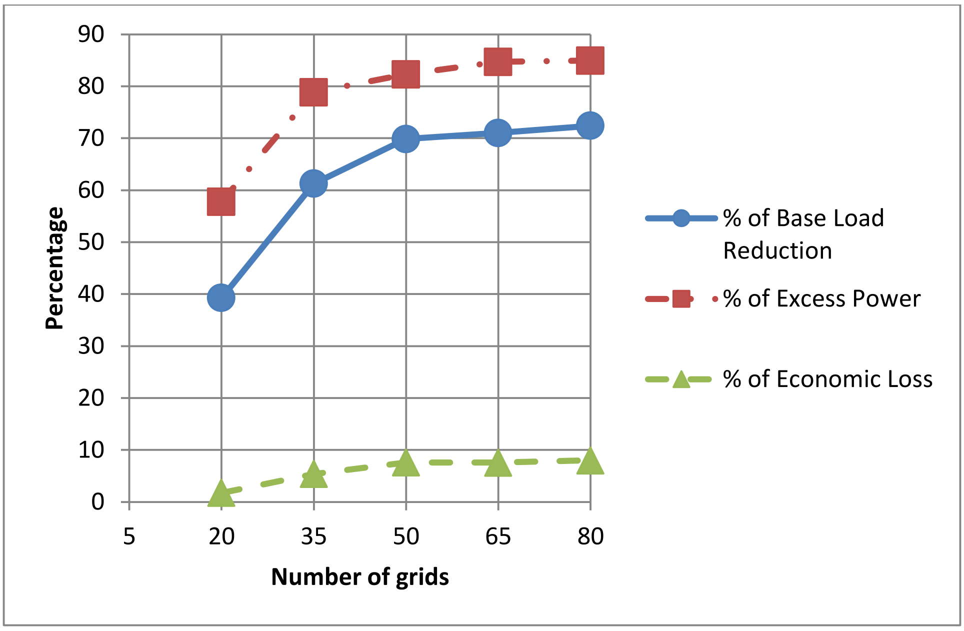

Figure 3-19: Percentage of improvement in terms of 5 micro grids in a realistic environment

As the number of micro girds increases, there are micro grids with different capacity in the system. These micro grids will be able to exchange more power among themselves. This will reduce the dependency on national grid. At the same time, the micro grids will be consuming more of their generated power. As a result, there will be a gradual increase in base load reduction parameter and a gradual decrease in the excess power. In both cases, it was observed that there was a significant change with 50 micro grids in the system while compared to 5 micro grids in the system. After that, the payoffs for increasing more micro grids are not that beneficiary. Similar pattern is also observed for the economic loss parameter. There is a significant improvement till using 50 micro grids system.

3.6 Conclusion

In this section, the conventional power systems and different aspects of the distributed generation and micro grid system have been discussed. The different operation modes of micro grids have also been discussed here. Then a power exchange algorithm has been used to set up a power exchange model for micro grids. The model was used observe and analyze the impacts of different practical factors on the power exchange system of micro grids. The parameters have been set to accommodate a realistic environment to evaluate the performance of the power exchange model in a practical environment. Based on the simulation results it can be concluded that a power exchange system assists significantly to reduce the base load requirement of national grid. It also significantly assists the group of micro grids to consume more of their own generated power. As a result, a group of micro grids, using the power exchange system, will have to pay less compared to a group of micro grids that do not use the power exchange system. So, it is financially profitable for a group of micro grids to use power exchange system. It also significantly assists the national grid to reduce its base load power generation.

Chapter 4

Variability of Wind Resources

4.1 Introduction

Power generation from renewable resources like wind can assist the national grid immensely to reduce its base load. Distributed wind resources, in forms of micro grid, can supply the local demand as well. However, the intermittency of wind resources is a big issue while handling with wind resources [16]. The wind resources in same location for over the years can be variable for the same time period. As a result, the wind power generation becomes variable as well. This makes the accurate forecast of power generation from renewable wind resources more difficult.

A climatological dataset is an average of weather conditions over a period of time [36]. It can be used as a model for approximate determination of the weather conditions based on previous years' experience. However, the real time weather conditions will be different compared to the climatological data. In this section, the variability of the wind resources over the years in same location for the same time period will be observed. The yearly weather data and the climatological data will be collected first. The data for wind resources (the wind speed) will be extracted from these datasets. The wind speed will be converted to a wind power data using Vestas V90 3 MW VAS wind model. Then the variation of wind resources of a particular area over the years will be calculated and represented with graphs and box plots. This will provide an idea regarding the variation of wind power generation from wind resources for different years compared to climatological data.

4.2 Methodology

The climatological data as well as the yearly weather data has been collected using North American databases. For this simulation, four databases of Canadian and U.S. arctic locations were chosen. These are CWEEDS, CWEC [37], NSRDB, and TMY3 [38]. These databases are also used for renewable energy studies. The Canadian Weather Energy and Engineering Data Sets (CWEEDS) is a digital database that contains hourly weather records [39]. The Canadian Weather for Energy Calculations (CWEC) database is a subset of the CWEEDS. Each CWEC file represents one year of the most typical meteorological conditions occurring at the particular location [40]. The National Solar Radiation Database (NSRDB) is based on locations of U.S. It was also developed for similar purposes and NSRDB is equivalent to CWEEDS. Similarly, the Typical Meteorological Year (TMY3) database is equivalent to CWEC. These datasets have a lot of parameters. From these parameters, only the wind speed parameter is chosen. The location chosen for the simulation is Whitehorse, the capital city of Yukon. The yearly wind speed data from 1996 to 2005 for Whitehorse location was collected for this simulation. This data is hourly wind speed data. The hourly climatological data for the Whitehorse location is also collected.

The Vestas V90 3MW VAS [41] wind turbine is used as model of generating power from wind resources. The power curve [42] of the model was used to convert the wind speed to wind power. Figure 4.1 represents the power curve of Vestas V90 3 MW VAS wind turbine. Interpolation is used to generate wind power from wind speed. The amount of power generated is calculated in every hour since the frequency of data collection for climatological data and weather data is hourly. In the Whitehorse location, the wind resources of different years were converted to wind power by using only one Vestas V90 3MW wind turbine.

The climatological data starts from July 1st and ends in June 30th. For this simulation, the years of 1996 July to 1997 June, 2000 July to 2001 June and 2003 July to 2004 June is chosen. Then the comparison with the climatological data for these years was performed and represented with graphs and boxplots.

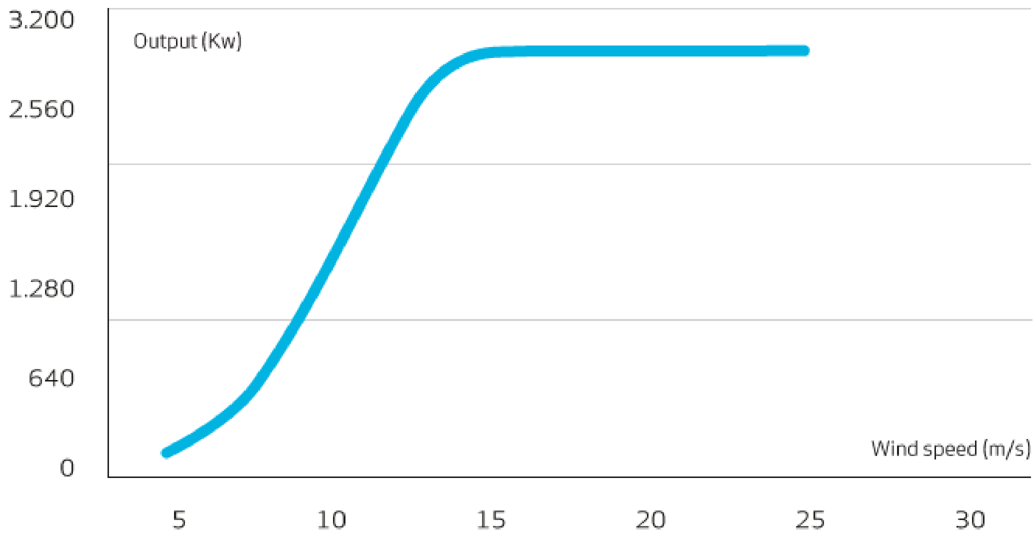

Figure 4-1: Power curve for Vestas V90 3 MW VAS wind turbine [42]

4.3 Result Analysis

The Figure 4.2 has three graphs. The first graph shows the wind power generated for Whitehorse location from the climatological data. The second graph shows wind power of July, 1996 to June 1997 and the third graph shows the variation of wind power compared to climatological data. Figure 4.3 shows the monthly variation of same data with boxplots.

In Figure 4.2, the first graph shows the wind power from climatological data. It is obvious that wind power will be variable due to its inherent nature of intermittency. The total power produced from climatological data in the 12 month period is 3,763.16 MW. The hourly average power production was 0.430 MW. Comparing with the 1996 July to 1997 June, the total power production was 3,472.80 MW and the hourly average power production was 0.396 MW. The wind power profile of period 1996 July to 1997 June is quite similar to wind power profile of climatological data. However there is large drop in wind power production during 1996 September to November period and 1997 February to April period compared to climatological data which can be observed from the third graph of the Figure 4.2. There is almost no wind power generation in the third week of October, 1996. These are the reasons why the wind power production is about 290.36 MW lower than the climatological data. The coefficient of variance of climatological data is 1.54 whereas for 1996 July to 1997 June, it is 1.65.

Table 4-1: Comparing wind power of climatological data & period of 1996 July to 1997 June

	Climatological Data	1996 July to 1997 June
Total wind power generation	3,763.16 MW	3,472.80 MW
Average wind power generation	0.430 MW	0.396 MW
Coefficient of variation	1.54	1.65

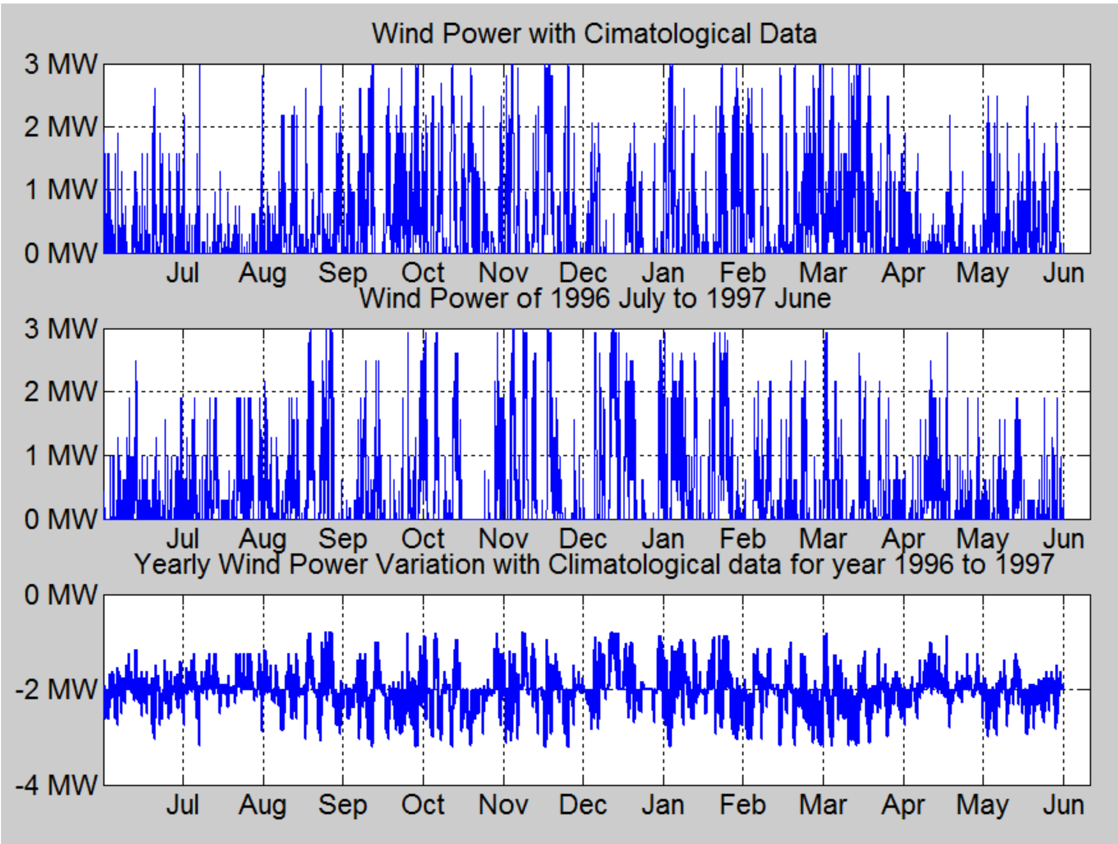

Figure 4-2: Comparison of wind power of climatological data & period of 1996 July to 1997 June with graphs

In Figure 4.3, the spread of power generation data in each month is provided with boxplots. This represents the variation of wind power generation in each month. The first set of boxplots in Figure 4.3 shows that in almost all the months, the spread of wind power from climatological data is mostly in the upper quartile whereas the wind power generation in 1996 July to 1997 is mostly towards its mean. In terms of variation of wind power, it is highly congested around mean with lots of outliers. This represents that wind power is highly variable.

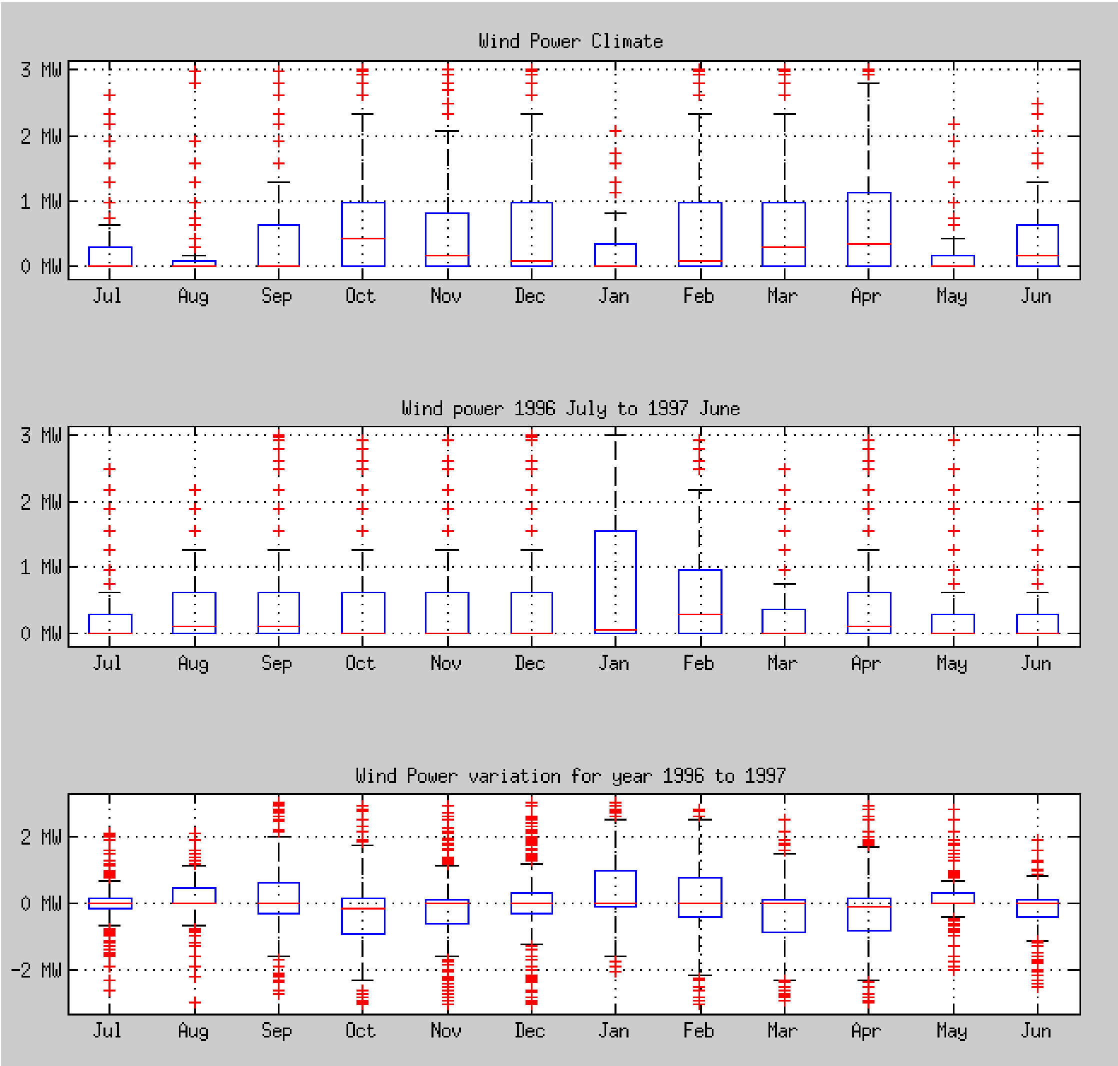

Figure 4-3: Wind power of climatological data & period of 1996 July to 1997 June with boxplots

In Figure 4.4, the second graph shows the wind power generation in 2000 July to 2001 June period. The total wind power generation is 5,515.59 MW which means the overall wind power generation is about 1,752.43 MW greater than the climatological data. The hourly average wind power generation is 0.630 MW which is almost one and half times greater than the hourly average wind power generation of climatological data. The coefficient of variation is 1.30 which is lower than the 1.54 of climatological data. From the third graph of yearly wind power variation compared to climatological data, it is observed that on the third and fourth week in November, the wind power generation was much lower than the climatological data. This means, wind power generation from other months of that period had to be much higher so that the total power generation is greater than the total power generation of climatological data. This is also observed in the yearly wind power variation curve.

Table 4-2: Comparison of wind power of climatological data & period of 200 July to 2001

	Climatological Data	2000 July to 2001 June
Total wind power generation	3,763.16 MW	5,515.59 MW
Average wind power generation	0.430 MW	0.630 MW
Coefficient of variation	1.54	1.30

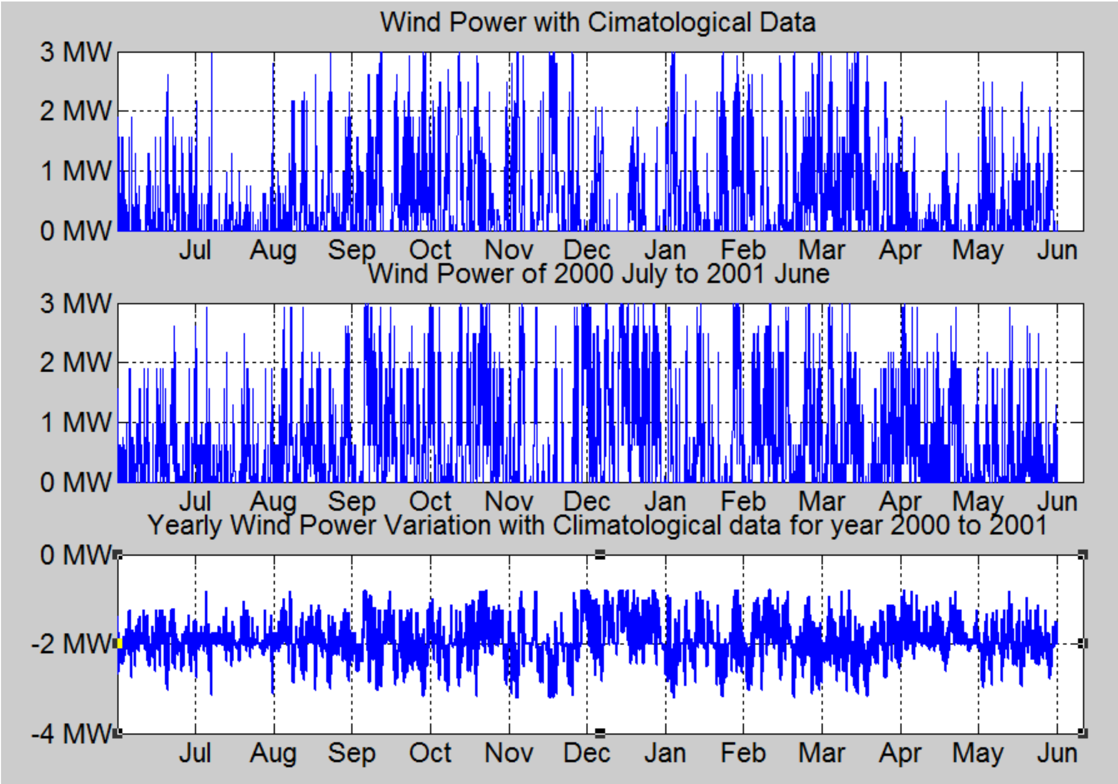

Figure 4-4: Comparison of wind power of climatological data & period of 200 July to 2001 June with graphs

In Figure 4.5, the second set of boxplots show that in January 2001, there was equal spread of wind power generation whereas the wind power generation from climatological data for month of January was mostly in upper quartile. For almost all other months, the wind power generation had similar spread compared to the climatological data. The boxplots of wind power variation shows different type of spread in different months. However, almost all the months have lots of outliers.

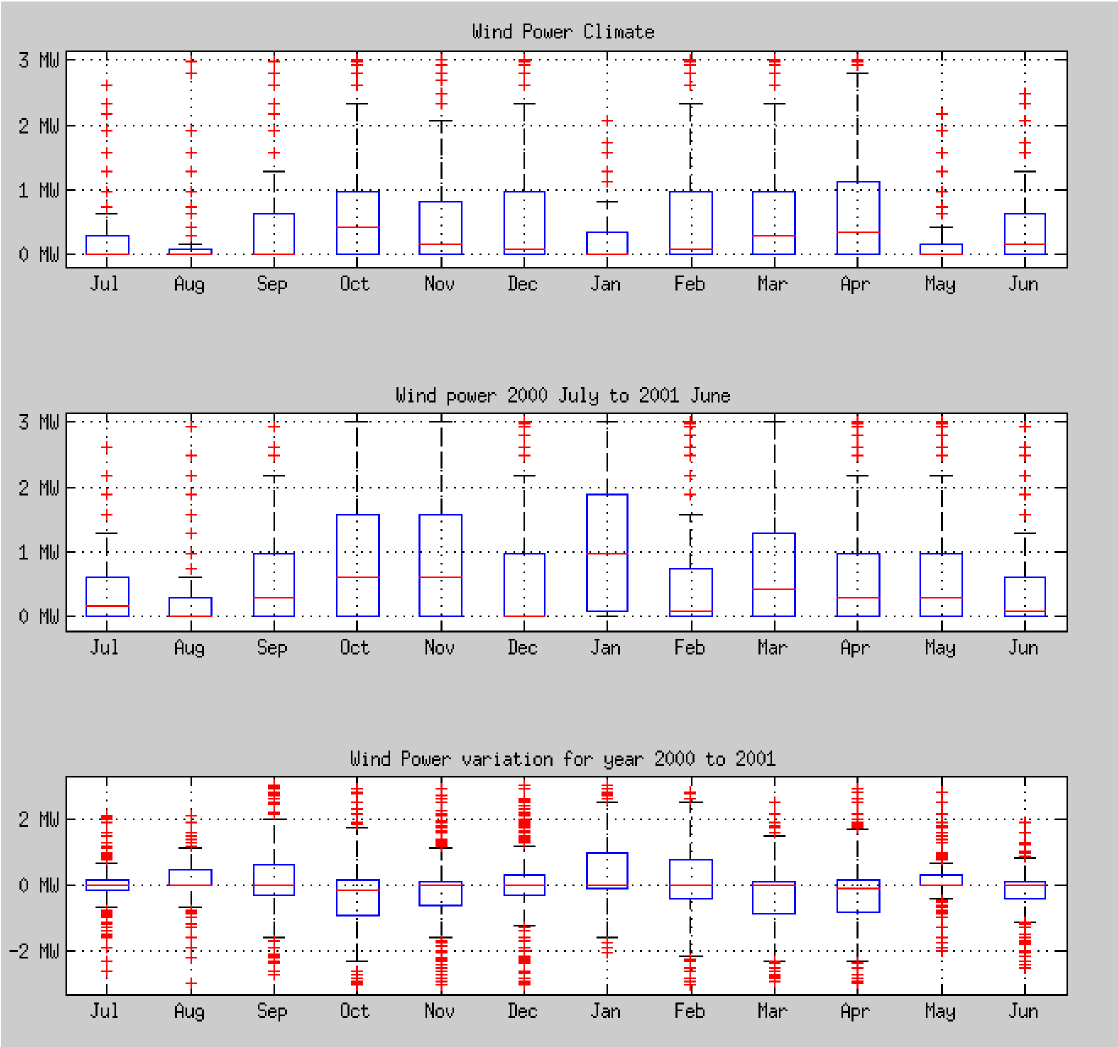

Figure 4-5: Wind power of climatological data & period of 200 July to 2001 June with boxplots

In Figure 4.6, the second graph shows the wind power generation in 2003 July to 2004 June period. The total power generation is 4,576.79 MW which is about 813.63 MW greater than the total wind power generation from climatological data. The hourly average power generation is 0.523 MW which about 93 KW greater than the hourly power generation of climatological data. From the third graph, it can be observed that in the month of July 2003, the wind power generation was almost always greater than the climatological data. Similar scenarios are again observed in second week of December 2003, as well as second and fourth week of April 2004. However, since the wind power generation of rest of the months was quite variable and a lot of the times below the climatological data, the hourly average and total power generation was comparatively lower than the period of 2000 July to 2001 June. This is also represented in the coefficient of the variation parameter which is 1.45. This coefficient of variation is higher compared to 2000 July to 2001 June period, but lower than the climatological data.

Table 4-3: Comparing wind power of climatological data & period of 2003 July to 2004 June

	Climatological Data	2003 July to 2004 June
Total wind power generation	3,763.16 MW	4,576.79 MW
Average wind power generation	0.430 MW	0.523 MW
Coefficient of variation	1.54	1.45

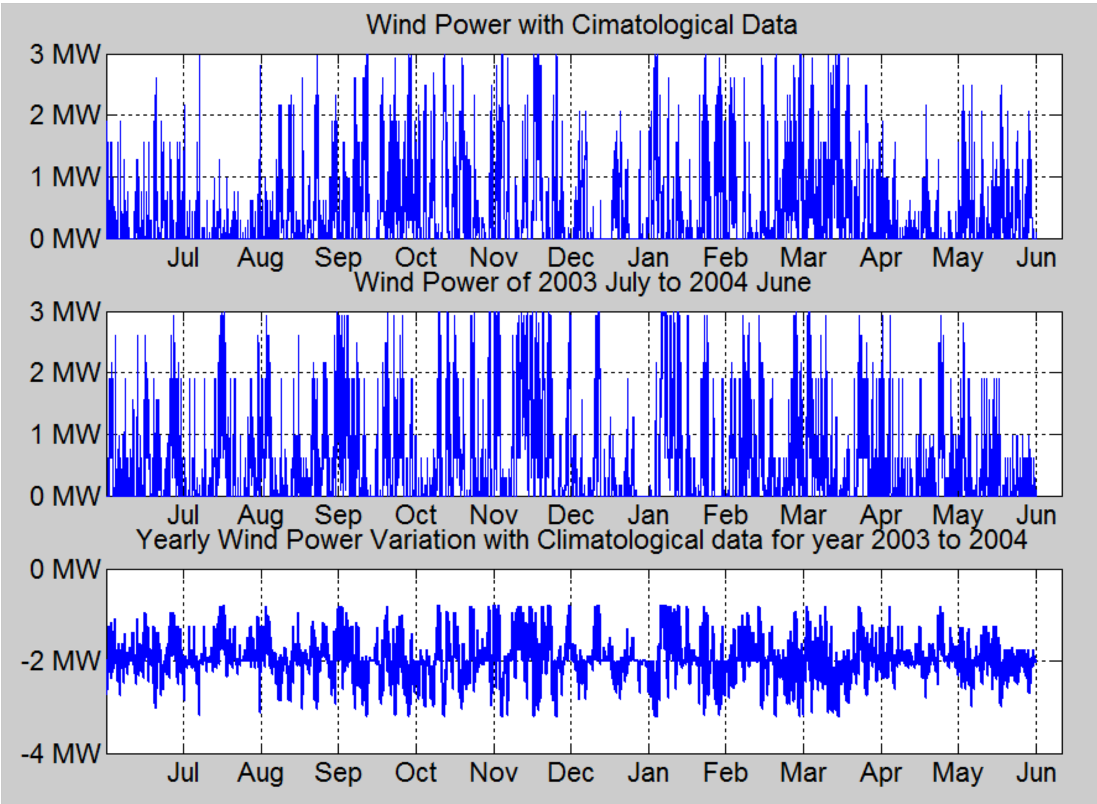

Figure 4-6: Comparison of wind power of climatological data & period of 2003 July to 2004 June with graphs

Figure 4.7 shows the spread of wind power generation in each month of the 2003 July to 2004 June period. It can be observed that in December 2003, the wind power generation was almost equally distributed around the mean whereas the wind power generation from climatological data was mostly distributed in upper quartile. For the month of June 2004, the opposite scenario is observed. The wind power generation is highly congested in the upper quartile and above the mean where the wind power generation was mostly distributed in the upper quartile for the climatological data.

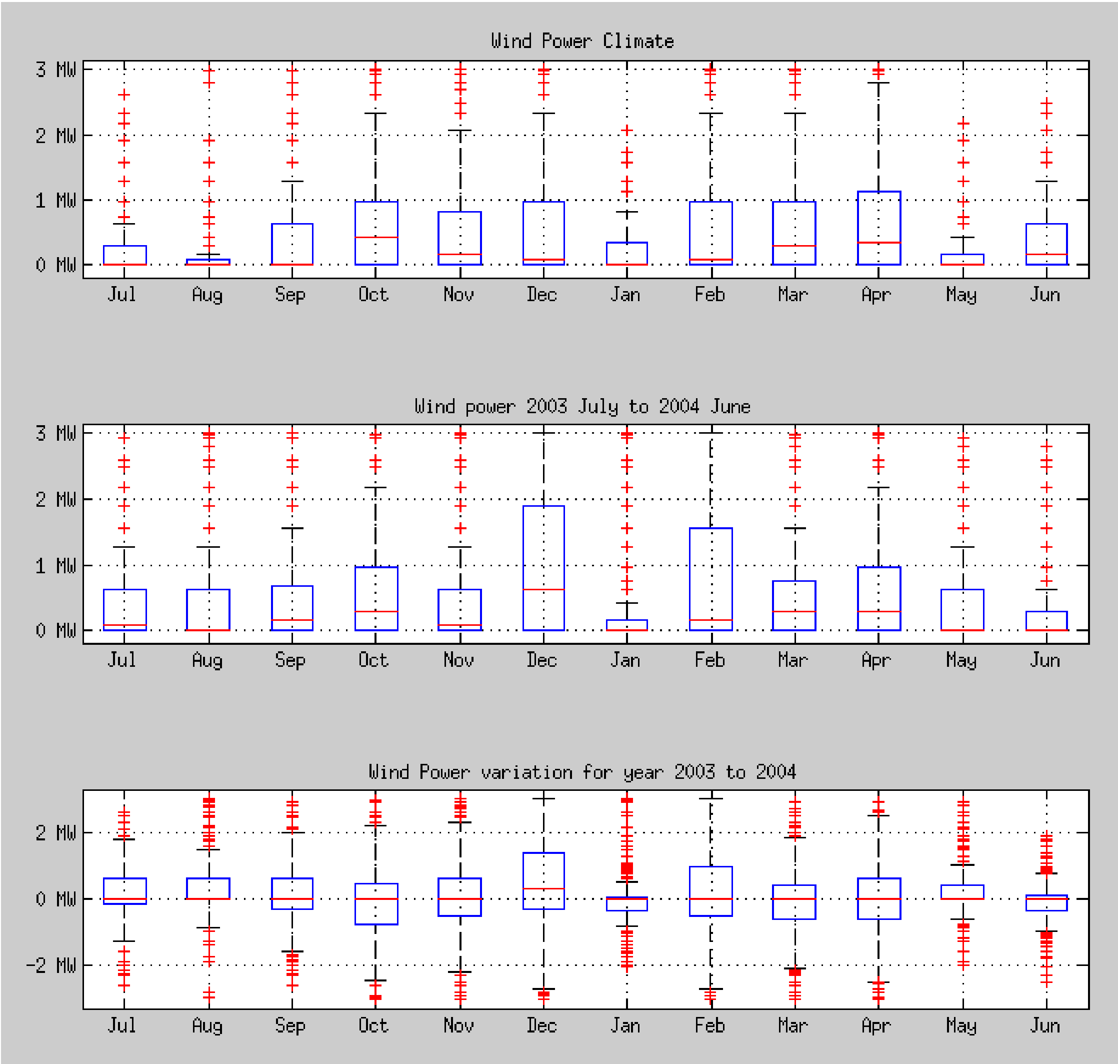

Figure 4-7: Comparison of wind power of climatological data & period of 2003 July to 2004 June with boxplots

From these observations, it can be concluded that wind power is highly variable. The wind power generation of a location in the same time period varies in different years. There might be a lot of wind power generation in one particular period of time and there might be no wind power generation at all in a different time. There can be times when wind power varies significantly within a very short period of time. These fluctuations in power generation can create a lot problem for national grid. So, setting up wind turbines in one location is prone to intermittency of wind resources which causes fluctuations in wind power generation.

4.4 Conclusion

Renewable energy resources like wind power can assist the national grid significantly to reduce its base load. However, wind resources are highly intermittent. This section shows the generated wind power from the wind resources of one area in same time period in different years. This is compared with the wind power generated from the climatological data. The comparison is represented with graphs and boxplots. From this analysis it can be concluded that wind resources are highly intermittent. There can be plentiful of wind power generation and no wind power generation in different time periods. It is also difficult to predict the availability of wind resources and it varies from the climatological data as well. As a result, setting up wind turbines only in one area will provide highly fluctuant wind power which is undesirable to the national grid.

Chapter 5

Distribution of Wind Power Plants to Reduce Variability of Renewable Generation

5.1 Introduction

The wind power has been used in human civilization for decades. The older ships used to sail using wind power. Wind power was used to pump water as well and for several other purposes. In recent years, wind is used to generate electricity and the wind power is getting more and more popular. Wind being a renewable energy resource, is a good inspiration for generating electricity in a clean way. Wind is free and wind is always blowing in different places. An inherent characteristic of wind is its intermittency. So, even though wind is always blowing in different places, it may not be blowing at the required place at the required time period. The wind speed also varies in the same location in different time periods as well. A distributed nature of wind resources over a wide area might provide the balance of wind power generation which can compensate the intermittent nature of wind.

Wind power generation is growing worldwide. Canada has a good prospect in terms of wind power. In North America, a technical standard for connecting wind power facilities to transmission grid was first developed in Alberta [43]. Figure 5.1 shows the growing installed capacity of wind power in Alberta. From year 2007 to year 2009, the installed wind capacity was within range of 450 MW to 590 MW. From year 2010 to year 2012 there has been a steady increase in wind power capacity in Alberta within the range of 780 MW to 1190 MW. By the year 2024, the capacity of wind power generation could reach 2,263 MW which could represent eleven percent of installed capacity [43]. This generation capacity could increase by about 1,245 MW by the end of 2034 [43]. Currently, the total generation capacity of wind power in Alberta is 1,419.10 MW [44].

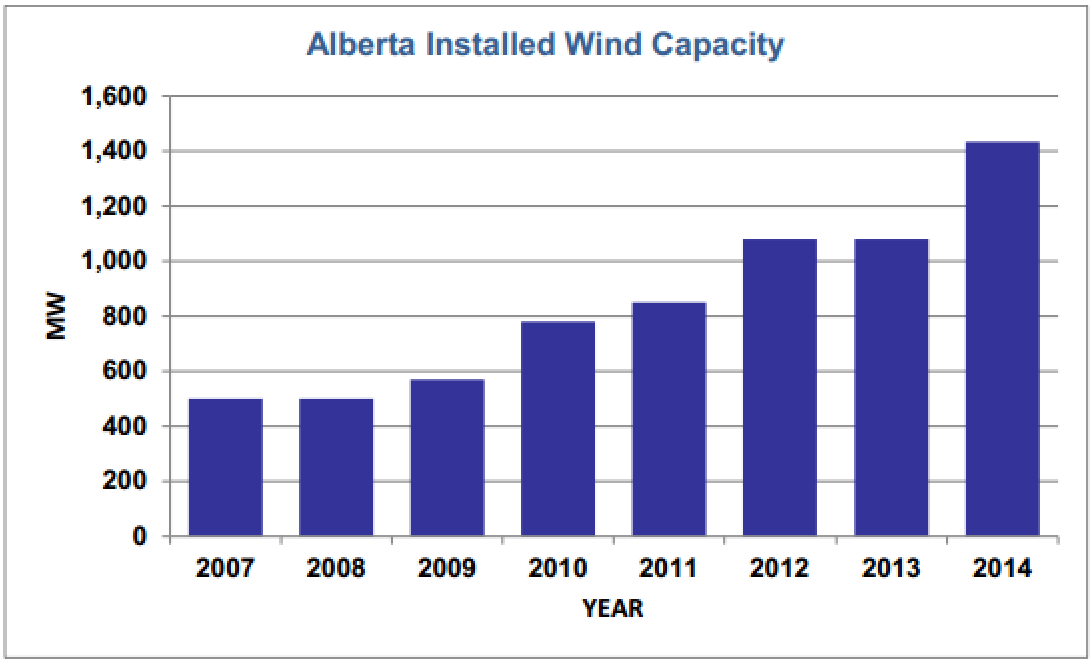

Figure 5-1: Alberta installed wind capacity and prospective wind additions

In British Columbia, the first installed wind power capacity was of 102 MW [45]. In 2011, the installed wind power capacity had reached to 247.5 MW [46]. Currently, the total generation capacity of wind power in British Columbia is 488.7 MW [44]. The Peace River valley has a great potential for wind power generation for its favourable geography [47]. It is located in prairies of Alberta, near to British Columbia border. It has strong and constant wind [47]. This location, along with some other location can be suitable sites for wind power generation.

In this section of the thesis, the possibility of integration of wind power from distributed wind resources over a wide, spatially distributed area to reduce the overall variability of wind-generated power will be analysed [48]. At first, the computational experiments to support the analysis are based on the wind resources of the province of Alberta. Later on, the similar experiments will be done by taking the province of Alberta and British Columbia together.

5.2 Integration of Spatially Distributed Wind Resources

Alberta, a province in Western Canada, has an area of 661,190 km^2. Its neighbors are the British Columbia (west), Northwest Territories (north), Saskatchewan (east), and Montana (south). The province of Alberta is mostly quite flat. The oil sands industry, located mostly in the northeast, is a major energy consumer. There are many industrial and population centers in the southern part of the province, and a few towards the west as well. The area of British Columbia is 944,735 km^2. On the west side, there is the Pacific Ocean. Yukon and Northwest Territories are on the north side where as the Washington, Idaho and Montana are on the south side. It shares its eastern border with Alberta. The Rocky Mountains in between Alberta and British Columbia creates an interesting wind pattern. There is an interest in studying the issues related to the large scale integration of wind generation [48]. This concern also includes the reliability of power supply. Wind power is associated with intermittency. Also, the wind power generation may not coincide with high demand periods. So to compensate the variability of wind power generation, power generation from alternative resources as a backup power generation is required. Hydro and gas fired power plants are quickly dispatchable power generation sources which can be used to compensate the variability of wind power. Another aspect might be to integrate wind resources in a wide spatially dispersed area. The idea is, since wind is not blowing everywhere in the same time, by integrating distributed wind resources, the total wind power generation may remain less variable. If wind power is not generated in one location due to lack of wind speed, wind power generation can be picked up in a different place where wind power generation may be available at that period of time due to sufficient wind speed. Alberta and British Columbia both are large provinces. The southern side of Alberta has good wind resources. The Rocky Mountains creates a barrier for wind in between Alberta and British Columbia. There is a ridge in southern side of Alberta and British Columbia. The province of Alberta is also quite flat. So by integrating wind power in the province of Alberta can reduce the variability of wind power generation which may reduce the base load requirement by the fossil fuel power generation resources. The variability of wind power generation may be reduced even more by integrating wind resources of Alberta and British Columbia together.

5.3 Description of Data

The wind data used for the experiments described in this section has been extracted from the North American Regional Reanalysis (NARR) database. This data is distributed on a native Lambert conformal grid that has a horizontal resolution of 32 km. The NARR database is produced using 29 vertical pressure levels. National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) are Global Reanalysis project. The observations in NCEP/NCAR Global Reanalysis project are used as input data for NARR database. It also includes wind profiler data, precipitation data, moisture data etc. To represent averages, output analyses are 3-hourly with additional 9 variables in the 3-hour forecasts. For this experiment, the NetCDF (Network Common Data Form) data from NARR database for year 2012 is used [49].

5.4 Methodology

A simulation model with MATLAB is developed for the integration of spatially dispersed wind resources to reduce the variability of wind power while keeping the average wind power generation as constant as possible. The flow diagram for the model is shown in figure 5.2.

At the beginning, the data is preprocessed. In this part, the data of the required province is first filtered out. Then it is converted to wind speed based on the Vestas V90 3MW VAS wind turbine model which is going to be used in the experiment.

The user provides the initial conditions for the experiment. Initial conditions that user provides are: the number of locations in a set of location, the total number of turbines, total number of iterations, the initial temperature and peak demand.

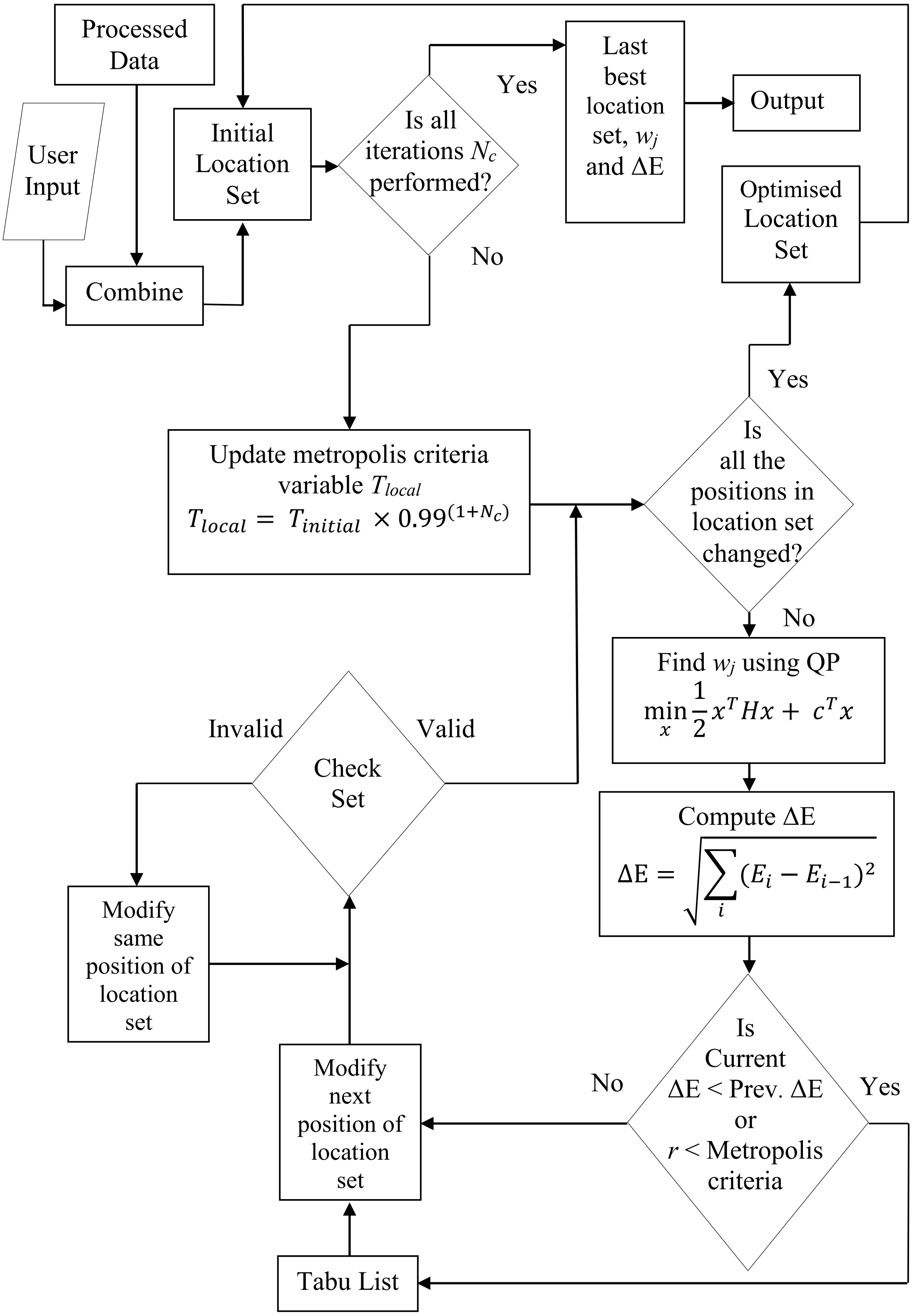

Figure 5-2: The flow diagram of the simulation model

Then based on the user provided input, the initial locations from the preprocessed data is chosen. The choice of the locations follows the uniform random distribution which provides every location an equal opportunity to be chosen. Here begins the first set of optimization which optimizes the locations in a location set. The set of locations first go through a validity check which ensures that there is no repetition of locations in the same location set as well as it checks whether this location set is already being experimented with. It is checked by comparing this set of location with the location sets which are stored in tabu list. This ensures that the same sets of locations are not repeated.

Then, the program checks whether the model is iterated for the required number of iterations. If yes, then the last best set of locations with their respective weight distribution for number of turbines and temporal variability are sent to the output. If the required number of iterations is not performed, then the metropolis criteria is updated.

In the metropolis criteria, the local temperature decreases with the increase of number of iterations. It ensures the balance between exploration and exploitation. At the beginning, the program explores for different set of locations. As the number of iterations increases, the program starts to exploit for the best set of location. In this way, the solution can avoid the local minima.

In this section, suppose a location set of 5 locations are being chosen. Here begins the optimization for the turbine distribution. The weights of turbines in each location will be assigned using the quadratic programming to obtain the minimum temporal variability. The wind power and the temporal variability of wind power will be calculated using the location set and the number of turbines for each location. Then the temporal variability of this location set will be compared to check whether it is smaller than the temporal variability of previous location set. At the same time, a random number, r, in range of 0 to 1 will be generated and compared to check whether it is smaller than the metropolis criteria. If either of them is true, then the tabu list will be updated by storing this location set. Otherwise, the next position in the location set (in this case, the first position) will be varied with a random uniform distribution. The location set then goes through the location set validity so that same locations are not repeated in same location set. It will remain in this loop until a unique set of location is identified. It will then check whether all the positions in the location set is changed or not. Then new weights for the number of the turbines will be assigned and the wind power as well as the temporal variability of wind power will be calculated. Again, the temporal variability of wind power of this new set of locations will be compared with the temporal variability of previous set of locations. At the same time, random number *r* will be generated and compared with the metropolis criteria. If the new temporal variability is not less than the temporal variability of previous set of locations, or *r* is not less than metropolis criteria, then this set of locations will not be accepted and the next position (second position in this case) in the location set will be changed with uniform random distribution. Otherwise, this set of locations will be stored in tabu list and the next (second position in this case) position of the location set will be changed and similar procedure will be followed. After all the locations in the location set (for this example, all 5 positions in the location set) are changed, then the program will save this set of locations and their corresponding weight distribution of the turbines as the optimized set of locations which will be used as the initial location set for next iteration. Then the program will go to next iteration and the metropolis criterion will be updated and the whole process will be repeated until the required number of iterations are performed.

5.4.1 Data Preprocessing

At the beginning of the program, the data from the NARR database is first extracted and preprocessed. Only the locations of the NARR database which are required for this experiment is first filtered out from the whole NARR database. For the first case, it's the locations that fall within the border of Alberta is chosen. For the second case, the locations within the border of Alberta and British Columbia are chosen. The five corner locations of the Alberta provinces outline have the following latitudes and longitudes (clockwise starting with the northwest corner):

- Latitude 60.0100, longitude -120.01470,
- Latitude 60.0429, longitude -110.03910,
- Latitude 48.9802, longitude -109.9951,

- Latitude 49.0091, longitude -114.0820,
- Latitude 54.5211, longitude -120.0586.

The nine corner locations of the Alberta and British Columbia provinces outline have the following latitudes and longitudes (clockwise starting with the northwest corner):

- Latitude 59.9989, longitude -139.0539,
- Latitude 60.0429, longitude -110.0391,
- Latitude 48.9802, longitude -109.9951,
- Latitude 49.0018, longitude -123.3215,
- Latitude 48.5020, longitude -124.7827,
- Latitude 54.7626, longitude -130.6549,
- Latitude 56.1210, longitude -130.1055,
- Latitude 59.7978, longitude -135.4806,
- Latitude 58.9117, longitude -137.5241.

These locations are considered for respective simulation. The NARR database contains two horizontal wind components u and v. The wind speed can be calculated from these components as follows

$$V = \sqrt{u^2 + v^2} \dots \dots \dots (6.1)$$

This formula calculates the wind speed at 10 m above ground level (a.g.l.). The wind turbine considered in this study is the model Vestas V90 3 MW VAS. The rotor diameter of this turbine is 90 m, and hub height for 80 m [41]. The wind speed at 10m a.g.l. can be converted to the hub height as follows [50]

$$V_z = V_r \left(Z / Z_r \right)^P \dots \dots \dots (6.2)$$

where, V_z is wind speed at hub height Z (assumed to be 80 m), V_r is the wind speed at the references height, Z_r is the reference height of 10m, and p is the surface roughness factor (0.143) from the wind profile power law [50].

5.4.2 Optimization Methodology

The problem of optimal distribution of wind power plants involves two optimization procedures. The first procedure is to select the locations. It chooses certain number of locations out of all NARR locations corresponding to province concerned. Suppose, for the province of Alberta, the NARR database contains 637 possible locations. This procedure is implemented using simulated annealing (SA) [51-52]. The second optimization procedure is to distribute the total required number of turbines across the locations selected in the first step. This is implemented using quadratic programming [53-54]. The goal of these two optimization procedures is to reduce the temporal variability of wind power generation through integration of power from distributed wind resources. All simulations use a simplified model of wind farms that assumes that all wind turbines are at the same location.

5.4.2.1 Location Optimization

The time series of wind power generation for each location is represented as Eij where i = 1, 2, 3, … … … , 2928 (since year 2012 was a leap year and data was collected every 3 hours), and j = 1, 2, 3, … … … , n, where n is the number of location to be selected from the filtered locations. Thus, the total wind power generation for n locations is $\sum_{i=1}^{2928} \sum_{j=1}^{n} w_j E_{ij}$

where w_j is a weight representing the relative number of turbines at location j, and $\sum_{j=1}^{n} w_j = 1$.

The general cost function used for optimization described in this study has the form

$$\Delta E = \sqrt{\sum_i (E_i - E_{i-1})^2} \;\dots\dots\dots\; (6.3)$$

that describes the temporal variability ΔE of the total wind power generation E [48].

The locations of wind farms are selected using simulated annealing. The procedure requires the following parameters: the number of locations n, initial temperature, number of iterations, the total number of turbines to be used, and the peak demand. In this first step, the relative number of turbines at individual locations are assumed to be equal, i.e.

$$w_j = \frac{1}{n}$$

At the beginning of the simulation, the NARR data is read, desired locations extracted, and the wind component data is converted to wind speeds. From the user provided number of locations n, the algorithm randomly generates a set of uniformly distributed locations. The wind speeds of the randomly selected locations are retrieved and then converted to wind power data using a model of Vestas V90 3MW turbines [42].

The initial annealing temperature, used to generate the local temperature for metropolis criterion [42], is set to T_{init}= 100, and the number maximum of iterations N_{max}= 1600. The value of local temperature is set at 100 because initially, when the number of iteration is very low, the local temperature will be very high. Figure 5.3 shows that the local temperature decreases and becomes close to zero as number of iteration increases. As a result, initially the metropolis criteria pushes for exploration by taking different type of location sets. As the number of iteration increases, the metropolis criteria pushes for exploitation. So a balance between exploration and exploitation is maintained.

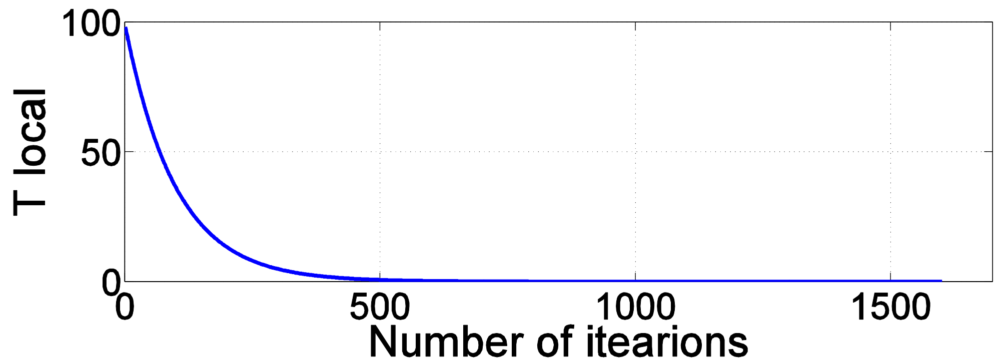

Figure 5-3: The curve for metropolis criteria showing local temperature with increasing number of iteration

Alberta has 14,003 MW of installed generating capacity [3]. The peak demand in 2012 (climatic year) was 10,599 MW down 10 MW from 10,609 MW in 2011 [3]. So, for this experiment, the peak demand is set as 11,000 MW.

The total number of turbines N used in the province of Alberta experiment is set to 30,000. This number is obtained by trial and error procedure to obtain about 5,000 MW of average wind power generation. Similarly, for the Alberta and British Columbia experiment, the total number of turbines used is 50,000 to obtain about 5,000 MW of average wind power generation.

The optimization process starts with a random selection of the first set of locations using a uniform random distribution. It is ensured that no duplicate location is in the same location set. Then the cost is calculated using the location set and distribution of turbines (explained in next sub-section) and the new location is accepted only if the new location set produces a lower cost than the previous set or if it justifies the metropolis criterion (this ensures that the simulation does not get stuck in a local minimum). The initial temperature, set to $T_{init} = 100$, determines the degree of exploration. The local temperature is determined as follows

$$T_{\text{local}} = T_{\text{init}} \cdot 0.99(1+N_c) \dots \dots \dots (6.4)$$

where N_c is the current iteration number. At the beginning, the metropolis condition is satisfied almost always so that almost all new location sets are considered. This is performed by comparing the metropolis criteria with a randomly generated number within the region of 0 to 1. This way, the simulation performs exploration. As the iteration count increases, N_c becomes higher. Consequently, variation of cost of previous and current set of locations becomes more prominent. Thus, at higher values N_c, a new set of locations will be accepted only if it produces a lower cost from previous set.

This process is repeated $n - 1$ times for a location set of n locations. This way, all locations in a location set are changed once, checked so that the same location is not repeated. Then the cost function is calculated within one iteration of N_c and this final optimized location set becomes the initial location set for the next iteration. The output of this step is a set of locations that produces the least cost.

5.4.3 Optimization of Turbine Allocation

Based upon the locations found in the first step, the second step optimizes the distribution of turbines in each location using quadratic programming. This optimization step uses the built in MATLAB function quadprog [53]. It minimizes the following quadratic function of vector **x**

$$min_x \frac{1}{2} x^T Hx + c^T x \dots \dots \dots (6.5)$$

subject to a linear constraint. The lower bound is set to 0 while the upper bound is left unbounded. The optimization tasks in this study have been performed using interior point algorithm [53-54] with the cost function (equation 6.3). After obtaining the relative number of turbines for each location, the wind power generation at each time step is recalculated. Then, the variability of wind power generation for that set of locations is calculated according to the cost function.

5.5 Result Analysis

This section will discuss the results of the experiments. There are three experiments which are performed. In the first set of experiments, only the wind resources of the province of Alberta is considered. In the second set of experiments, the wind resources of the province of Alberta and British Columbia together is considered. In the third set of experiments, the wind resources of Alberta and British Columbia province is considered, but with a different cost function. In the third set of experiments, the coefficient of variation will be used as cost function and results will be analyzed.

5.5.1 Integration of Distributed Wind Resources in Alberta

The simulation model is first executed for one location in a location set. However, an acceptable convergence curve is visible from two locations in a location set. Then the number of locations in the location set is gradually increased by one until the number locations reaches 15. Figure 5.4 shows the convergence curve in terms of variability as cost function using equation (6.3). For the iterations among about 500 to 590, it can be observed that a local minima for 15 locations in a location set is obtained. However, due to the exploration principle of metropolis criterion, a new set of 15 locations were found whose variability was higher. This phenomenon is called hill climbing [51-52]. As number of iterations increases, it was observed that new set of 15 locations were found whose variability is much lower than previous set of locations. The curve clearly shows how exploration using metropolis criteria helps to escape local minima. The algorithm gradually finds a set of locations that produces smallest variability of total wind power generation. Similar trend can be observed for each size of location set between 2 and 15.

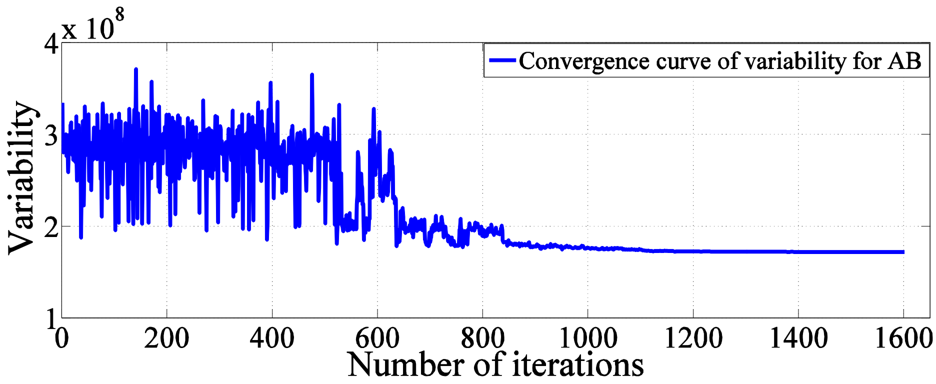

Figure 5-4: Convergence curve of temporal variability for 15 locations in a location set

Figure 5.5 is a map showing an outline of the province of Alberta with 15 locations selected using SA. It can be observed that the 15 selected locations are spatially dispersed all over the area of the province. Apparently, they can be grouped into four clusters in the four corners of the province. There are few locations close to the Rocky Mountains where as few locations are on the farthest northwest of Alberta. There are some locations in northeast and southeast border as well. It can be concluded that since the locations are spatially distributed all over Alberta, the wind profiles of these locations complement each other. When generated wind power in these locations are integrated, the total power provided from all locations has smaller variability compared to the individual locations. In other words, wind profiles of these locations are different from each other and complements each other.

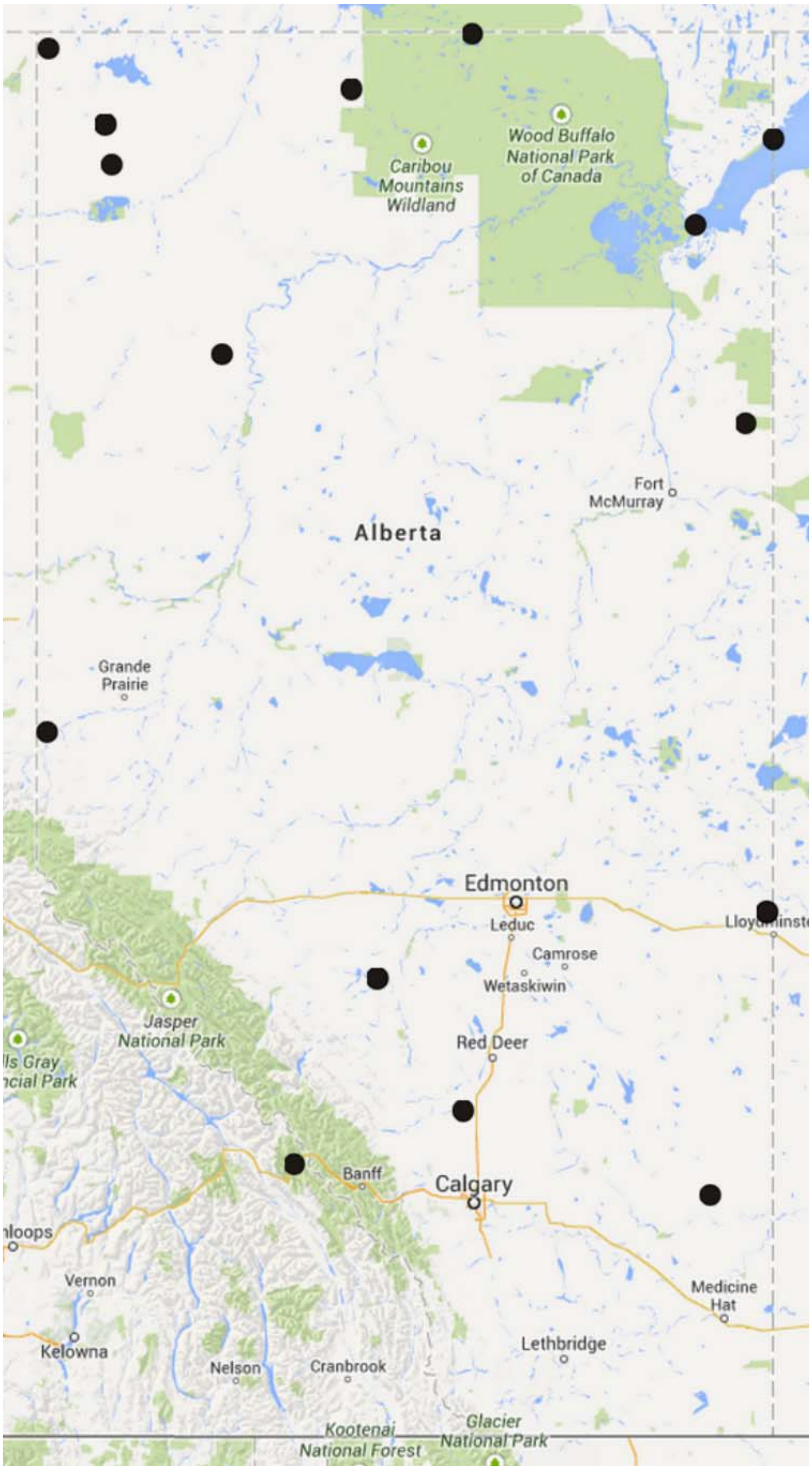

Figure 5-5: Map of 15 optimized locations in Alberta [55]

Figure 5.6 shows the coefficient of variation for increasing number of locations. Coefficient of variation is the ratio of standard deviation to average. As distributed wind resources are integrated together, the coefficient of variation of wind power generation also decreases. Since wind is highly intermittent, the wind resources from spatially dispersed locations can have different wind profile. These spatially dispersed wind resources can complement each other in such a way that when wind is not available at one location, it may be available at a different location. By integrating wind power from distributed wind resources, the overall variability can be reduced.

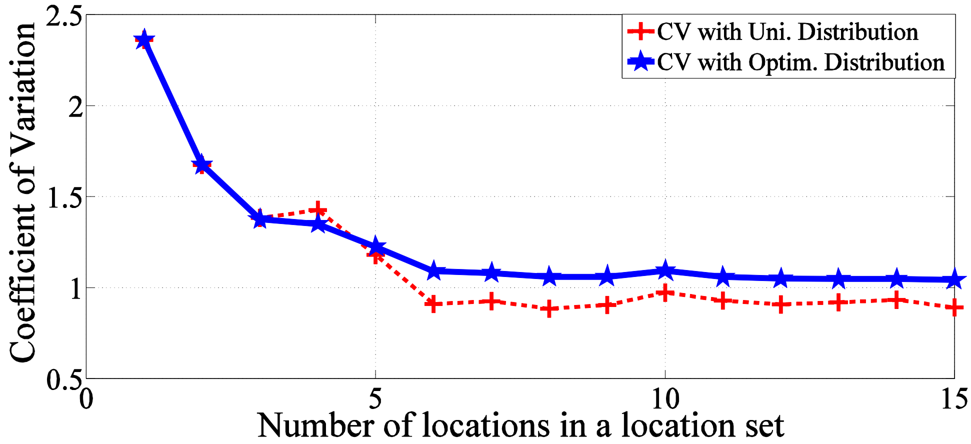

Figure 5-6: Coefficient of variation (CV) for increasing number of wind sites

In this simulation model, the distribution of turbines in different locations is optimized. This is done to further reduce the variability. The results of this second optimization task are shown in table 5.1 and figure 5.7. The simulation model also considers the case where turbines are distributed uniformly across all locations. From Figure 5.6, it can be seen that the coefficient of variation has lower values in uniformly distribution of turbines compared to the optimized distribution of turbines. This can be explained in terms of the average power shown in figure 5.9. The average power generated with uniformly distributed turbines is significantly higher than with the optimized distribution. Since coefficient of variation is a ratio of standard deviation to average, the higher average power production with uniform distribution of turbines produces lower values of the coefficient. However, the graphs of figure 5.6 also indicate that with optimized distribution of turbines, the coefficient of variation is more consistent (it levels off) for higher number of sites, compared to the uniform distribution.

Table 5-1: Relative distributions of turbines across locations for n = 1-15 for Alberta

n	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	W_{11}	W_{12}	W_{13}	W_{14}	W_{15}
1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	.636	.363	-	-	-	-	-	-	-	-	-	-	-	-	-
3	.508	.282	.209	-	-	-	-	-	-	-	-	-	-	-	-
4	.492	.261	.17	.075	-	-	-	-	-	-	-	-	-	-	-
5	.484	.221	.164	.069	.06	-	-	-	-	-	-	-	-	-	-
6	.469	.212	.161	.067	.057	.031	-	-	-	-	-	-	-	-	-
7	.452	.184	.183	.059	.049	.043	.027	-	-	-	-	-	-	-	-
8	.436	.175	.16	.062	.049	.046	.039	.028	-	-	-	-	-	-	-
9	.432	.16	.158	.055	.045	.045	.038	.035	.027	-	-	-	-	-	-
10	.438	.157	.15	.053	.045	.041	.032	.029	.026	.025	-	-	-	-	-
11	.43	.155	.15	.051	.044	.04	.035	.029	.026	.023	.011	-	-	-	-
12	.428	.157	.148	.051	.042	.034	.031	.031	.025	.025	.012	.009	-	-	-
13	.429	.156	.139	.052	.042	.034	.03	.026	.025	.024	.021	.008	.007	-	-
14	.427	.156	.138	.051	.042	.029	.027	.025	.024	.024	.019	.013	.01	.008	-
15	.427	.156	.139	.052	.042	.029	.028	.025	.024	.024	.019	.014	.008	.006	.002

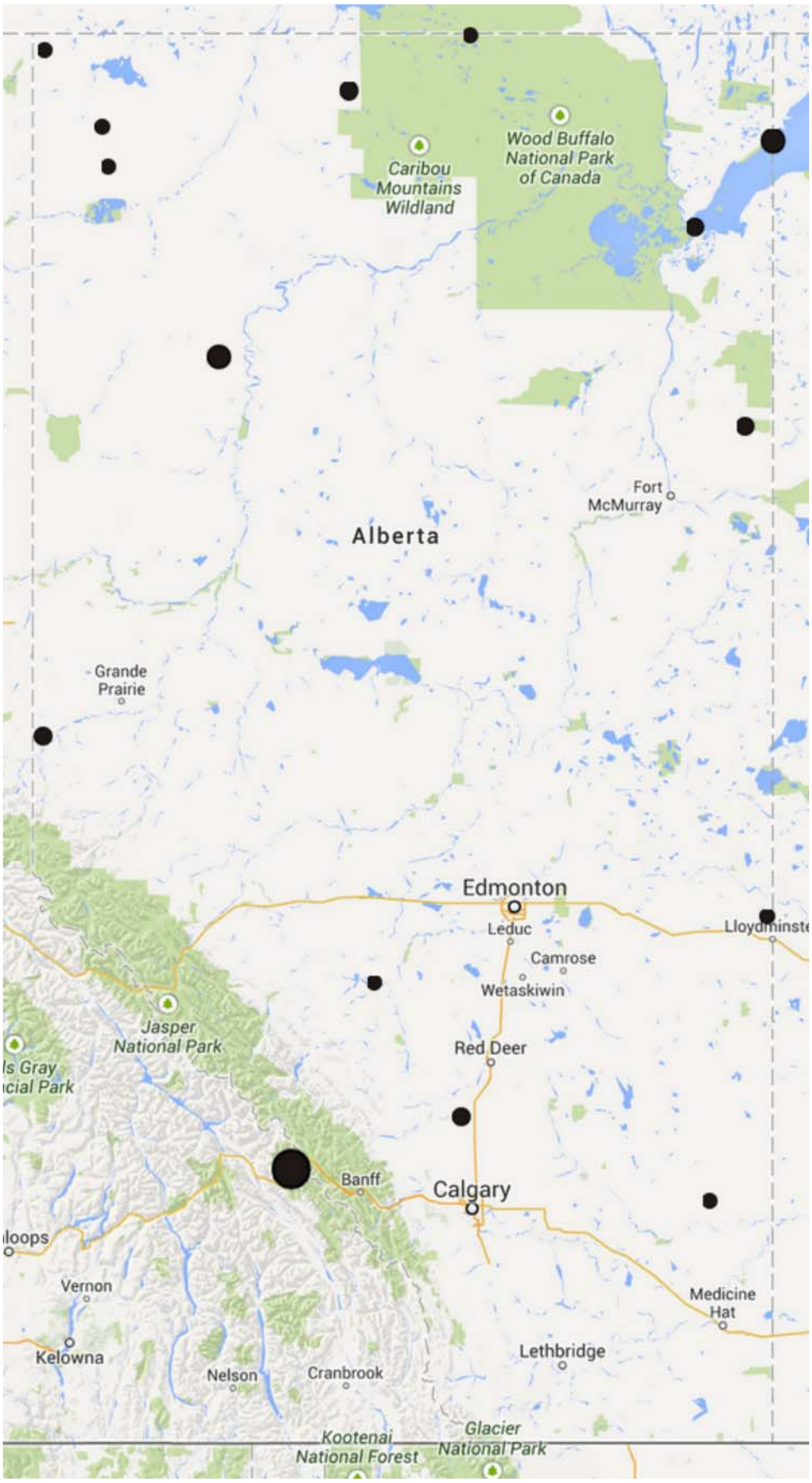

Figure 5-7: Map of selected wind resources with optimized distribution of turbines (number of turbines is expressed by the relative size of circles, and corresponds to row 15 of table 5.1)

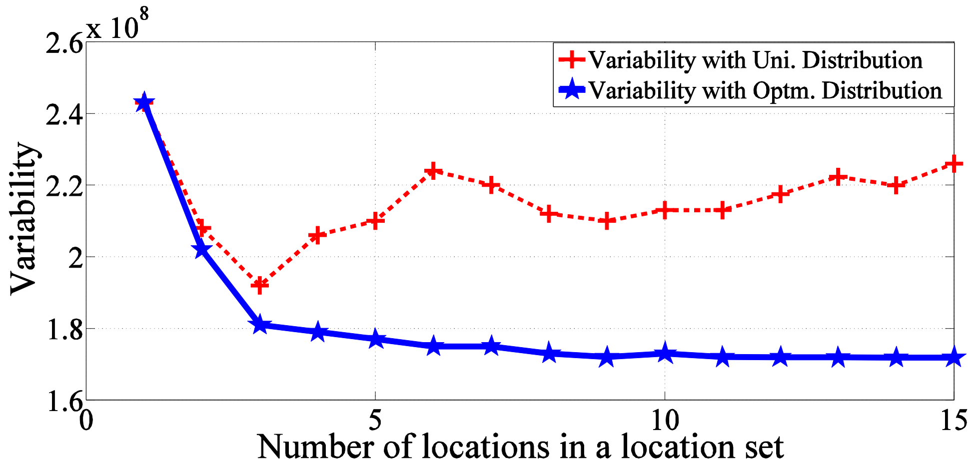

Figure 5-8: Temporal variability of wind power generation

Figure 5.8 represents the cost function (6.3), i.e. the temporal variability of the total wind power generation. The variability of power generation with uniformly distributed turbines exhibits significant fluctuation. However, the integration of wind power from optimally distributed wind resources reduces the overall variability. As the number of locations increases, the variability of integrated power generation keeps decreasing before it levels off. This is the most significant feature of the experiment. This shows that by integrating wind resources over a wide area reduces the variability of wind power generation. Wind profiles of different locations can complement each other. Based on the wind profile of different locations, it is necessary to optimize the distribution of turbines in different locations to reduce the variability of wind. In this process, it is possible for power systems to cope up with the intermittency of wind power generation.

Graphs in figures 5.9 and 5.10 represent the of average and total power generation, respectively. These two figures are quite similar. There is a steep increase in average and total wind power generation with uniform distribution of turbines until the location set includes 6 sites. After that, these graphs fluctuate with addition of more locations. Till 10 locations in a location set, the average and total power decreases with a uniform slope for uniform distribution of turbines. However, both the graphs start to increase for more than 10 locations in a location set. As turbines are distributed uniformly, the power generation from different resources are increased with the uniform distribution turbines. As a result, the ability of wind resources to complement each other is not fully utilized.

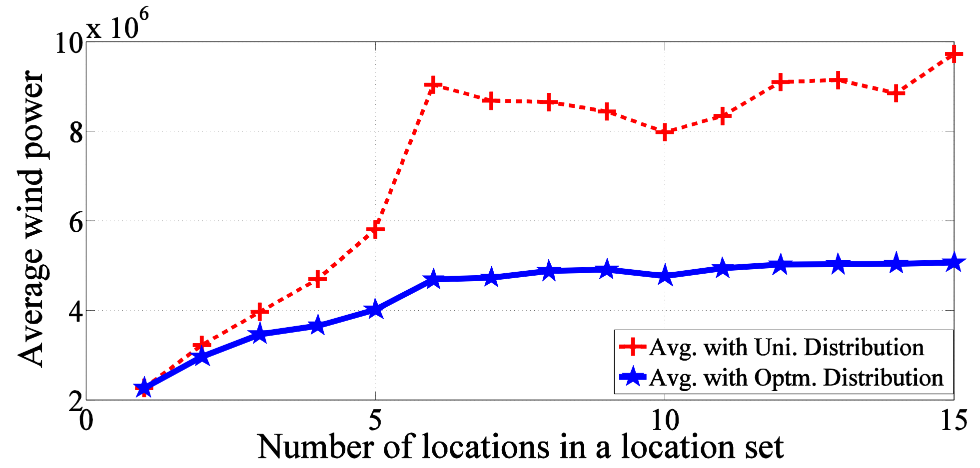

Figure 5-9: Average wind power generation

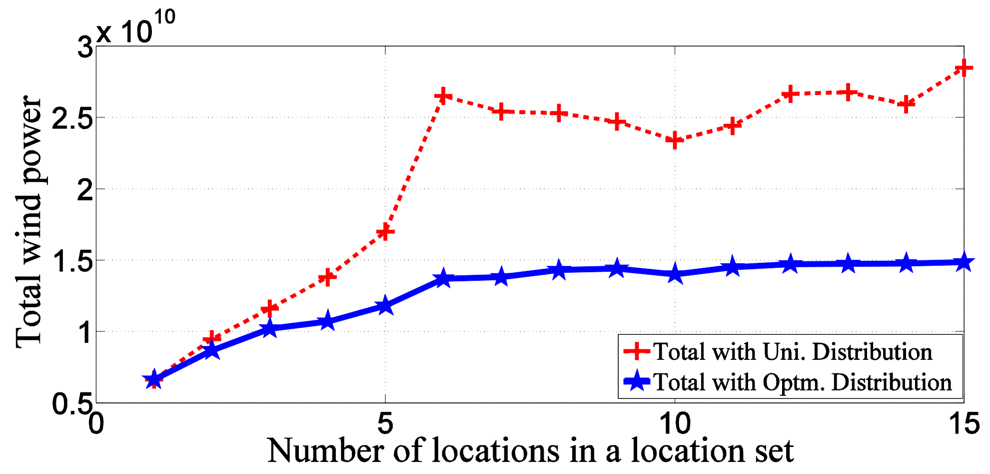

Figure 5-10: Total wind power generation

In comparison, the graphs where optimized distribution for turbines is used, show a slower increase in average and total power generation. Similarly to the uniformly distributed wind farms, the average and total power generation level off for more than 6 locations. The slope of average and total power generation is increasing but smaller for 6 to 10 locations in a location set compared with 1 to 5 locations in a location set. For more than 10 locations in a location set, the average and total power generation with optimized distribution of turbines becomes almost constant. The average wind power generation is close to 5,000 MW. This means that the power generation from different wind resources is less variable and the amount of generated power is more consistent. This is a very important finding which indicates that power can be generated more economically when both location and size of wind farms are optimized. This, in turn would allow reduction of the base load generation and reduction of the required reserve of dispatchable conventional generation. From figure 6.6, it can be observed that average wind power generation is close to 5,000 MW. So, ideally 5,000 MW of base load capacity can be reduced is by integration of wind power over spatially distributed wide area.

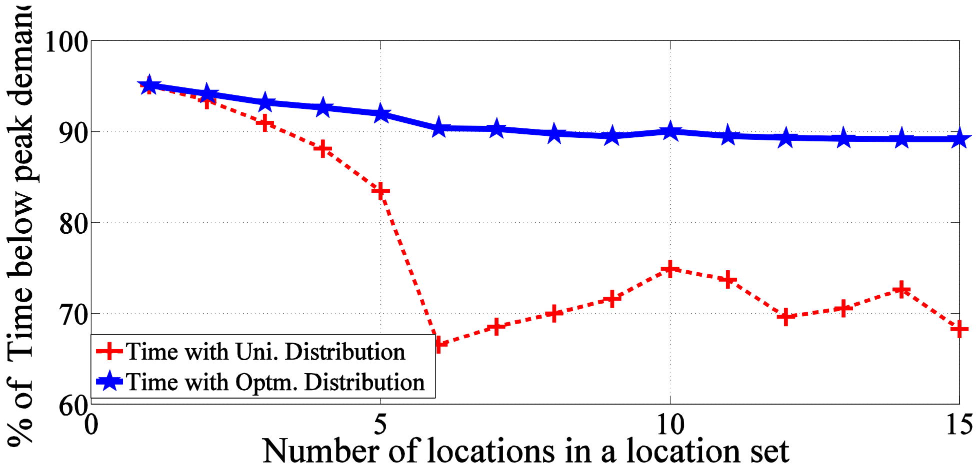

Figure 5-11: Percentage of time power generated below peak demand

Figure 5.11 represents the percentage of time the generated wind power is below the peak demand of the system. The peak demand of Alberta in 2012 was 10,599 MW [3]. For the simulation model, the peak demand of 11,000 MW was considered. Figure 5.10 shows that the total power generation with uniform distribution is significantly higher than the optimized distribution. As a result, with the uniform distribution, the percentage of time below the peak demand is always much lower than in the optimized case. The curve for uniform distribution is decreasing with a steep slope up to 6 locations and then fluctuates. This is because the total power generation with uniform distribution of figure 5.10 has similar profile. However, the curve for the percentage of time below the peak demand with optimized distribution is less variable compared to the uniform distribution case. It decreases with a smaller slope up to 6 locations and then flattens out.

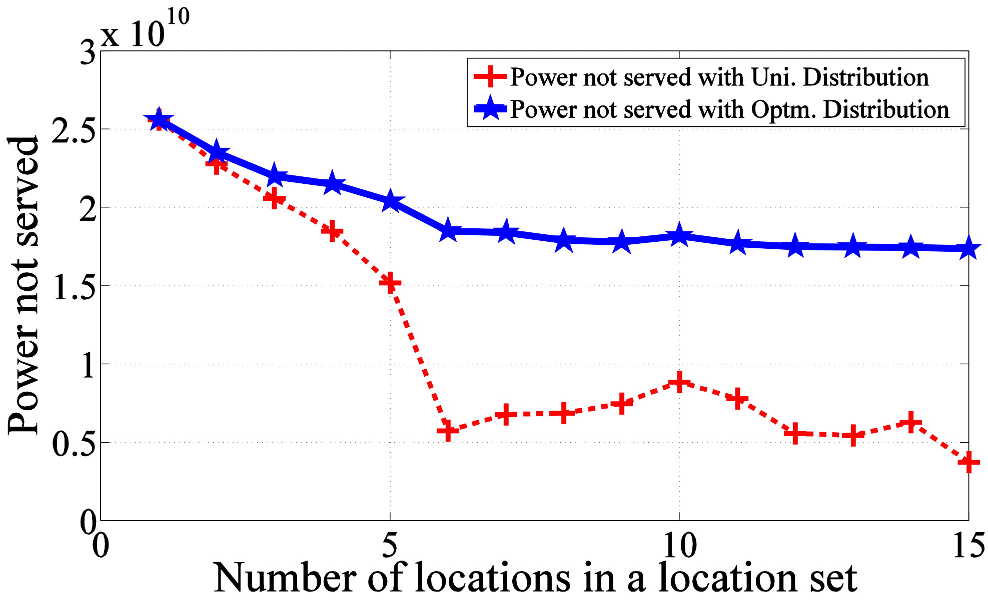

Figure 5-12: Amount of power not served compared to peak demand

Figure 5.12 represents the amount of power not served compared to the peak demand. Similar to previous cases, it can be seen that the curve for uniform distribution is much lower than for the optimized distribution case. But the curve for uniform distribution is also more variable. On the other hand, the optimized distribution curve shows that there is a less variable amount of power which is not served compared to peak demand. Based on these graphs, it can be easily concluded that the requirement of base load for power generation can be reduced. The amount of quickly dispatchable power generation sources to accommodate the intermittency of wind power can also be reduced. This means that a steady amount of power can be generated using spatially distributed wind resources with optimized allocation of turbines.

5.5.2 Integration of Distributed Wind Resources in Alberta and British Columbia Province

In this section, the wind resources of Alberta and British Columbia provinces are considered together. There are 1,516 locations which fall into Alberta and British Columbia province in NARR database for boundary corners expressed in section 5.4.1. In this set of experiments, the total number of turbines used as 50,000 to generate about 5,000 MW of wind power on an average. The maximum number of 15 locations will be included in the location set. Rest of the parameters will remain same.

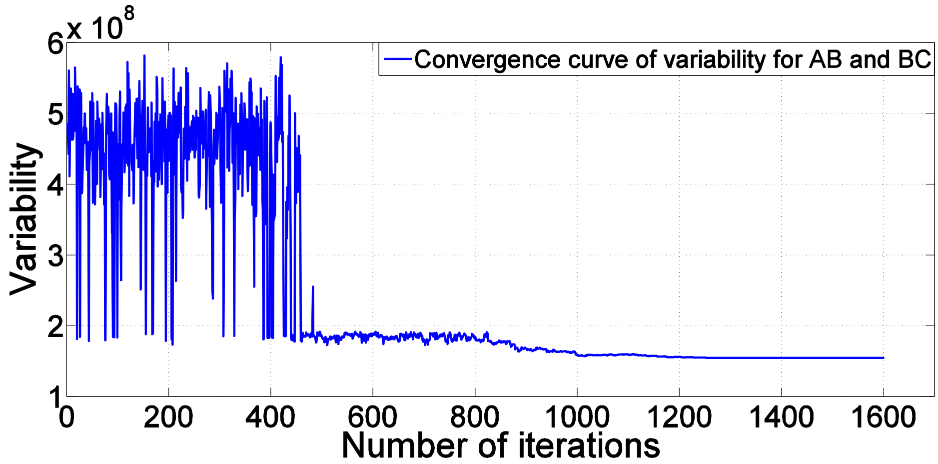

Figure 5-13: Convergence curve of variability for 15 locations of AB and BC

The figure 5.13 shows the convergence curve of temporal variability for 15 locations in Alberta and British Columbia province. From this graph, it can be observed that several times, when the number of iteration was relatively low, several sets of locations were generating wind power at a lower variability. However, due to ensuring the balance of exploration and exploitation, the model chose newer set of locations to explore newer options which sometimes were producing more temporal variability. In later part of simulation, model exploited location set and found location set with lower variability.

The figure 5.14 shows the 15 optimum locations which produced the lowest variability of wind power generation. It can be observed that the locations are distributed in a wide area with 4 locations in Alberta and 11 locations in British Columbia. From locations in Alberta, it was observed that there was one location in the highly resourceful southern part of Alberta near the Rockies and the other three locations were widely distributed. There are lots of locations chosen in the Western border of British Columbia which is a coastal area. These locations are close to the Pacific Oceans. As a result, the wind resources of these areas are supposed to be very good and less intermittent. The northern border of Alberta and British Columbia also has a lot of locations. So, here it is also observed that the locations chosen by the model are widely distributed all over Alberta and British Columbia.

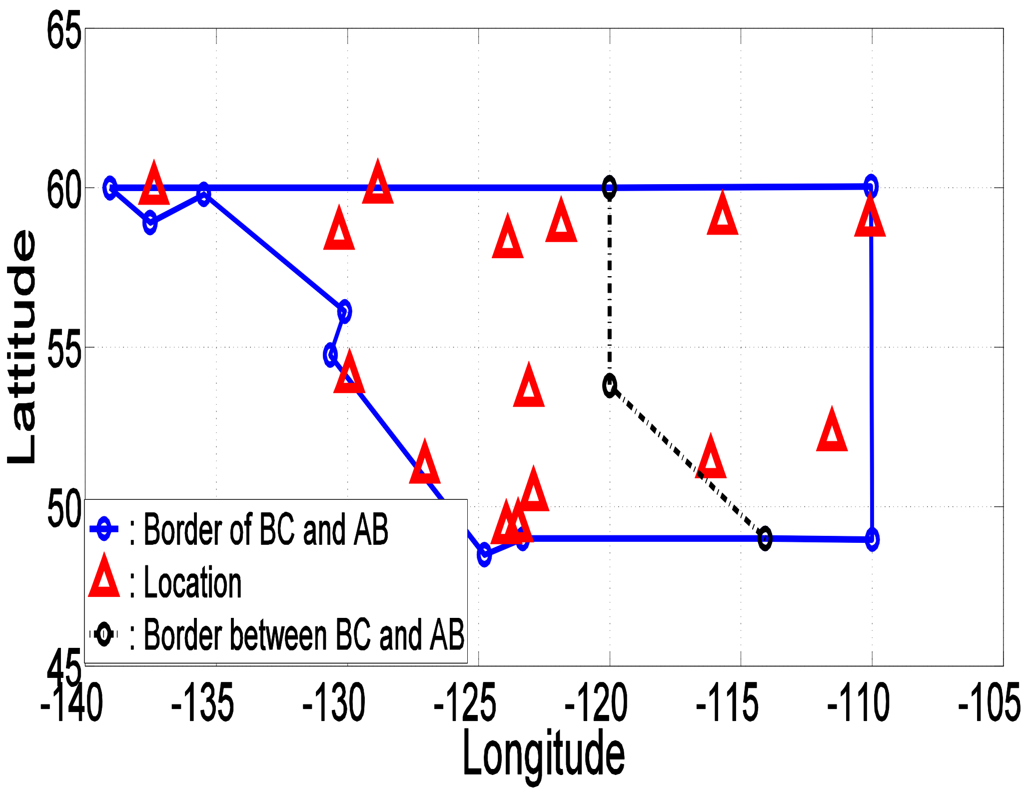

Figure 5-14: 15 optimized locations of wind resources for Alberta and British Columbia

Figure 5.15 represents the coefficient of variation of generated wind power. It can be observed that the coefficient of variation is very high as the location set consists of fewer locations. It gradually decreases as the number of locations in the location set increases. This means, as more locations are chosen, the chances of the wind profile to complement each other are higher. As the number of locations increases, the coefficient of variation for locations in Alberta becomes less variable for uniform and optimized distribution of turbines. However, when locations of Alberta and British Columbia are put together, the coefficient of variation of wind power becomes more fluctuant.

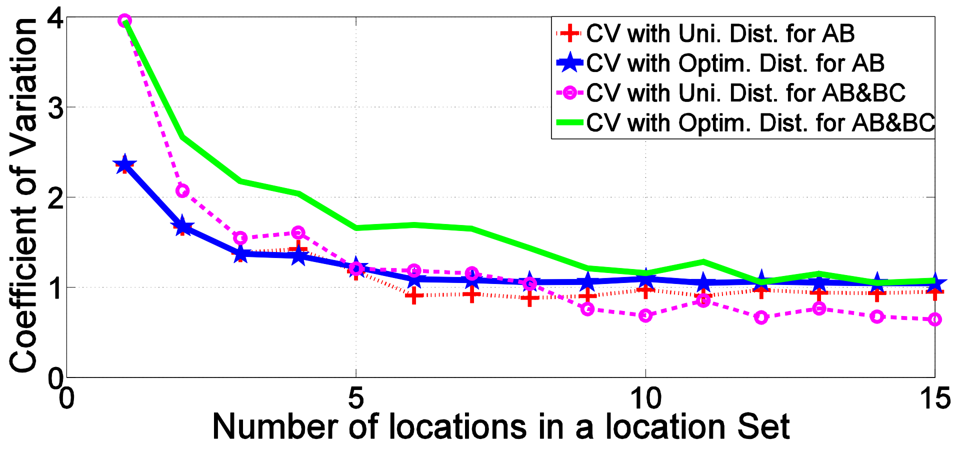

Figure 5-15: Coefficient of variation of wind power generation

Figure 5.16 shows the temporal variability. When locations only in Alberta and when locations in both of the provinces are considered together, the uniform distribution of turbines are more fluctuant. The generated wind power for Alberta and British Columbia are highly variable with uniform distribution of turbines. However, for optimum distribution of turbine, both the graphs are quite stable. Here, power generation is less variable when locations are chosen from both of the provinces with optimum distribution of turbines. As the locations are chosen from a spatially distributed area, there are more probabilities of finding locations with complementing wind profiles. And if the turbines are distributed with optimization, the generated wind power can be much less variable.

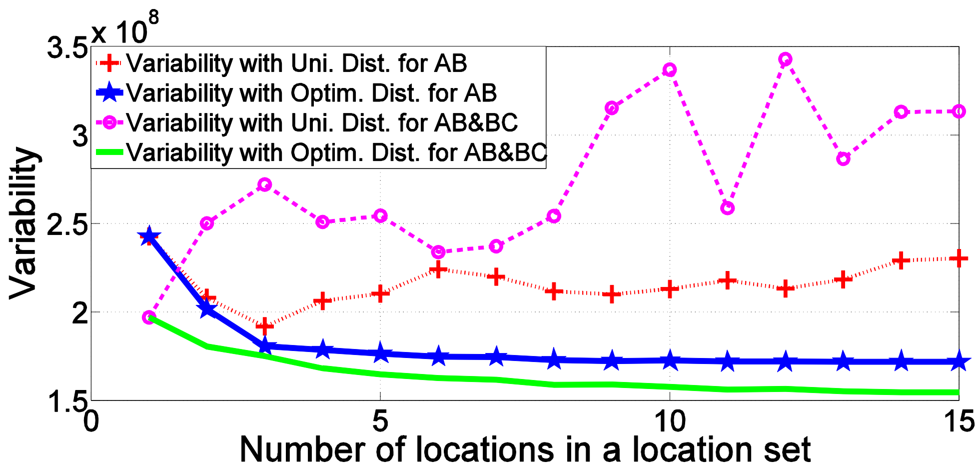

Figure 5-16: Temporal variability of wind power generation

Figure 5.16

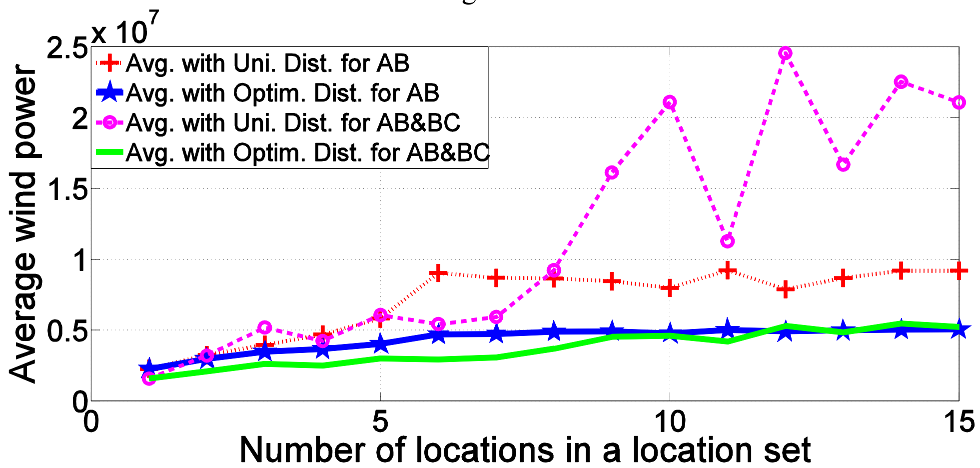

Figure 5-17: Average wind power generation

The figure 5.17 represents that it is possible to reduce the intermittency of wind power generation and produce a steady average wind power generation with optimum distribution of turbines with more locations in the location set. It can be observed that for Alberta province and for both the provinces, about 5,000 MW of average wind power generation is possible. However, it requires a total of 30,000 turbines for locations in the province of Alberta whereas it requires 50,000 turbines in total to generate this average wind power from locations in Alberta and British Columbia together. The model is designed to choose locations so that wind power generation is less variable. This can be observed from figure 5.17. As more complementing wind profiles are chosen, more number of turbines are required to generate same average of wind power with less variability.

Figure 5.18 represents the total wind power generation. These graphs are quite similar in shape with the average wind power generation graphs, but with higher magnitude. This figure also shows that with optimum distribution of wind turbines, a less variable wind power generation is possible by integrating wind resources over a wide area.

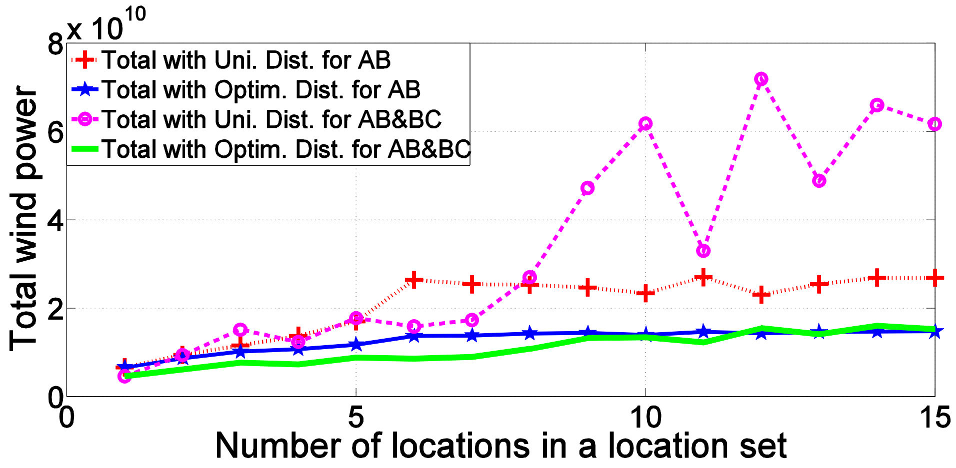

Figure 5-18: Total wind power generation

Figure 5.19 represents the percentage of time the generated wind is below peak demand. For uniform distribution it is observed that Alberta and British Columbia provinces together generate wind power a lot more compared to locations situated only in Alberta. Even though the percentage of time the generated wind power with uniform distribution is below peak demand for both the provinces together, it is also more variable. With the uniform distribution of turbines in locations in Alberta, this graph is less variable and 30% of the time it can match the peak demand. With the optimized distribution of turbines, wind power is able to meet only 10% of the peak demand for higher number of locations in location set, but this percentage is quite stable throughout.

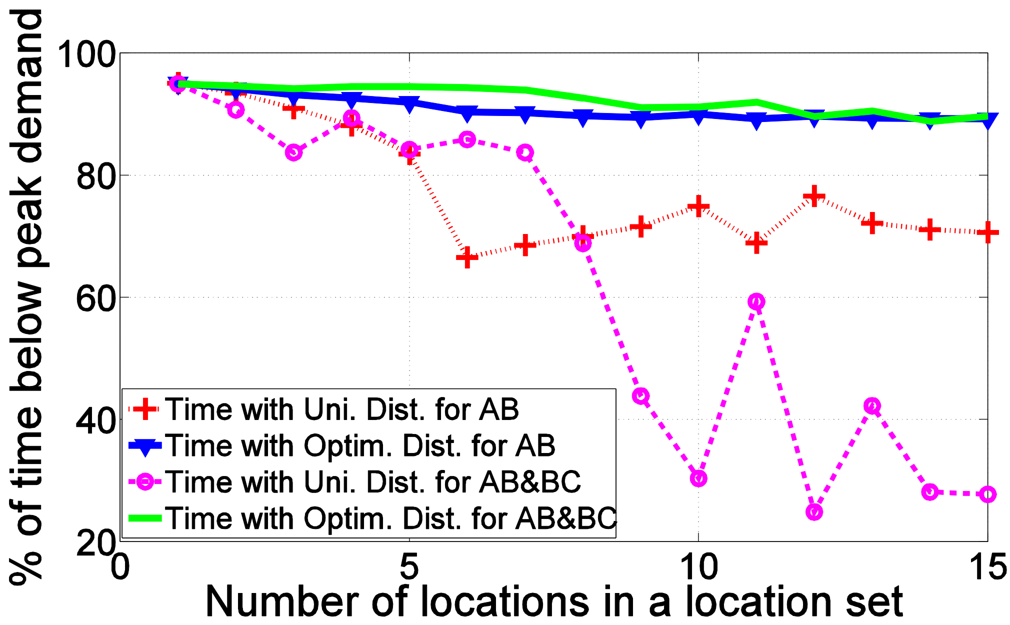

Figure 5-19: Percentage of time generated wind power is below peak demand

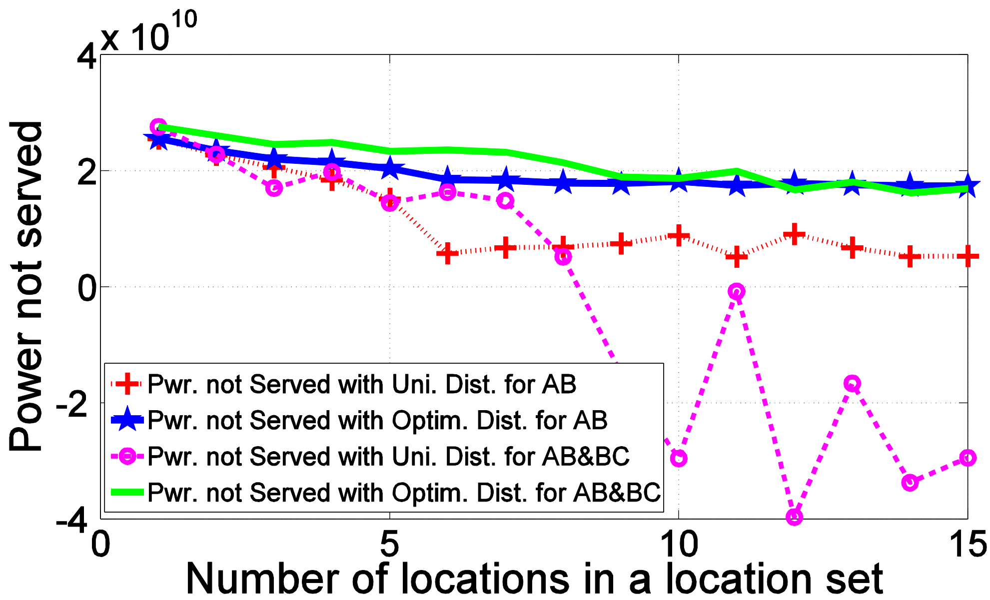

Figure 5-20: Power not served compared to peak demand

Figure 5.20 represents the amount of power that is not served with the generated wind power to meet the peak demand. In other words, this is the amount of power which is required from the conventional power plants to meet the peak demand. It can be observed that for wind power generation with optimized distribution of turbines, the power required from the conventional power plants is almost constant. So, in this way, the base load requirement can be reduced significantly along with the reserve capacity and hence, the variability of wind power generation can be compensated.

5.5.3 Integration of Distributed Wind Resources with Coefficient of Variation as Cost Function

In this section of the thesis, coefficient of variation (CV) will be used as a new cost function instead of temporal variability. The locations will be chosen from Alberta as well as Alberta and British Columbia provinces together. The total number of turbines used in these set of experiments is 7,500 to produce an average of 5,000 MW of power from the province of Alberta. For locations from Alberta and British Columbia together, 9,000 turbines will be used. A maximum of 15 locations will be chosen in a location set. The rest of the parameters will be same.

The coefficient of variation is the ratio of standard deviation to average. This ratio can be used to identify the variability of a parameter. In this experiment, the model is updated with this ratio as the cost function instead of temporal variability. So the objective of the model would be to reduce the coefficient of variation of wind power generation.

The first set of simulations are operated to find the convergence curve of coefficient of variation. The figure 5.21 shows the convergence curve of coefficient of variation for location in Alberta and British Columbia province together. From this curve, it is observed that the model does a lot of exploration and after around 1,000 iterations, there is a gradual decrease in coefficient of variation which represents exploitation.

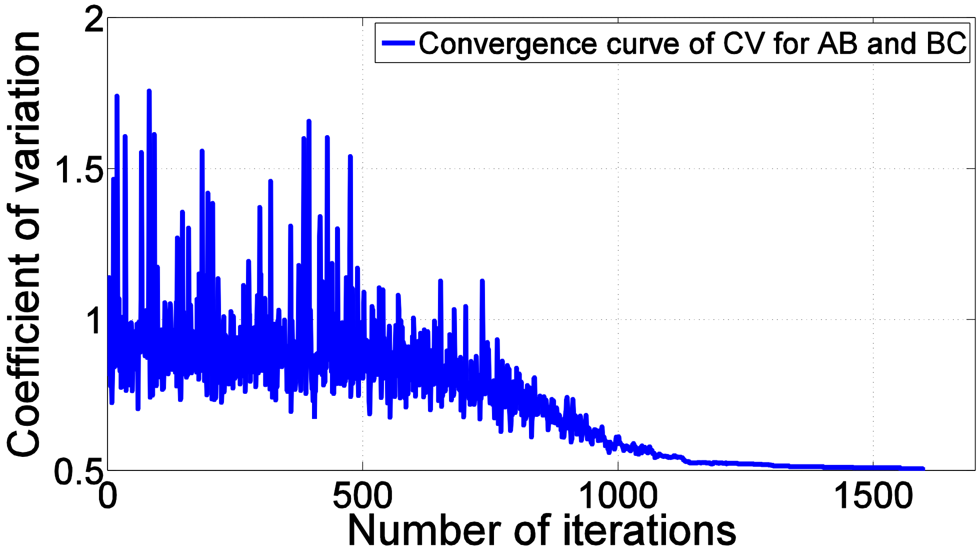

Figure 5-21: Convergence curve of coefficient of variation for 15 locations from AB and BC

Figure 5.22 represents the coefficient of variation with increasing number of locations in the location set. From this figure it can be observed that, the coefficient of variation decreases similarly for uniform and optimum distribution of turbines. However, compared to the locations only in Alberta, the coefficients of variation is about one and half times lower than locations from Alberta and British Columbia together. As the number of location increases in the location set, the coefficient of variation decreases. However, the slope of this decrement is not that significant after 5 locations in a location set.

Figure 5.23 shows the temporal variability of wind power generation when the coefficient of variation is cost function. It can be observed that the variability decreasing as number of locations increases in the location set. The optimum distribution of turbines performs better compared to the uniform distribution of turbines. Another feature of this figure is, even though variability is lower for the locations in the province of Alberta and British Columbia, the variability curves are more fluctuant for these locations. Even though the locations in Alberta produces more variability, the variability is less fluctuant for both uniform and optimum distribution of turbines.

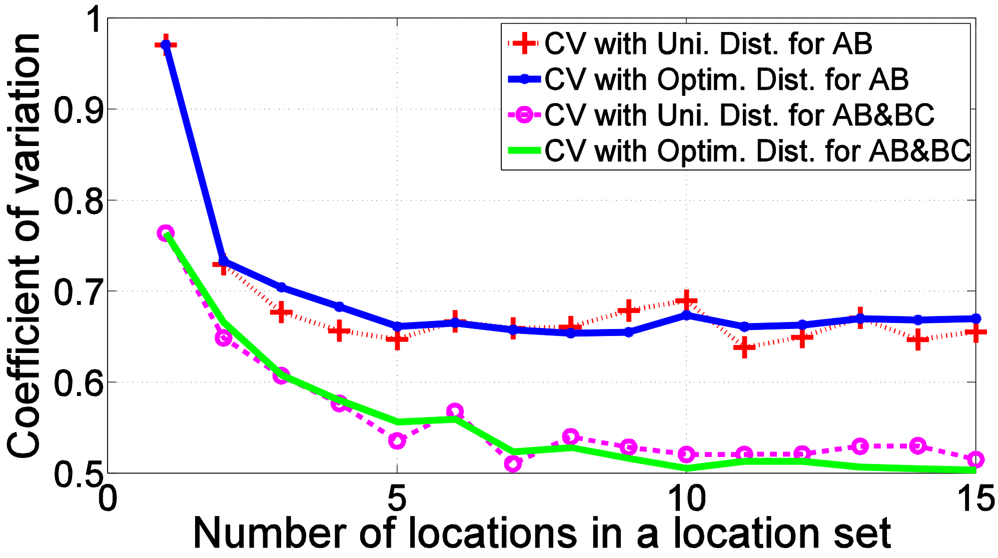

Figure 5-22: The coefficient of variation of wind power generation with CV as cost function

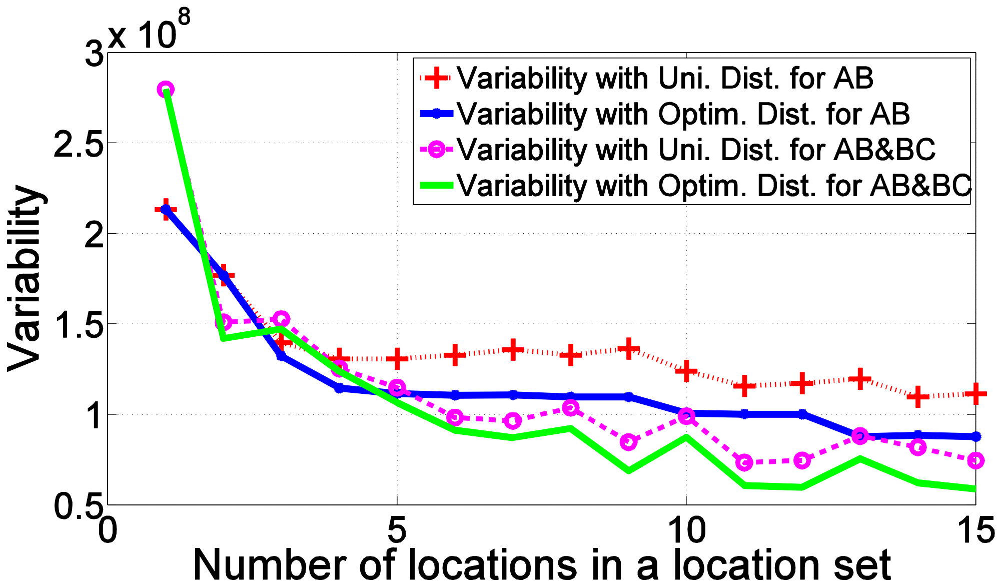

Figure 5-23: The variability of wind power generation with CV as cost function

Figure 5.24 represents the average wind power generation with coefficient of variation as cost function. In this figure of 5.24, it can be observed that the average wind power generation is higher for uniform distribution of turbines compared to the optimal distribution of turbines. The average wind power generation gradually decreases as the number of locations in the location set increases. Compared to figure 5.9 and figure 5.17, this is quite the opposite when the temporal variability of wind power generation was used as the cost function. Also, even though the average wind power generation gradually decreases, but it never settles down, rather the average wind power generation remains variable throughout.

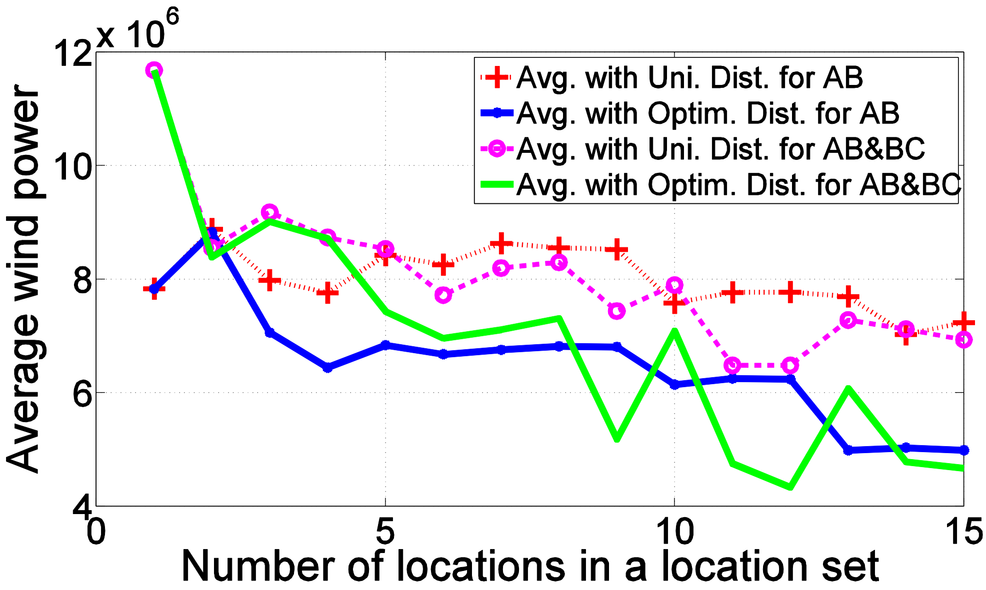

Figure 5-24: The average wind power generation with CV as cost function

The total wind power generation with coefficient of variation as cost function is similar in shape with average wind power generation but higher in magnitude which is shown in figure 5.25. The optimum distribution of turbines for locations in Alberta and British Columbia is highly variable. The optimum distribution of turbines for locations in Alberta is less variable for 5 to 12 locations in a location set, however it decreases after that. The wind power generation with uniform distribution of turbines in Alberta as well as locations in Alberta and British Columbia is close in terms of magnitude. From the figures of average wind power generation and total wind power generation, it can be observed that there is lot of randomness in the graphs when the coefficient of variation is used as cost function.

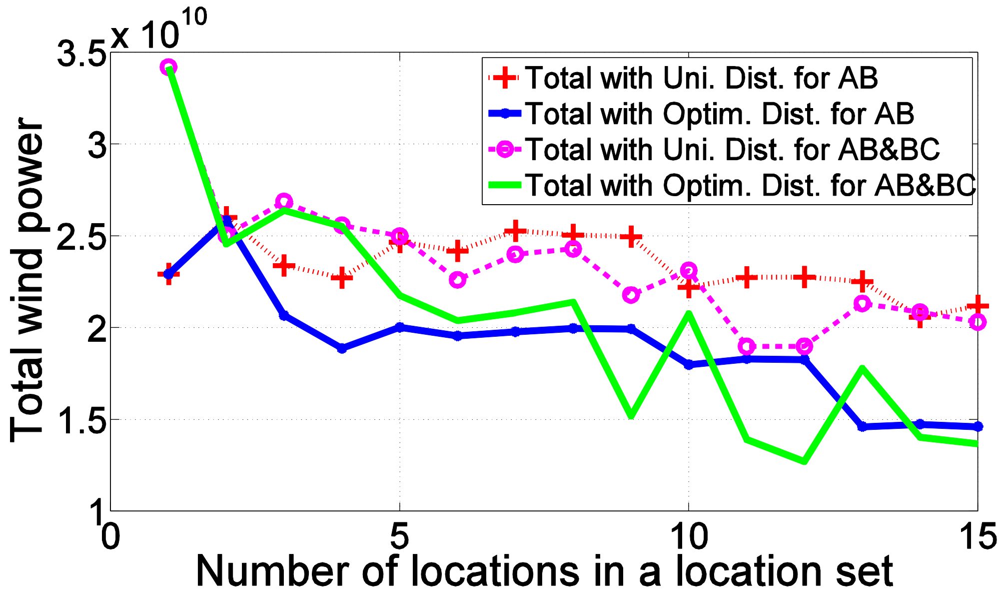

Figure 5-25: The total wind power generation with CV as cost function

Figure 5.26 represents the percentage of time the wind power generation is below peak load with coefficient of variation as cost function. Again, compared to previous figures, a lot of variability is observed. The uniform distribution of turbines generates more wind power and hence shows less time below the peak demand. The optimum distribution of turbines with locations in Alberta remains within 82% to 88% below peak demand for 4 to 12 locations in the location set. The uniform distribution of turbines with locations in Alberta remains within 65% to 71% below peak demand for 5 to 13 locations in the location set. The optimum distributions of turbines are highly variable for locations in Alberta and both the province together.

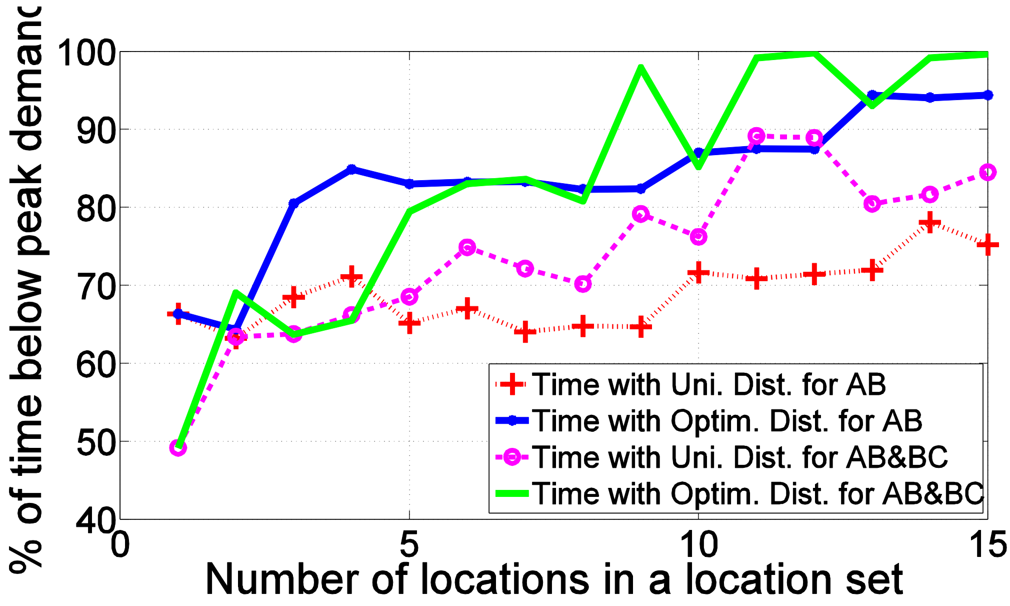

Figure 5-26: Percentage of time wind power generation is below peak demand with CV as cost function

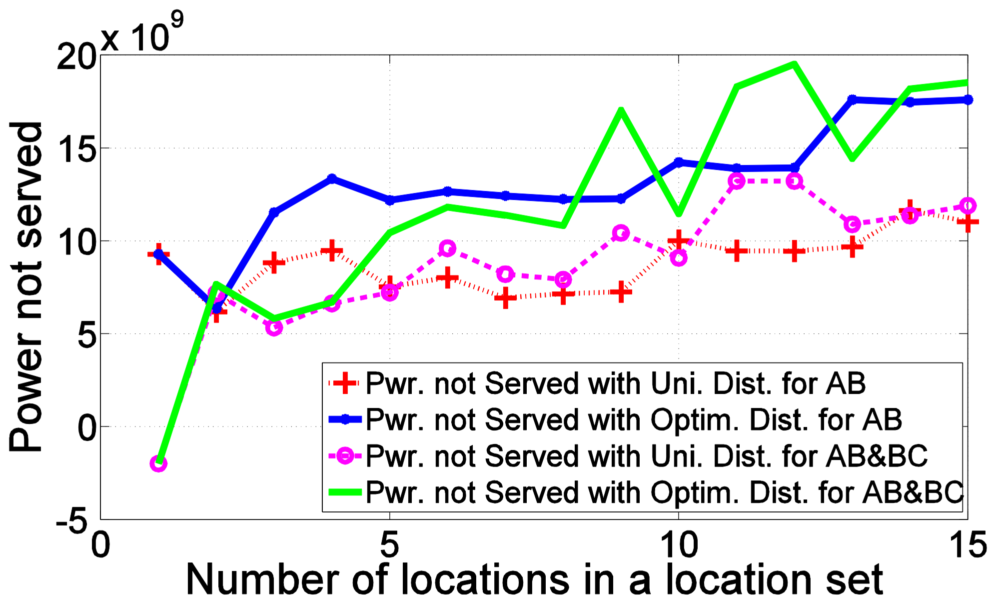

Figure 5-27: Amount of power not served with wind power generation compared to peak demand using CV as cost function

Figure 5.27 represents the amount of power not served from wind power generation compared to peak demand with the coefficient of variation as cost function. In this figure it is observed that uniform and optimum distribution of turbines for locations in Alberta are less variable. The graphs from the locations of Alberta and British Columbia for uniform and optimum distribution are highly fluctuant. It is also observed that by providing all the turbines in one or two locations, a huge amount of wind power can be generated which can surpass the peak demand or be very close to the peak demand. In general, it can be concluded that even though the coefficient of variation as a cost can reduce the variability as well as coefficient of variation of wind power generation with increasing the number locations in the location set, it produces highly variable wind power generation. The locations in Alberta in some cases perform slightly better than the combination of locations in Alberta and British Columbia together. By using coefficient of variation of wind power generation as cost function, it highly unlikely to be able to reduce the variability of wind power generation.

5.6 Conclusion

This section examines the possibility to optimize the spatial distribution of wind power plants over an extended area to decrease the overall variability of wind power generation in a system. The temporal variability of generated wind power as well as the coefficient of variation of generated wind power is used as cost function. The distribution of power plants is optimized using simulated annealing and quadratic programming. Wind turbines are distributed in the wind sites with uniform distribution as well as with optimum distribution using quadratic programming to reduce the variability of wind power generation. The results clearly show that the variability of wind power generation can be reduced if the wind resources are integrated over a wide geographic area with optimized distribution of turbines.

In particular, this study considers the integration of spatially distributed wind power generation in the wind-rich province of Alberta and British Columbia. The results are obtained through two step optimization process. The first step only selects locations of multiple power plants while keeping the relative size of the wind farms uniform across all locations. The second step then optimizes the relative size of individual wind farms to minimize the wind generation variability while keeping a steady wind power generation. In both cases, the principle of simulated annealing is used to run the simulation. The minimization of the temporal variability of wind power generation is used as a cost function. Later on, the coefficient of wind power generation is also used as cost function. This approach is evaluated using a number of power generation metrics including temporal variability of wind power generation, average power generation, percentage of power generate below peak demand and amount of power not served and few others.

From the experiments it can be concluded that the integration of wind resources over spatially distributed wide area can significantly reduce the variability of wind power generation with optimum distribution of turbines. The locations in the province of Alberta can generate average wind power of 5,000 MW with 30,000 wind turbines. The locations in the province of Alberta and British Columbia can generate average wind power of 5,000 MW, but with 50,000 wind turbines. Even though the minimization of coefficient of variation of wind power generation as well as the temporal variability of wind power generation can be achieved using coefficient of variation as cost function, it does not have any significant impact on reducing the variability of wind power generation. In fact, wind power generation is highly variable with coefficient of variation of wind power as cost function. Temporal variability as cost function performs significantly better for generating steady average wind power with reduced variability.

Wind is a highly intermittent renewable energy resource. Variability is one of the main characteristics of wind power generation. The integration of wind power generation requires additional reserve capacity and quickly dispatchable additional power generation resources to accommodate the variability of wind power. However, the integration of wind resources over a spatially distributed wide area can reduce the variability of wind power generation significantly. This can reduce the reserve capacity and quickly dispatchable power generation resources and hence reduce the base load required by the grid. The integration of wind power over spatially distributed area can significantly reduce the variability of wind power generation as well as reduce the dependency on conventional power plant.

Chapter 6

Conclusions and Future Recommendations

6.1 Conclusions

Social awareness of the people for environment friendly power generation to meet the increasing demand of electricity is one of the main motivation for power generation from renewable resources. Renewable resources have a good prospect in assisting the conventional power generation from fossil fuels to meet the ever increasing demand of electricity in everyday life as well as in the industrial development of a country. The renewable power generation helps to reduce the greenhouse gas emission which can improve the global warming scenario. The impact of the electrical power demand all over the world on climate change can also be reduced in long term by using renewable resources. Also, it assists the search of alternative fuel resources for conventional fossil fuels. Many aspects need to be studied and reviewed to integrate renewable energy resources to the existing power grid.

There are different technical and financial challenges of integrating power generation from renewable resources to existing power grid. Renewable resources are characteristically intermittent by nature. So the variability of renewable power generation, the uncertainty in the availability of renewable resources, the accuracy in forecasting of the renewable resources in a given period of time and the confidence level on the forecast are some of the major issues. These factors impacts the scheduling of the power generation from conventional resources. These also create difficulty in determining the dependency on conventional resources. As renewable resources are highly variable, quickly dispatchable power generation resources are required for the integrating renewable power generation to accommodate the variability of renewable energy. The dependency on energy storage increases as renewable power generation schedule may not synchronize with the peak demand. Renewable resources are widely distributed over a large area. The variable nature of renewable resources can be reduced by integrating renewable power resources over a spatially dispersed wide area. Renewable power generation in different locations may complement each other in different time periods which can reduce the variability. In this case, the transmission of generated power to the grid as well as to the local load centers becomes another major issue. Long distance transmission lines are required. Also, security and power quality issues are required to be maintained for accommodating different scales and types of renewable resources to the existing grid. These technical challenges are associated with the financial challenges as the technology associated with renewable power generation is mostly under research and development. The installation cost of renewable power generation is comparatively much higher compared to conventional power generation resources.

The integration of renewable power generation could be assisted by a power exchange system which will allow the generated power to be exchanged among the renewable power generation resources. Micro grids can be representative of small scale renewable power generation sources with associated load. The power exchange system will ensure that at first, the generated power by the micro grids will be used and exchanged by the group of micro grids to meet their respective demand. Then the rest of the required demand of micro grids will be met by importing power from national grid. The excess power that the group of micro grids has after meeting their group demand can be sold to national grid. Different aspects and parameters of the power exchange system can be varied and their impacts on the overall system can be used to analyse how the power exchange system can perform under realistic environment. The results show in this power exchange simulation model that the system can significantly contribute to reduce the dependency of group of micro grids on national grid instead of each micro grid acting as their own. The base load requirement of the national grid can be reduced if the group of micro grids work together as the group of micro grids will utilize their generated power to its maximum potential to meet their group demand. In terms of economic loss, it was also observed that the group of micro girds concur less economic loss compared to when the micro grids work as individuals. So, a group of micro grids, using the power exchange system, will have to pay less compared to a group of micro grids that do not use the power exchange system and acts individually. So, it is financially profitable for a group of micro grids to use power exchange system and at the same time, the dependency on the national grid in terms base load requirement can also be reduced by using the power exchange system.

Wind is one of the popular renewable energy resources for power generation from renewable resources. There are good wind resources available in wide open area, near a mountain range, near the sea shore etc. locations. At the same time, wind can be highly intermittent. Climatological data is a data based on historical weather data which represents the probable weather conditions of a location in a time period. The yearly weather conditions can be different in different years in the same location. This variability of wind power in same location in different years is shown with graphs and boxplots in this thesis. The results show that there can be abundant wind flow in one time period and no wind at all in a different time period. The wind power in same location also varies in different years compared to the climatological data. So, instead of installing wind turbines in one location, it is desirable for reducing the overall variability of wind power generation to spread the wind turbines over different areas where wind resources complement each other. This helps the national grid to predict a steady amount of average wind power generation which can assist the national grid to reduce its base load.

The integration of wind resources over spatially distributed wide area has the potential of reducing the temporal variability of wind power generation. The province of Alberta has good prospect in wind power and new wind power installations are under progress. Alberta is quite flat with the Rocky Mountain Range to its west. This creates an interesting wind profile. The wind resources of Alberta are first considered in the simulation model which is developed in MATLAB. The simulation model uses two optimization techniques. Locations are optimized as well as the distributions of turbines in those locations. The Simulated Annealing and Quadratic Programming are used here. The chosen locations with optimized distribution of turbines produces the temporal variability of wind power generation. The location set and the optimized distribution of turbines are updated to find less temporal variability. The balance of exploration and exploitation is ensured with metropolis criteria. The turbines are also distributed with uniform distribution and results are compared. The results show that, by increasing number of locations in the location set, wind power with less temporal variability and a steady average wind power is achievable by integrating wind resources over spatially distributed wide area. The optimized distribution of turbines performs better compared to uniform distribution of turbines. Similar simulations are performed by taking the wind resources of Alberta and British Columbia together. It was observed that the temporal variability of wind power generation with optimized distribution of turbines can be even lower with wind resources in Alberta and British Columbia together. It was observed that a steady average wind power of around 5,000 MW, which about half of Alberta's peak demand, can be generated with 30,000 optimized distribution of wind turbines in wind resources all over Alberta. For wind resources in Alberta and British Columbia together, a steady average of around 5,000 MW wind power can be generated in similar way, but with 50,000 optimize distribution of wind turbines. It was also observed that using coefficient of variation as cost function instead of temporal variability of wind power generation as cost function, integrating increasing number of wind resources do reduce the coefficient of variation of wind power generation with optimum distribution of turbines. However, this cost function is not successful in terms of generating a steady average wind power generation. So, the temporal variability as cost function performs much better to reduce the variability of wind power generation. So, it can be concluded that by using the temporal variability of wind power generation as cost function, the integration of wind resources over spatially distributed wide area with optimized distribution of wind turbines can cope up with the inherent intermittency of wind and has the ability to reduce the variability of wind power generation as well as generate a steady average of wind power. This assists the power grid significantly to reduce its base load requirement as power grid can expect a steady wind power generation. This also assists in reducing the reserve capacity which is required for accommodating variable nature of renewable power generation. This way, the dependency on fossil fuel power generation can be reduced which in return will reduce the greenhouse gas emission and improve the global warming situation. It will also assist the conventional power generation plants to meet the ever increasing demand of electricity.

6.2 Contributions

The variability of wind power generation can be compensated by integrating wind resources with different wind profiles that complements each other. Canada is a huge country with enormous land area. There is a growing demand in wind power generation in Canada. Alberta is one of the provinces which has a good potential in wind power generation. It has mostly flat land with Rocky Mountains in the west. It has lots of lakes as well. So there is possibility in identifying wind resources with different wind profiles that complements each other. The allocation of wind turbines in best wind resources would generate a lot of wind power, however, due to inherent intermittency of wind, it will generate a lot of variable wind power as well. Variable wind power requires additional reserve capacity to accommodate the variability of wind power generation. This work is unique for Canada, especially for the province of Alberta, as it has a wide area which can have different wind profiles in different areas. By integrating wind resources over a wide area can help to reduce the variability of wind power generation. This can allow to shut down a few of the coal power plants in Alberta. At the same time, it will allow the conventional power plants to import additional steady average wind power generation to meet the demand. The Alberta and British Columbia have the Rocky Mountain Range in between. There are existing transmission lines that transport power within Alberta and British Columbia. So accommodating the wind resources of these two provinces can help to reduce the variability of wind power generation even more. Canada being such a big country, the learning of this work can be applied in other provinces as well. The combination of Simulated Annealing and Quadratic Programming for optimized distribution of turbines with temporal variability of wind power generation as cost function helps to find out the wind resources over spatially distributed wide area which can be able to generate less variable wind power with a steady average wind power generation. This can assist the future development of wind power installations in Canada, or in the province of Alberta or in any combination of wide areas.

6.3 Future Recommendations

The power exchange system uses Alberta internal Load data which was obtained from Alberta Electric System Operator (AESO). This is not a micro grid data. The power exchange system can be simulated using original power generation and demand data of micro grids. In that case, the result analysis and the advantages of applying power exchange system will be more realistic. The peak and off-peak hour rates for electricity can be included in the power exchange system following the peak and off-peak hours of the load centers. The sample micro grids are connected virtually with no transmission loss included in the model. By obtaining original micro grid data with their real time demand and generation, the transmission loss based on the distance and other factors can be included with peak and off-peak hour rates which will provide results in more realistic and practical environment.

The variability of wind power is observed in one location. This can be done for several other locations. Different model of turbines can also be used for this observation. Future work can be performed to represent the variation of wind power generation in a more visually attractive way as well as with more efficient analysis technique.

The integration of wind power resources are performed with 3 hourly wind resources data and with a fixed peak demand. The simulation can be performed with real time wind resources data. Instead of using a fixed peak demand, the real time demand could be used. As wind resources are highly variable, the wind resources data of different locations in different time periods could be randomly mixed and matched to accommodate the variability of wind resources. The wind resources of same location in different time periods can also be mixed and matched randomly. This way the stochastic distribution of variability could be included in the model. Several other optimization techniques with different type of cost functions can be used in the model. This way, different optimization techniques and cost functions can be compared. A different wind turbine model can be used. An economic analysis of the model performance can also be done in future.

Another future extension of this work would be to work with existing wind power plants over a wide area with their real time data. The existing wind power plants will be situated closed to transmission lines and load centers. In this way, the transmission loss can be included in the model. This will also help to understand how beneficiary it is by integrating wind power plants over spatially distributed wide are to reduce the variability of wind power generation as well as to generate a steady average wind power in terms of the existing system. Since it will deal with real data, the applicability of this process can be analyzed further. This analysis will be very helpful for future development of wind power plant installations.

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