Reliability/Cost Evaluation of a Wind Power Delivery System

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ABSTRACT

Renewable energy policies, such as the Renewable Portfolio Standard, arising from increasing environmental concerns have set very ambitious targets for wind power penetration in electric power systems throughout the world. In many cases, the geographical locations with good wind resources are not close to the main load centers. It becomes extremely important to assess adequate transmission facility to deliver wind power to the power grid.

Wind is a highly variable energy source, and therefore, transmission system planning for wind delivery is very different from conventional transmission planning. Most electric power utilities use a deterministic ‘n-1’ criterion in transmission system planning. Deterministic methods cannot recognize the random nature of wind variation that dictates the power generated from wind power sources. This thesis presents probabilistic method to evaluate the contribution of a wind power delivery system to the overall system reliability. The effects of site-specific wind regime, system load, transmission line unavailability, and redundancy on system reliability were studied using a basic system model. The developed method responds to the various system parameters and is capable of assessing the actual system risks.

Modern power system aims to provide reliable as well as cost effective power supply to its consumers. Reliability benefits, environmental benefits and operating cost savings from wind power integration should be compared with the associated investment costs in order to determine optimum transmission facility for wind power delivery. This thesis presents the reliability/cost techniques for determining appropriate transmission line capacity to connect a wind farm to a power grid. The effect of transmission system cost, line length, wind regime, wind penetration and customer interruption cost on the optimum transmission line sizing were studied using a basic system model. The methodology and results presented in this thesis should be useful in transmission system planning for delivering wind power to a power system.

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LIST OF ABBREVIATIONS

ARMA	Auto Regressive Moving Average
COPT	Capacity Outage Probability Table
CRM	Capacity Reserve Margin
DPLVC	Daily Peak Load Variation Curve
ECOST	Expected Customer Interruption Cost
EENS	Expected Energy Not Supplied
EPO	Expected Power Output
EES	Expected Energy Supplied
EUE	Expected Unsupplied Energy
FOR	Forced Outage Rate
GHG	Green House Gas
IEAR	Interrupted Energy Assessment Rate
km	Kilometer
km/h	Kilometer/hour
kW	Kilowatt
kWh	Kilowatthour
LDC	Load Duration Curve
LLU	Loss of Largest Unit
LOEE	Loss of Energy Expectation
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
MCS	Monte Carlo Simulation
MM$	Million dollars
MW	Mega Watt
MWh	Mega Watt Hour
NERC	North American Electric Reliability Council
REC	Renewable Energy Credits
RPS	Renewable Portfolio Standard
RTS	Reliability Test System
WECS	Wind Energy Conversion System
WPPI	Wind Power Production Incentive
WTG	Wind Turbine Generator

CHAPTER ONE

INTRODUCTION

1.1 Power System Reliability

Power system reliability is the measure of the ability of the system to deliver electricity as demanded to various points of utilization within acceptable standards. A quantitative measure of system reliability can be represented by numerical values using various reliability indices. The primary function of a power system is to ensure economic and reliable supply of electrical energy to its customers. Power system reliability evaluation provides a measure of the overall ability of the system to perform its intended function. Power system reliability evaluation is an important part of various facilities planning, such as generation, transmission and distribution networks. The evaluation of sufficient system facilities is essential in providing adequate and acceptable continuity of supply. Power system reliability can be described by two important attributes: adequacy and security. The two attributes are shown in Figure 1.1.

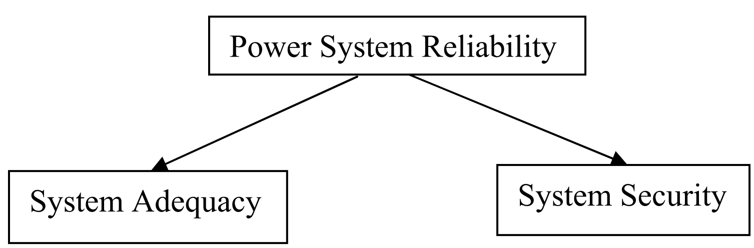

Figure 1.1: Attributes of power system reliability

Adequacy is the measure of a power system to satisfy the consumer demand in all steady state conditions. It is related to providing sufficient facilities to generate energy and to transport the energy through transmission and distribution networks to all the consumers. It is the ability of a power system to supply its customers with the installed system components. Adequacy does not include system disturbances.

Security is a measure of the system ability to withstand a sudden & severe disturbance in the system while maintaining system integrity. This disturbance can be an electric short circuit or an unexpected loss of system components, such as major generation and transmission. Security is associated with the system response to different disturbances.

The work done and reported in this thesis is in the domain of system adequacy. System adequacy evaluation is an important part of power system planning and decision making process.

1.2 Hierarchical Levels in Adequacy Studies

Modern power systems are generally complex, integrated and very large. It is not practical to conduct an adequacy evaluation of an entire power system. The system is generally divided into different functional zones of generation, transmission and distribution systems. System adequacy can be analyzed separately at the three different hierarchical levels (HL) [1], as shown in Figure 1.2.

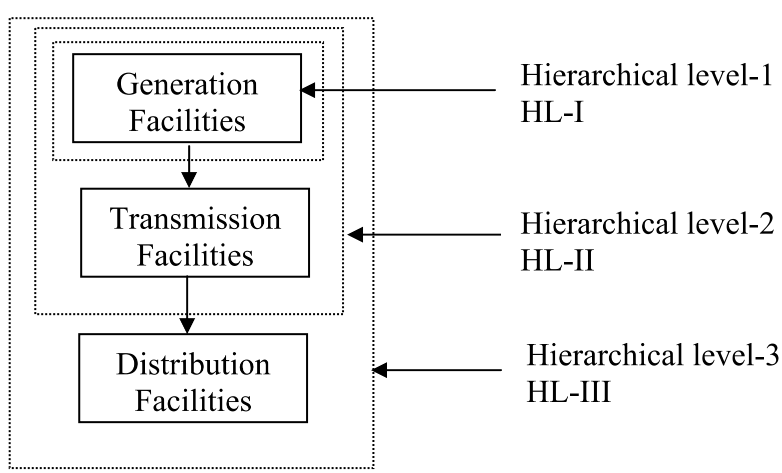

Figure 1.2: Hierarchical levels

HL-I refers to generation facilities and their ability to supply the demand. HL-II refers to the ability of the combined generation and transmission system to generate and deliver energy to the major load points. HL-III refers to the complete system including generation, transmission and distribution systems. Adequacy evaluation is usually only done at the distribution system level and not at the HL-III level. Outputs from HL-II can be used as the inputs for distribution system adequacy evaluation.

The scope of the work reported in this thesis is at the HL-I level. Limited transmission facilities can also be considered at the HL-I level. HL-I studies can generally include a transmission system connecting remote generation facilities. This thesis contains adequacy studies that consider transmission line that connects remotely located wind generation to a power system grid.

1.3 Application of Wind Energy in Power Systems

Renewable sources are getting considerable attention in power generation due to growing public concern with environmental degradation caused by conventional electricity generation. Wind is the most promising choice for producing substantial amount of electricity from green energy source. A number of generation companies are offering green electricity as an attractive product to customers in a competitive electric utility environment. Wind power has grown rapidly in the last decade and is expected to grow more in the next decade.

1.3.1 Growth of Wind Power

Wind power has been continuously growing throughout the world at an annual rate of 25% since the last decade. It has grown to 47,317 MW by the end of year 2004 [2]. Wind power of 7976 MW was installed globally during the year 2004 alone, which amounts to a 20% increase in comparison to the previous year. Figure 1.3 shows the global distribution of the installed capacity of wind power at the end of year 2004.

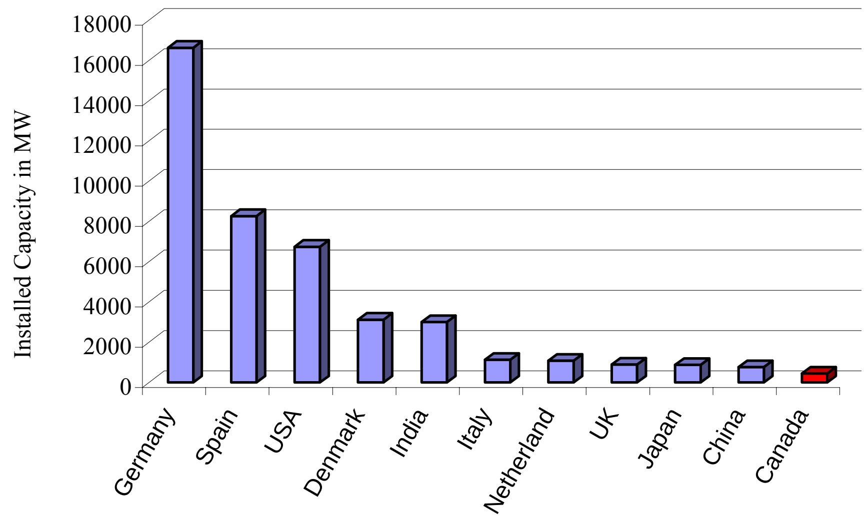

Figure 1.3: Installed capacity of wind power at the end of 2004

It can be seen from Figure 1.3 that Europe plays a leading role in power generation from wind sources. Germany has the highest total installed capacity of 16629 MW. In Canada, 122 MW of wind capacity was installed in 2004, and an additional 126 MW by mid 2005. Canada's current installed wind power at the beginning of 2006 is 683 MW and is expected to grow approximately to 2100 MW in next decade [3].

Significant growth of wind power in the near future is largely driven by renewable energy policies such as the Renewable Portfolio Standard (RPS). RPS ensures the production of certain amount of renewable energy such as wind, solar, photovoltaic, biomass and geo thermal by a specified date.

Many jurisdictions around the world are implementing or are in the process of implementing the RPS either voluntarily or mandatory. More than 17 states in the USA have made commitments to the RPS. Developing countries like India and China are also in process of adopting the RPS policy. Different jurisdictions have made commitments to generate renewable energy from 5% to 25% of the total electricity generation within a decade. Wind is the most potential source of renewable energy that can provide the specified targets, since other renewable technologies are not yet capable of bulk power generation.

Canada's total installed generating capacity at the end of 2003 was 114,980 MW out of which only 317 MW was wind capacity. This translates to about 0.27% wind penetration, which is the ratio of the installed wind capacity to the total generating capacity. Ontario, Nova Scotia and Prince Edward Island provinces of Canada have committed to generate 10%, 5% and 15% respectively of the total electricity production from renewable energy sources by the year 2010. Quebec government has announced 2000 MW of wind energy target by the year of 2013, and New Brunswick has planned to add 400 MW of wind energy by the year 2016 [3].

1.4 Problems Associated with Wind Power

It has been discussed in the previous section that wind power is expected to grow many folds in the near future. Significantly high wind penetration in power systems can introduce serious problems in adequate system planning and reliable system operation.

Wind power is mainly viewed only as a fuel saver, and is not normally considered in power system planning. Most of the electric utilities do not consider wind power in generation planning. Although wind power can help in avoiding new conventional power plants in a system, it is not given any credit in generation planning. Wind power has significant effect in improving system reliability up to a certain level. There has been some work done in resolving adequacy problems associated with generation system planning [4-6]. There has been significant work done for economic assessment of wind energy utilization in power systems [7-10].

Geographical sites with good wind resources are being explored for potential large wind farms in order to meet the high penetration targets set by RPS. Many of these sites can be far away from a power grid. The large wind farms that are located far away from a power grid need to be connected to the grid with transmission lines. Determining an adequate transmission system to deliver wind power to a power grid is a difficult problem. Wind power generation randomly fluctuates between zero and the wind farm's rated capacity. Designing a transmission system to match the wind farm's installed capacity can lead to over investment. On the other hand, it is important to provide fair access to the power transmission network to all the participating power producers in many power systems. In deregulated systems, an equal access to the system network must be provided to each of the participating generation companies (GENCOS). This problem needs to be addressed by applying suitable power system reliability evaluation techniques and economic assessment. There has not been sufficient work done in this area. There is a need to develop proper methodology and evaluation approach for evaluating transmission system adequacy on wind power delivery.

High penetration of wind power can also cause various problems related to system operation and power quality. Wind power affects power system dynamics and stability, reactive power control, voltage control and flickering. Some of these problems have been studied by different researchers in previous work [11-13].

1.5 Reliability/Cost Worth Analysis

The basic function of an electric power system is to provide reliable and economic supply of power to all the consumers. It generally requires an increased investment in the system facilities to enhance the reliability of the system. It is therefore quite conflicting to supply power economically with a high level of reliability. It is a challenging work for power system planners and operators to design and operate the system with an optimum balance between reliability level and investment cost. The continuously increasing application of wind power in conventional power systems has created more challenges in system planning and operation.

Conventional generating units are capable of producing the rated power output most of the time. Conventional transmission planning is done based on the rated generating capacity installed at various locations within the system. Wind power fluctuates continuously with available wind speed. Unlike conventional generation, the power output from a WTG is uncertain and the probability of getting rated power is very low. Sizing a transmission system to deliver wind power based on the rated capacity of the wind farm can lead to over investment. It is however important to provide fair access to transmission facility to all power generators including wind power producers. An optimum transmission system to obtain maximum benefits from wind energy can be determined using appropriate reliability and cost analysis.

One of the key benefits from wind power application in a conventional power system is the offset in fuel cost. Wind power generation can also contribute to overall system reliability, and help in reducing customer cost of electric power interruption. Offsetting conventional fuel consumption means reducing harmful emissions produced by fuel and therefore, providing environmental benefits. Environmental benefits are realized by monetary values in the form of governmental incentives or renewable energy credits (REC). Wind power producers are eligible to obtain incentives such as wind power purchase incentives (WPPI) on each unit of the renewable energy generated. The cost savings due to these benefits can be compared with the investment in the transmission system for wind power delivery.

1.6 Importance of Study

Renewable energy sources are getting more importance in power generation due to increasing environmental concerns. Many countries around the world have made commitments to the Kyoto protocol, which specifies a target to significantly reduce Green House Gas (GHG) emissions. Electric power generation is a major contributor to global GHG emission. The application of green energy sources in power generation can be helpful in reducing GHG. Wind energy sources are recognized as the most promising renewable energy sources capable of replacing conventional energy generation and making significant reduction in GHG emission,

Global public awareness leading to energy policies such as the RPS and different forms of governmental incentives to promote renewable energy have become the driving force for wind power proliferation. WPPI are available to wind power producers in many jurisdictions to promote wind power and to compete with the relatively less costly conventional power generation. Wind power production is favored by many independent/small energy producers due to its relatively small installation time compared to other conventional power plants. Power system deregulation has opened opportunities for many private energy producers by providing open access to the grid.

It is discussed in section 1.3.1 that wind power penetration in electric power systems will grow many folds in the next decade as utilities move towards wind power to meet their RPS targets. Bulk power generation from the wind can be obtained from geographic locations with good wind resources. Such locations need to be connected to a power system grid to transmit wind energy. It becomes very important to determine adequate transmission facility to connect large wind farms to the system grid. Wind farms cannot provide rated power most of the time as the power produced by wind turbine generators (WTG) varies randomly with the site wind speed. Realistic reliability/ cost evaluation techniques should be developed and utilized in determining adequate transmission facilities. This will be important for both vertically integrated system and deregulated power systems in order to determine proper investment in the transmission system.

1.7 Research Objective

The basic objective of this work is to assess the optimum transmission system to deliver wind power by comparing reliability and energy benefits available from wind energy with the investment cost in the system. A WTG is not able to generate power at its rated capacity most of the time. The design of a transmission system based on the wind farm's installed capacity can lead to excessive investment costs, and therefore, fail to meet the objective of a power system to supply reliable and economic power to consumers. The objective of this thesis is to present suitable techniques for adequacy and cost evaluation of a transmission system for delivering wind power.

Different system parameters such as the system peak load, transmission line size, length and outage probability, and wind regime at the wind farm location can have significant impact on the over all system cost and reliability. The objective of the research work also includes an analysis of the effect of these various system parameters in determining appropriate transmission system for wind power.

Many electric utilities use a ‘n-1’ reliability criterion in transmission system planning. This criterion specifies that the system should be able to withstand the outage of any major single system component, such as a transmission line. It is very important to analyze the credibility of that criterion in transmission planning considering wind power. Another objective of this research work is to evaluate the ‘n-1’ criterion for wind power transmission and recommend appropriate reliability criteria for transmission planning considering wind power.

1.8 Overview of Thesis

The rapid growth of wind power has dictated a need to develop new methods to determine appropriate transmission facility to maximize the benefits from wind energy application in power systems. Analytical probabilistic techniques have been utilized in the work reported in this thesis in order to determine adequate transmission system to connect wind power sources to a power system.

Chapter 1 introduces the basic concepts of power system reliability. This chapter provides information on the growth of wind energy applications through out the world. The RPS energy policy and its consequence on wind power development are described. It also describes the problems associated with increasing wind power penetration in power systems and related research work previously done in that field. The chapter describes the importance and the main objectives of the research work.

Chapter 2 describes various power system reliability techniques that can be applied to evaluate power system reliability evaluation considering wind power. Different deterministic and probabilistic techniques using analytical and simulation methods are briefly discussed. An analytical technique known as the Tie Line Constrained

Equivalent Unit Approach is explained for incorporating limited transmission system in a reliability evaluation at the HL-I level. The reliability indices such as the Loss of Load Expectation (LOLE) [1] and the Loss of Energy Expectation (LOEE) are described in this chapter.

Chapter 3 presents system modeling and evaluation methods and the associated mathematical expressions. System modeling is explained in three major steps consisting of wind speed modeling, WTG modeling and system risk modeling. This chapter also introduces a basic system model used for this research work. The flow diagram is presented to show the system reliability evaluation process.

Chapter 4 presents the application of the developed reliability techniques on an example system to evaluate the contribution of the wind transmission system to the overall system reliability. The impact on the reliability contribution of various system parameters, such as the transmission line capacity, unavailability and redundancy are analyzed. The effect of the transmission line size and the other parameters on the Expected Power Output (EPO) is evaluated, and its importance is discussed. Studies were done on a wind system with and without considering its integration to a large power system. The results from both the studies are presented and discussed in this chapter.

Chapter 5 presents reliability cost/worth evaluation techniques to determine appropriate transmission facility to connect a wind farm to a power system. The investment cost associated with the transmission system is compared with the overall benefits obtained from the wind energy application. The optimum transmission line size depends on different parameters, such as the transmission line cost and length, wind regime at the wind farm location, wind penetration, customer cost of interruption, etc. The effect of these parameters on the optimum transmission line sizing is analyzed in this chapter.

Finally, Chapter 6 discusses the important conclusions drawn from the various analyses, and also presents the summary of the research work.

CHAPTER TWO

RELIABILITY EVALUATION TECHNIQUES

2.1 Introduction

Power system reliability evaluation is an important process in system planning and designing in order to ensure healthy system operation in the future. Different methods have been used by electric power utilities for adequacy evaluation at the HL-I level in generating system planning. Reliability techniques can be broadly grouped in deterministic and probabilistic techniques. Deterministic techniques were the earliest methods used in power utilities to determine adequate generating capacity. These techniques have been replaced by probabilistic techniques in most of the major power utilities.

2.2 Deterministic Techniques

Deterministic techniques were used by almost all utilities in the past to determine adequate generating capacity to meet projected load demand in power system planning. The most widely used criteria within this method are described below.

1. Capacity Reserve Margin (CRM)

   Under this criterion, the installed capacity must be at least equal to the expected system peak load plus a fixed percentage of the peak load. This method is also known as the percentage reserve margin. The CRM criterion accounts for unexpected load growth in capacity planning.

2. Loss of the Largest Unit (LLU)

   A power system should be capable of satisfying the system peak load with the loss of largest generation unit under this criterion. The system capacity reserve required is at least equal to the capacity of the largest unit in the system in this case. The LLU criterion helps in avoiding load curtailment due to an outage of single unit in the system.

3. Combination of CRM and LLU

   The capacity reserve required in this case is equal to the capacity of the largest unit in the system plus a fixed percentage of either the installed capacity or the expected peak load. This criterion ensures system reliability by anticipating an outage of any single generating unit and the uncertainty in the peak load.

Electric utilities in isolated systems, in island nation and the developing world, still use some form of deterministic methods in generation planning. A deterministic method, however is not capable of recognizing stochastic behaviour of a power system and cannot provide consistent system risk evaluation. Major power utilities have shifted from using deterministic to probabilistic techniques in generation planning. Table 2.1 shows the reliability criteria used by Canadian utilities from results of surveys [14] conducted in different years.

Table 2.1: Reliability Criteria Used in Capacity Planning

Method	Criterion	Survey Date					
		1964	1969	1974	1977	1979	1987
Deterministic	Percentage Margin	1	4	2	2	3	1*
	Loss of Largest Unit	4	1	1	1	-	-
	Combination of 1 and 2	3	6	6	6	2	-
	Other Methods	2	1	-	-	-	-
Probabilistic	LOLE	1	5	4	4	6	6
	EUE	-	-	-	-	-	2

* with supplementary checks for LOLE

It can be seen from Table 2.1 that only one utility used a probabilistic criterion in the year 1964. The survey results show that more utilities have adopted probabilistic criteria in subsequent years. In 1987, only one utility was using deterministic criterion in Canada, while the rest had shifted to probabilistic methods.

Most power utilities use deterministic techniques for conducting adequacy studies in transmission system planning. The most widely used approach is the ‘n-1’ criterion. Under this criterion, the system should be able to withstand the loss of a single major system element, such as a transmission line.

Probabilistic approaches to composite generation and transmission system reliability evaluation are relatively complex. Most utilities are, therefore, reluctant to use these methods. Deterministic methods, on the other hand, are quite straightforward and used widely in transmission system planning. Deterministic techniques neither recognize the actual risk in a system nor can compare relative risks between different system conditions.

2.3 Probabilistic Techniques

Power system behaves stochastically and it is rational to assess system reliability based on techniques that respond to the random system behaviour in various scenarios. Probabilistic techniques have been developed to overcome the limitations of deterministic techniques and to provide quantitative measure of system reliability.

Many utilities around the world have adopted probabilistic techniques for system risk evaluation at the HL-I level. It can be seen from Table 2.1 that the LOLE index is the most widely used index for system reliability evaluation at the HL-I level. The North American Electric Reliability Council (NERC) has provided LOLE index of 0.1day/year as a guideline for system planning at the HL-I level. This criterion requires that the generation system be designed such that the system load does not exceed the total generation for a long-term average value of 0.1 days in a year. Many utilities use this LOLE criterion in generation planning. Few utilities use the energy-based index such as the Loss of Energy Expectation (LOEE) or the Expected Unused Energy (EUE).

It is discussed earlier that probabilistic approach is quite complex in composite system planning. Many utilities use the 'n-1' deterministic criterion for transmission system planning. Few utilities use software tools capable of conducting HL-I studies to obtain probabilistic measure of composite generation and transmission system adequacy. Probabilistic techniques can be categorized under analytical and simulation techniques that can be useful in obtaining various statistical system risk indices.

a) Analytical Technique: The system is represented by a mathematical model in an analytical technique, which provides direct numerical solutions. The majority of existing techniques are based on analytical methods.

b) Simulation Technique: This technique treats the problem as a series of real experiments and hence requires large amount of computing time. The system reliability indices are estimated by simulating the actual process and random behaviour of the system. Simulation techniques are receiving greater attention with the continuous development of high-speed computers with enormous memory/storage capacity.

2.3.1 Analytical Techniques

Analytical techniques developed for HL-I adequacy evaluation are widely accepted and routinely applied by power utilities in generation planning. It is relatively difficult to apply analytical techniques in composite system planning that requires system risk evaluation at each load point in the system. However, limited transmission system can be incorporated in HL-I adequacy evaluation. Such an analysis is usually done to consider an important transmission line under study.

2.3.1.1 Generation System Adequacy Evaluation

The basic HL-I system model can be represented by the model shown in Figure 2.1. The overall system generation is denoted as G, which provides power supply to the system load. The basic approach to system reliability evaluation at the HL-I level can be represented by Figure 2.2. The evaluation process consists of three parts: a) generation modeling b) load modeling and c) risk modeling.

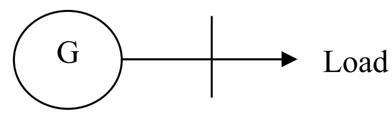

Figure 2.1: Basic HL-I system model

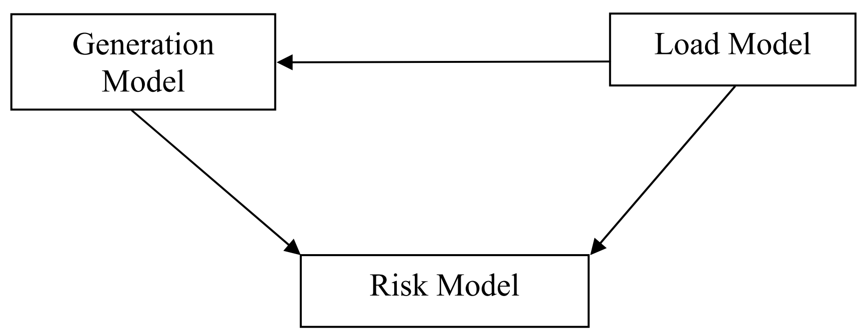

Figure 2.2: Basic concepts of HL-I adequacy evaluation

The forced outage rate (FOR) is an important parameter in generation system modeling. It can be defined as the probability of finding the unit on forced outage at some distant time in the future. The FOR of a generating unit can be calculated using Equation 2.1 [1].

$$FOR = \frac{\sum[downtime]}{\sum[downtime] + \sum[uptime]} \tag{2.1}$$

The generating unit capacity ratings and the corresponding FOR are the important data inputs that are used to create a capacity outage probability table (COPT). It is an array of capacity levels and the associated probabilities of existence. The COPT can be formed by using the recursive algorithm shown in Equation 2.2 [1].

$$P(X) = \sum_{i=1}^{n} pi * P'(X - Ci) \tag{2.2}$$

Where P'(X) and P(X) refer to the cumulative probabilities of the capacity outage state of X MW before and after the unit is added respectively. The above algorithm is initialized by setting P'(X) = 1 for $X \leq 0$ and P'(X) = 0, otherwise. Generating unit may partially fail and reside in derated states. 'n' is the number of outage states with Ci MW on outage with a probability of pi.

The load model represents the variation in the system load with time within a certain period. The basic period used in system planning and reliability study is a calendar year. It can also be presented in per unit of time. The system load can also be represented in per unit of the peak load. There are a number of load models, which can be used to produce different risk indices. The Daily Peak Load Variation Curve (DPLVC) and the Load Duration Curve (LDC) are widely used load models in analytical evaluation. The DPLVC is a model that represents the variation in the daily peak loads in the descending order. The resultant cumulative load model is known as the LDC when the individual hourly load values are used. Figure 2.3 shows a simple load model.

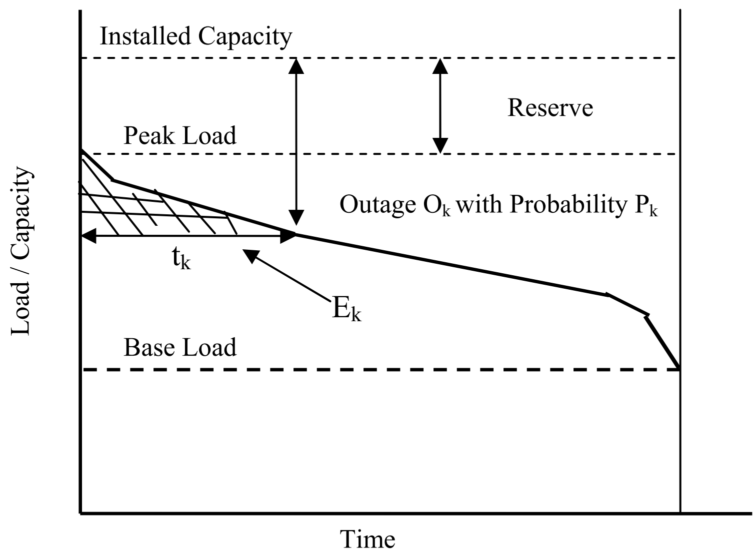

Figure 2.3: Load model and risk indices

The generation model is combined with the load model to evaluate different risk indices. The Loss of Load Expectation (LOLE) is being considered as one of the most important risk indices. It can be defined as number of days in specific duration in which daily peak load exceeds the available generation capacity. Figure 2.3 also shows the system installed capacity and the convolution of generation and the load model. It can be seen from the figure that any capacity outage in excess of the reserve will cause a load curtailment. Figure 2.3 shows that time t_k is the duration for load curtailment due to capacity outage O_k, which is more than reserve capacity. P_k denotes the individual probability of the capacity outage O_k. The system LOLE can be evaluated by Equation 2.3 [1].

$$LOLE = \sum_{k=1}^{n} P_k . t_k \tag{2.3}$$

where n = number of capacity outage states in the COPT

P_k = individual probability of capacity outage O_k

t_k = time duration of load curtailment due to outage O_k

If the time is in per unit of total time period, the above equation gives the Loss of Load Probability (LOLP) in lieu of the LOLE. The unit of LOLE is in days per year when using a DPLVC, and in hours per year when using a LDC load model.

The area under the LDC represents the total energy demand in a year by the system. Figure 2.3 is a LDC, the shaded area (E_k) corresponds to an energy curtailment due to capacity outage O_k with a probability of P_k. Each outage state in the COPT is superimposed on the LDC to calculate the total energy curtailed. The energy based index Loss of Expected Energy (LOEE) can be calculated using Equation 2.4. This index is also known as the Expected Unsupplied Energy (EUE).

$$LOEE = \sum_{k=1}^{n} E_k . t_k \tag{2.4}$$

2.3.1.2 Incorporating Transmission System in Adequacy Evaluation

It is stated earlier that important transmission system can be incorporated in system adequacy evaluation at the HL-I level. The basic model incorporating transmission line is shown in Figure 2.4. Figure 2.4 represents a remotely located generation facility, such as a large wind farm, which is connected to a conventional grid system through a transmission system. TL is the transmission line, which connects a remotely located generation plant (RG) to the rest of the generation system (G) in a power grid.

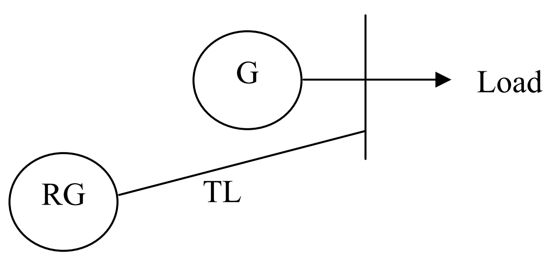

Figure 2.4: HL-I system model incorporating transmission line

The generation system adequacy evaluation model in Figure 2.2 can be extended to incorporate limited transmission system as shown in Figure 2.5. A tie line constraint equivalent unit approach [1] can be used to develop a generation model that includes transmission system. Additional data on transmission line capacity, length and failure rate are required to create a COPT for the system.

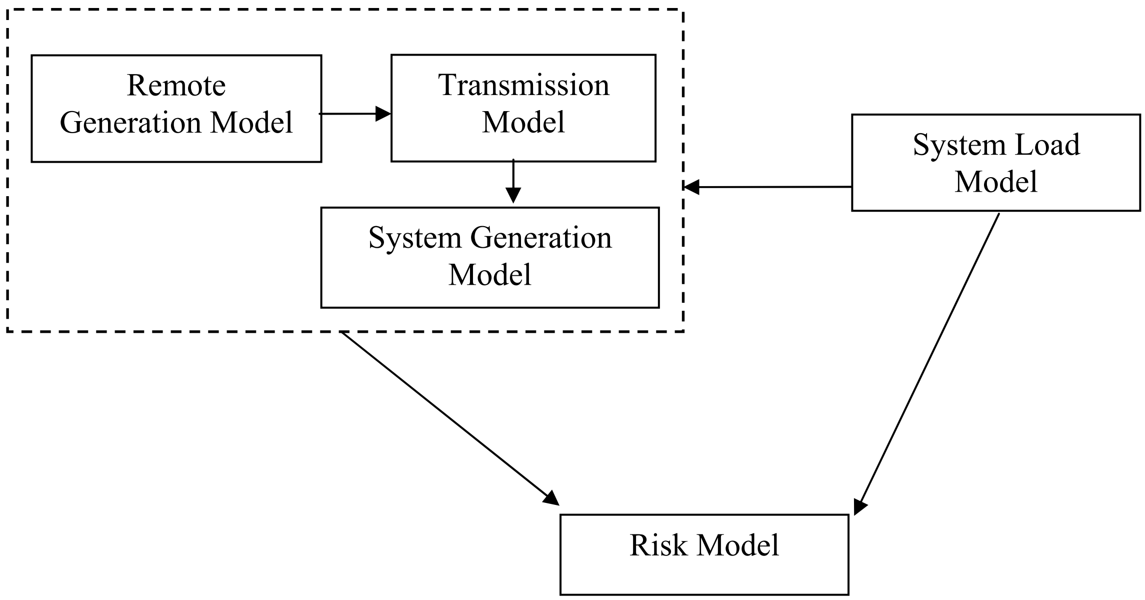

Figure 2.5: Evaluation model incorporating transmission system in HL-I

The model in Figure 2.5 can be used to incorporate a transmission line that connects a remote power source to a power system. System adequacy evaluation considering transmission system can be conducted as shown in the model using the following steps.

1) A generation model for the remotely located generation plant is first developed in the form of a COPT.
2) The generation model developed in step-1 is modified to include the transmission line constraints. The available generation capacity of the remote plant is constrained by the transmission line capacity. Any generation capacity in excess of the tie line capability is replaced by the tie line capacity to create a COPT that incorporates the effect of the transmission line. The probabilities of the various capacity conditions in the generation model in step-1 are weighted by

the availability of the transmission line. The modified COPT represents a single unit that includes wind generation and transmission system models.

3) The total system generation COPT can finally be obtained by adding the equivalent unit model obtained in step-2 to the rest of the generation system using the recursive algorithm shown in Equation 2.2.
4) The total system generation model is convolved with system load model to obtain the system risk indices.

The analytical technique described above is used and extended in this research work to include a remotely located wind generation in adequacy evaluation of a wind power delivery system. A computer program named SIPSREL [15] developed at the University of Saskatchewan incorporates HL-I analytical techniques to evaluate various risk indices and energy indices. It is a useful graphical user interface software tool for generation system reliability studies. It has been developed as an educational tool, and has also been used in reliability studies of electric power utilities. This tool has been used in the analysis conducted in this research work.

2.3.2 Simulation Techniques

Simulation techniques are the other type of probabilistic methods used in power system reliability evaluation. Unlike analytical technique, this technique simulates the actual system process on a computer to evaluate various risk indices. The advancement in computing facility has made simulation process faster. Monte Carlo Simulation (MCS) process is based on random variable generator and it may provide different numerical solution every time the simulation is repeated. These techniques use chronological load variation for system risk evaluation.

MCS process can be mainly used in two ways, random and sequential. The random approach simulates the basic duration of the system lifetime by choosing intervals randomly. The sequential approach simulates the system interval chronologically [16]. This approach is very essential to analyze the system for which one basic interval has significant effect on the next interval. Simulation techniques can be very useful in system risk evaluation at the HL-1 as well as at the HL-II level. Simulation techniques require large computation time and memory space. Slightly different results are usually obtained when a simulation process is repeated. These techniques are normally not used when direct analytical techniques are available.

2.4 Summary

Power system reliability evaluation techniques are being continuously developed over the last fifty years. Deterministic techniques were widely used in power system planning and used by many utilities across Canada. These techniques cannot recognize the random nature of component failures or load variations in power systems. The development of probabilistic techniques has attracted utilities to employ these methods in generation system planning.

Probabilistic techniques using analytical and simulation technique are discussed. The basic concepts behind analytical methods for risk analysis are described. Risk indices such as LOLE and LOEE are explained. Most of the utilities use these indices for generation system reliability evaluation. Analytical HL-I adequacy evaluation methods can also incorporate limited transmission system. The method of incorporating transmission line in adequacy evaluation using a tie line capacity equivalent unit approach is described in this chapter. The analytical techniques described in this chapter are incorporated in the software tool SIPSREL.

Probabilistic techniques are not used widely in transmission system planning. Most utilities use a deterministic ‘n-1’ adequacy criterion in transmission planning. The probabilistic techniques to incorporate a transmission system in HL-I evaluation are extended in this research work in order to assess the benefit from wind power delivery.

CHAPTER THREE

SYSTEM MODELING AND EVALUATION METHOD

3.1 Introduction

Generation of electric power from the wind has been growing continuously since the last decade. The importance of wind power in meeting global energy demand has increased because of increasing environmental awareness and emerging energy policies that promote renewable power. It has become increasingly important to determine adequate transmission facility to connect remotely located large wind farms to power systems in order to optimize the benefits from wind energy. It is earlier discussed that wind power fluctuates randomly, and is therefore important to assess adequate transmission system from a reliability /cost point of view. Such analysis is required to maximize the benefits from wind while avoiding unnecessary investment in transmission system. This chapter presents system evaluation models and techniques that were developed to evaluate adequate transmission facility required to deliver wind power. The evaluation approach is illustrated using an example.

Wind power system evaluation model consists of three major steps: 1) wind speed modeling 2) WTG system modeling 3) system risk modeling. The graphical presentation of the evaluation process is shown in Figure 3.1.

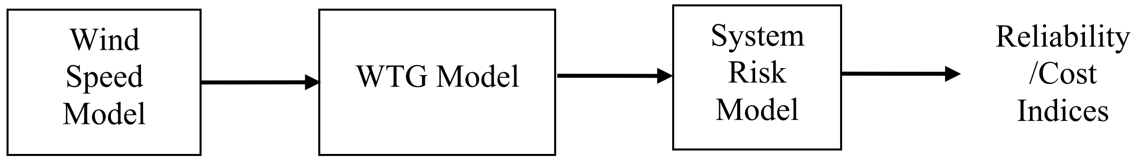

Figure 3.1: Basic system evaluation model

3.2 Wind Speed Modeling

The amount of wind power generated depends on the density of air, wind turbine rotor area, and the wind speed. The relationship is shown in Equation 3.1[17].

$$P = \frac{1}{2} \rho A V^3 \tag{3.1}$$

where, P = Wind power generated in w (watts)

ρ = Density of dry air in kg/m^3 (kilograms per cubic meter)

A = Rotor swept area in m/s (meter per second)

V= Wind speed in m (meter)

Wind power generation is proportional to the cube of the wind speed. It indicates that accurate wind speed modeling is essential for studying wind power effect on system reliability and cost.

Wind speed varies continuously with time, and wind regimes vary with geographic conditions. A wind simulation model simulates the variation of wind speed over a specified period of time for a selected geographic site. Hourly wind speeds for a selected wind farm site were simulated using a time series Auto Regressive Moving Average (ARMA) model [18], which is mathematically expressed in Equation 3.2.

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \ldots + \phi_n y_{t-n} + \alpha_t - \theta_1 \alpha_{t-1} - \theta_2 \alpha_{t-2} - \ldots - \theta_m \alpha_{t-m} \tag{3.2}$$

where, y_t is the time series value at time t, ϕ_i (i = 1,2,3…n) and θ_j (j=1,2,3…. m) are the auto regressive and moving average parameters of the model respectively. $\{\alpha_t\}$ is a normal white noise with zero mean and a variance of σ_a^2 (i.e. $\alpha_t \in$ NID $(0, \sigma_a^2)$), where NID denotes Normally Independently Distributed.

The simulated wind speed SW_t at the tth hour can be obtained using Equation 3.3 from the historical mean speed μ_t, standard deviation σ_t and the time series values y_t.

$$SW_t = \mu_t + \sigma_t * y_t \tag{3.3}$$

The hourly mean wind speed and the standard deviation data for a given site should be collected using a data collection scheme over a number of years. A computer program was developed to use respective hourly wind speed data for a particular site and to implement ARMA (4, 3) model [18] in order to generate simulated wind speed data. This model represents the first step of wind system modeling discussed in the previous section.

3.3 WTG System Modeling

Electrical power generated through WTG depends on the availability of wind and energy conversion characteristics of the WTG unit. A WTG system or a wind farm usually consists of a large number of WTG units. WTG system modeling requires combining the wind speed model at the wind farm location with the WTG power generation characteristics of all the WTG units located in the wind farm. The following sections describe the concepts behind wind power generation that are utilized in the modelling process.

3.3.1 Wind Energy Conversion System

The basic working principal of wind energy conversion system (WECS) consists of two energy conversion processes. The wind turbine rotor extracts kinetic energy from wind and converts it into mechanical energy at the rotor shaft. The generator converts mechanical power into electrical power. Electrical power is delivered to the main grid system to share the system load. The symbolic representation of the general working principle of wind energy conversion system is shown in Figure 3.2.

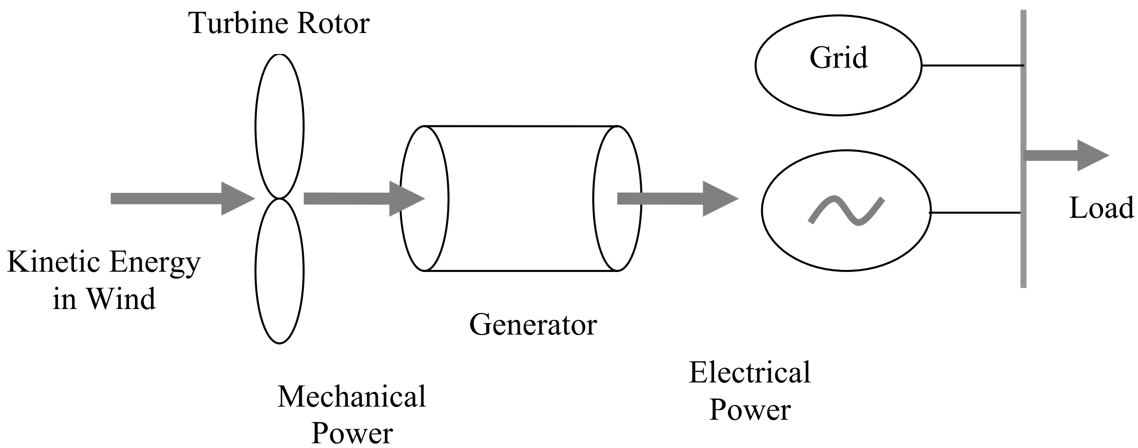

Figure 3.2: General principal of WECS

Wind power generation varies with the WTG characteristics. It depends on proper selection and design of the generator and the turbine system. It can be seen from Equation 3.1 that power produced is directly proportional to the rotor area. Hence, it is equally important to choose appropriate WTG design parameters to match a specific wind site.

3.3.2 Wind Power Generation

Wind power generation mainly depends on the availability of wind and the design parameters of the WTG unit. The main characteristics that influence generated power are the cut-in wind speed, cut-out wind speed, rated wind speed, and the rated power. Wind power generation varies non-linearly with the wind speed and can be obtained from the power curve of a WTG as shown in Figure 3.3 [8].

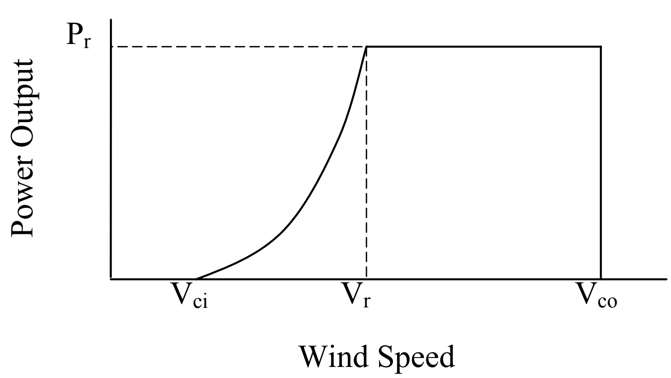

Figure 3.3: Power curve of WTG

It can be seen from Figure 3.3 that wind turbines are generally designed to start running at specific minimum wind speed. This wind speed is called the Cut-in wind speed, V_{ci}. The generated power increases non-linearly as shown in Figure 3.3 with the increase in the wind speed from V_{ci} to the rated wind speed V_r. A WTG generates the rated power Pr at the rated wind speed. Wind turbines are designed to stop at high wind speed in order to avoid damaging the turbine. This maximum allowable wind speed is called the Cut-out wind speed, V_{co}. The power generated remains constant at the rated power level P_r when the wind speed varies between the rated wind speed and the cut-out wind speed. The relation between the power output from a WTG and the available wind speed, which is shown by the power curve in Figure 3.3, can also be mathematically expressed by Equation 3.4.

$$P_t = \begin{cases} 0, & 0 \leq SW_t \leq V_{ci} \\ (A + B * SW_t + C * SW_t^2), & V_{ci} \leq SW_t \leq V_r \\ P_r, & V_r \leq SW_t \leq V_{co} \\ 0, & V_{co} \leq SW_t \end{cases} \qquad (3.4)$$

where, P_t is the wind power output at the t^{th} hour. V_{ci}, V_r, V_{co} and P_r are cut-in speed, rated speed, cutout speed and rated power output of a WTG respectively. The constants A, B and C can be found using V_{ci}, and V_r in Equation 3.5 [19].

$$\begin{aligned} A &= \frac{1}{(V_{ci} - V_r)^2} * \left[V_{ci}(V_{ci} + V_r) - 4V_{ci}V_r \frac{(V_{ci} - V_r)^3}{2*V_r} \right] \\ B &= \frac{1}{(V_{ci} - V_r)^2} * \left[4(V_{ci} + V_r) \frac{(V_{ci} + V_r)^3}{2*V_r} - (3V_{ci} + V_r) \right] \\ C &= \frac{1}{(V_{ci} - V_r)^2} * \left[2 - 4 \frac{(4V_{ci} + V_r)^3}{2*V_r} \right] \end{aligned} \qquad (3.5)$$

3.3.3 Wind Power Generation Model

The hourly electric power generated from a WTG can be calculated from the wind speed data using the power curve of the WTG. The simulated hourly wind speed obtained from step-1 of Figure 3.1 was used to calculate the hourly wind power generated from a WTG. The total power generated from a particular wind power system (also known as a wind farm) can be calculated by aggregating the power outputs of all the WTG installed in the wind farm. The hourly wind power outputs were grouped into a number of different power output steps, and the probability of occurrence of each output step was calculated. Hence, the wind power generation model was created for a particular wind farm located at specific wind site. The generation model consists of all the power output levels and their associated probabilities for the wind farm. A computer program was developed to obtain the wind power generation model by superimposing the simulated wind speed on the power curve of WTG.

The software tool SIPSREL, discussed in the previous chapter was designed [15] for evaluating reliability of a conventional power system. SIPSREL can take a generation unit with five de-rated power output steps. The wind generation model should therefore be developed in a 5-step model to comply with SIPSREL. It can be seen from Equation 3.4 that WTG cannot produce electric power when the wind speed is greater than the cut out wind speed and lower than the cut in wind speed. This condition was used to form the two steps comprising of rated output and zero output of generation model. The remaining three steps were formed by dividing the non-linear characteristics of WTG power curve into three different power output levels. These three different power levels were determined such that the expected power output (EPO) of the 5-step wind power generation model is the same as that of the original wind power generation model. This condition was applied to maintain the wind power generation model accuracy while employing SIPSREL in the system risk evaluation.

A wind farm generation model consists of a number of different power generation states and their corresponding probabilities. This is obtained by first determining the different simulated wind speeds. The probability p_{wi} of a simulated wind speed SW_i is given by Equation 3.6.

$$p_{wi} = \frac{N_i}{(N * 8760)} \qquad (3.6)$$

where N is the number of simulation years, and N_i is the number of occurrences of wind speeds in the range (SW_j, SW_{j+1}), where,

$$SWi = \frac{(SW_j + SW_{j+1})}{2} \quad (3.7)$$

The power generated P_i by each individual WTG in the wind farm was calculated using Equation 3.4, and aggregated to obtain the wind farm generation model which consists of the wind farm power generation states WP_i and their corresponding probabilities p_i. WP_i corresponding to wind speed SW_i is given by Equation 3.8.

$$WP_i = \sum_n Pi \quad (3.8)$$

where n is the number of WTG in the wind farm.

EPO is the long-term average power output, and is a useful power index in adequacy evaluation of a wind farm. It can be expressed by Equation 3.9.

$$EPO = \sum_{i=1}^{n} WP_i * p_i \quad (3.9)$$

where, WP_i represents a generation state of WTG with probability p_i and n is the number of generation states.

This model was applied to a wind farm located at Swift Current, Saskatchewan, Canada. Historical wind speed data for Swift Current site obtained from Environment Canada were used to obtain the respective ARMA time series model. The mean wind speed for this geographic location is 22.01 km/h with the hourly mean standard deviation ranging from 5.1 to 8.9 km/h. It was assumed that 100 identical WTGs each rated at 2.5 MW were installed in a wind farm at the Swift Current site. The cut-in speed, the rated speed and the cut-out speed of each WTG are 14.4 km/h, 45 km/h and 90 km/h respectively. The resulting 5-step wind system/farm generation model is shown in Table 3.1.

Table 3.1: Wind Power Generation Model

Wind power generation states WPi (MW)	Probability (p_i) associated with wind generation state
0	0.1373664
42	0.4875411
115	0.3337295
240	0.0401198
250	0.0012432

3.4 System Risk Modeling

System risk modeling is the final step in the system adequacy evaluation process shown in Figure 3.1. The wind system generation model obtained from step-2 is modified to incorporate the wind power transmission system using the tie line constrained equivalent unit approach. The equivalent unit, which represents the wind farm and the transmission line, is then combined with the rest of the system generating units to create the overall system generation model. This model is finally convolved with system load model to obtain the system risk and energy based indices.

3.4.1 System Generation Model

The effect of transmission line can be included in the wind generation model using the tie line constrained equivalent unit approach. The concept can be explained using Figure 3.4.

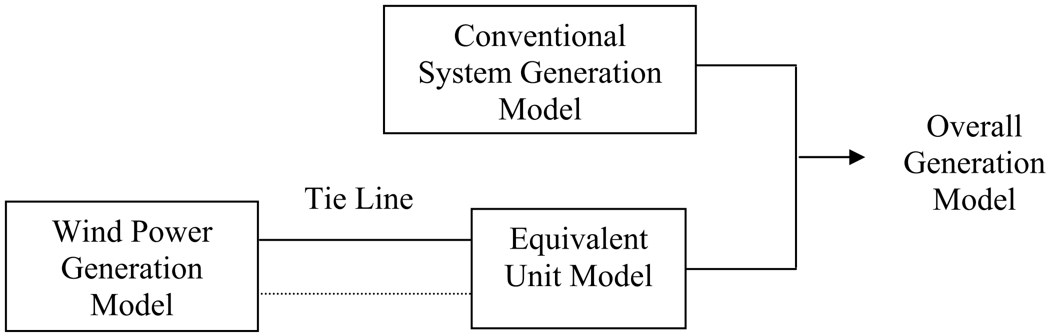

Figure 3.4: Wind system connected through tie line

It can be seen from Figure 3.4 that the wind power delivery is constrained by the tie line capability and its availability. An equivalent unit model is evaluated to represent the wind generation and delivery system. The model incorporates the effect of the tie line capacity and its availability in the wind power generation model. The probability (p_i) associated with wind power generation states are weighted by the probability of the tie line being available. It is mentioned earlier that each wind power generation state (WPi) greater than the tie line capacity is replaced by the tie line capacity, under the tie line constrained equivalent unit approach.

The next step of the evaluation process is to develop the wind farm generation model at the grid access point. This model incorporates the transmission line, the power transfer capability and the forced outage probability of which constrains the wind farm generation model. The wind power available at the grid access point WP_{Gi} is constrained by the transmission line capacity T_{cap} as expressed in Equation 3.10.

$$\begin{aligned} WP_{Gi} &= WP_i, \quad \text{for} \quad WP_i < T_{cap} \\ &= T_{cap}, \qquad\quad WP_i \geq T_{cap} \end{aligned} \tag{3.10}$$

The probability p_{Gi} of the generation state WP_{Gi} is given by Equation 3.11.

$$\begin{aligned} p_{Gi} &= U_T + (1 - U_T) * p_i, \quad \text{for} \quad WP_{Gi} = 0 \\ &= (1 - U_T) * p_i, \qquad\qquad 0 < WP_{Gi} < T_{cap} \\ &= (1 - U_T) * \sum_{j=1}^{s} p_j, \qquad WP_{Gi} = T_{cap} \end{aligned} \tag{3.11}$$

where U_T is the transmission line forced outage probability, s is the total number of j generation states constrained by the line transfer capability.

In this way, Equations (3.8), (3.10) and (3.11) were used to determine the different power generation states and their corresponding probabilities at the grid access point. This model was used to determine the EPO using Equation 3.12.

$$EPO = \sum_{i=1}^{s} WP_{Gi} * p_{Gi} \tag{3.12}$$

The development of the equivalent unit model at grid access point, which includes a wind farm and its transmission system, can be illustrated with an example. It is assumed that the wind farm located in Swift Current is connected to a power grid through a transmission line of 240 MW capacity and 100 km in length. Transmission system failure rate (λ) and average repair time (r) were assumed at 0.2 failure/km/year and 8.93 hours respectively. Transmission system unavailability (U_T) and Availability (A_T) can be calculated using Equation 3.13-a and 3.13-b respectively. In this case, U_T and A_T were calculated 0.02 and 0.98 respectively.

$$U_T = \frac{\lambda}{(\lambda + 1/r)} \tag{3.13-a}$$

$$A_T = 1 - U_T \tag{3.13-b}$$

The resulting wind generation model incorporating transmission line unavailability is shown in Table 3.2. The EPO at the grid access point is 67.4 MW.

Table 3.2: Wind Power Generation Equivalent Unit Model

Wind power generation states WP_{Gi} (MW)	Probability (p_{Gi}) considering transmission line unavailability
0	0.1546191
42	0.4777903
115	0.3270549
240	0.0405357

The probability values (p_{Gi}) in Table 3.2 were obtained using Equation 3.11 by weighing the probability values (p_i) in Table 3.1 by the availability of the transmission line. The wind generation state of 250 MW in Table 3.1 is constrained to the tie line capacity of 240 MW in Table 3.2. The sample calculations for wind power generation of 0 MW, 42 MW and 240 MW states are shown below.

Sample Calculation of Probability (p_{Gi}):

(1) For WP_{Gi} = 0 MW

$$p_{Gi\,(0)} = p_{i\,(0)} * A_T + U_T = (0.1373664)*(0.98) + 0.02 = 0.1546191$$

(2) For WP_{Gi} = 42 MW

$$p_{Gi\,(42)} = p_{i\,(42)} * A_T = (0.4875411)*(0.98) = 0.4777903$$

(3) For WP_{Gi} = 240 MW

$$p_{Gi\,(240)} = (p_{i\,(240)} + p_{i\,(250)}) * A_T = (0.0401198 + 0.0012432)*(0.98) = 0.0405357$$

The wind power output is 0 MW under two conditions: when the transmission system is available and the WTG are not able to generate power, and when the transmission system is unavailable. This effect can be included and shown by sample calculation (1). The probability values (p_{Gi}) for wind generation states less than tie line capacity were weighted by availability (A_T) of transmission line and can be shown by sample calculation (2). The probability values of wind generation states greater than and equal to tie line capacity were combined and formed a single wind power generation state. Table 3.2 consists of four wind power generation states instead of five states in Table 3.1. The probability values of 240 MW and 250 MW stages in Table 3.1 were combined in a single 240 MW states in Table 3.2. The probability value (p_{Gi}) for 240 MW state in Table 3.2 was calculated by summing the probability values (p_i) of wind generation states greater than and equal to the tie line capacity, and multiplying the summed value by the availability (A_T) of transmission line. This calculation is shown in sample calculation (3).

3.4.2 System Load Model

The system load in an electrical power system varies with time and that variation can be represented by a load model. The description of different load models and its applications in evaluating various system risk indices are presented in the previous chapter. Figure 3.5 shows the load duration curve of the IEEE-Reliability Test System (RTS) [20], which is a test system used by many researchers in system reliability studies.

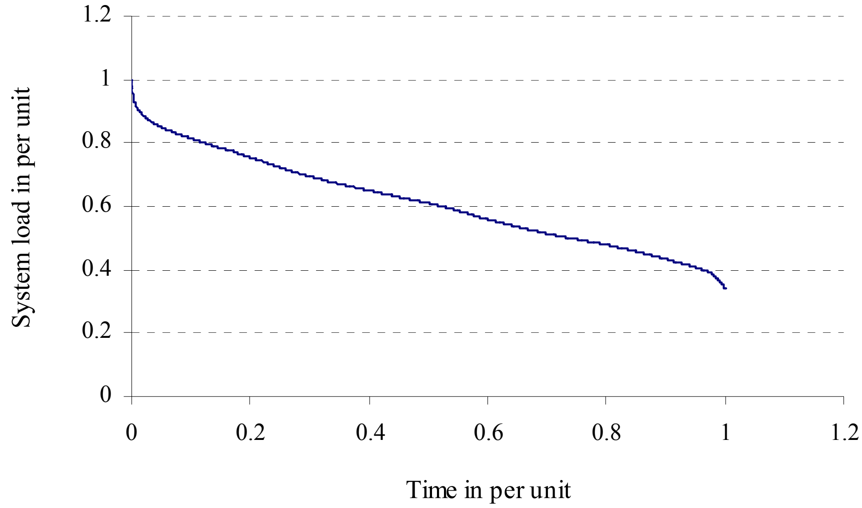

Figure 3.5: Annual load duration curve for the IEEE-RTS

The variation in annual load shown in Figure 3.5 is in per unit (PU) value. This variation is non- linear in an actual power system. The shape of a load curve is often simplified in practical application. It can be seen from Figure 3.5 that load varies from 1 PU to 0.7 PU for about 20% of total duration and from 0.7 PU to 0.3 PU for 80% of total duration. Figure 3.6 shows the approximation of actual load duration curve of the IEEE-RTS [20].

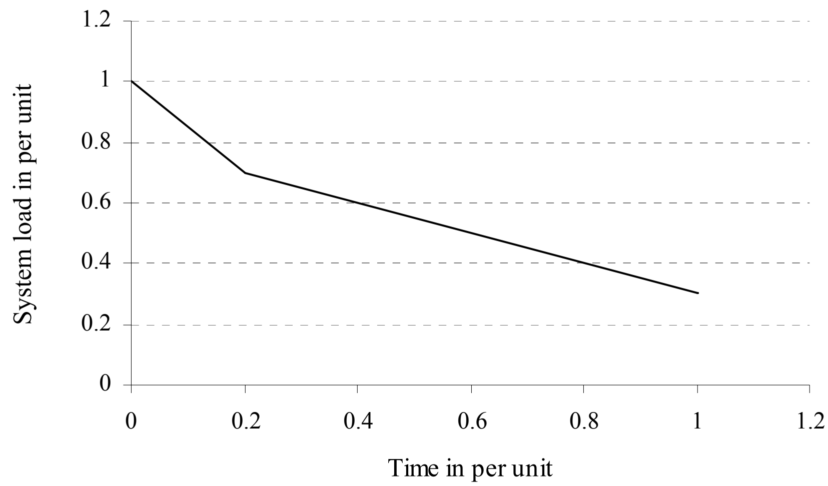

Figure 3.6: Approximate IEEE-RTS load model

3.4.3 Adequacy Evaluation Method and Risk Indices

The software tool SIPSREL was used to combine the equivalent wind system generation unit with a conventional generation system units for obtaining total generation system model. SIPREL is capable of integrating up to five de-rated power output states of any generation unit. This feature has made SIPSREL a useful tool in incorporating wind power to a conventional system for overall system reliability evaluation. The five steps wind farm generation model formed by incorporating transmission system was used in SIPSREL. Figure 3.7 shows the pictorial representation of SIPSREL application in overall system adequacy evaluation.

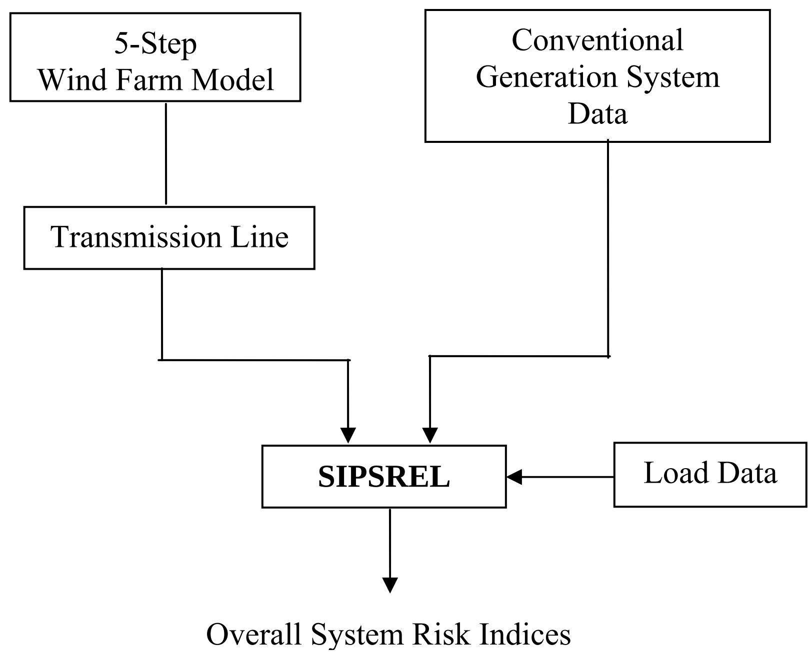

Figure 3.7: Application of SIPSREL in adequacy evaluation

SIPSREL provides system reliability indices such as LOLE and energy indices, such as LOEE and Expected Energy Supplied (EES) by each generating unit. These indices can be used for evaluating reliability and cost associated with wind power integration with a conventional system through a transmission system.

3.5 Evaluation of Reliability /Cost Indices

There are number of benefits associated with utilization of wind energy in a conventional power generation system. Wind power offsets conventional fuel, helps in reducing system down time and also reduces environmental degradation. Many governments provide incentives to wind power producers for endorsement of green energy. The reduction in environmental pollution is being estimated under social cost or environmental credits and used in estimating green energy benefits. This study recognizes benefits from fuel offset by wind power, reliability worth and environmental benefits. There is a saving in fuel cost due to fuel offset by wind energy. The reliability benefits can be expressed in terms of customer interruption costs [1]. The environment benefits can also be indirectly related to monetary values as described later in this chapter.

3.5.1 Fuel Offset by WTG

The study conducted in this research considers a wind farm connected to a conventional system. The savings in fuel cost can be obtained by determining the energy offset from burning conventional fuel. The energy offset is equal to the expected energy supplied (EES) by wind sources. The EES by wind sources can be obtained from SIPSREL. The concepts behind EES evaluation are provided in [1]. The energy supplied by the wind farm offsets the conventional fuel cost, and can be calculated by Equation 3.14.

$$FOW = EES_w * FC \qquad (3.14)$$

Where FOW = Fuel offset by wind energy

EES_w = Expected energy supplied by WTG in MWh

FC= Average fuel cost in Canadian $/MWh

3.5.2 Environment Benefits from WTG

The environmental benefits from WTG are well perceived. Energy policies have been formulated to recognize these benefits in terms of monetary values. Renewable Energy Credits (REC) are obtained through renewable energy utilization in certain jurisdiction, and can be traded in the market. Other jurisdictions provide financial incentives recognizing the environmental benefits of wind power. WPPI is an incentive to promote wind power in electric power generation.

Wind power is the most mature source of green energy that can be useful in mitigating environmental degradation. Wind power technology and cost of electricity generated from wind are costlier than power generation from most conventional sources.

According to Canadian wind energy association [3], cost of generation electricity from wind varies between 6 to 12 cents per kWh, depending upon wind farm site. To offset the difference in cost of electricity, some governments offer WPPI. The incentive offers for each unit of wind energy in Canada is shown in Table 3.3 [21]. The monetary values are in Canadian dollars.

Table 3.3: Wind Power Production Incentives in Canada

Commissioning Date	**Amount of Financial Incentive for the ten- year period**
April 1, 2002 to March 31, 2003 inclusive	1.2 cents per kilowatt-hour (¢/kWh)
After March 31, 2003 and on or before March 31, 2006	1.0 ¢/kWh
After March 31, 2006 and on or before March 31, 2007	0.8 ¢/kWh

The WPPI program extended until April 1, 2010 and has a target of 4000 MW of wind power addition in Canada. The incentive provided by WPPI will remain at 1 ¢/kWh for the duration of the entire program. This latest information was included from the Canadian Wind Energy Association's president message regarding wind energy and federal budget [3].

The monetary value of the environmental benefits can be calculated using Equation 3.15.

$$BOI = EES_w * WPPI \tag{3.15}$$

The BOI index stands for benefits obtained from incentive in dollars.

3.5.3 Reliability Worth

A number of different techniques to evaluate customer impacts due to electricity interruption have been developed and presented in previous research work [22-24].

Incorporating wind power to conventional system can be useful in supplementing energy to system and in reducing expected customer interruption cost (ECOST). The simplest way of estimating ECOST without introducing great inaccuracies is presented by Equation 3.16 [1].

$$ECOST = IEAR * LOEE \qquad (3.16)$$

The IEAR represents interrupted energy assessment rate and is expressed in $/kWh of unsupplied energy. The LOEE represents the loss of energy expectation and is also known as the expected energy not supplies (EENS).

The addition of wind power to a power system will normally improve the overall system reliability. This can be quantitatively measured by the reduction in system LOLE, which can be obtained of using Equation 3.17.

$$\Delta LOEE = EENS - EENS_W \qquad (3.17)$$

Where ΔLOEE is the reduction in system LOEE as a result of wind energy utilization.

EENS = Expected energy not supplied before adding wind power

$EENS_W$ = Expected energy not supplied after adding wind power

The reduction in outage cost to the customer or the benefit available from saving in ECOST can be estimated using Equation 3.18.

$$BOC = IEAR * \Delta LOEE \qquad (3.18)$$

where, BOC represents benefits from saving in ECOST in dollars

The total benefit (B_w) from wind power can be obtained using Equation 3.19.

$$B_w = EES_w (FC + WPPI) + IEAR \times \Delta LOEE \qquad (3.19)$$

An optimal transmission system to deliver wind power will depend on system variables, such as the transmission line cost, length, system IEAR, wind location, and penetration levels. The effect of these parameters is discussed later in this thesis.

3.6 Evaluation Approach

The basic system model considered for study is shown in Figure 3.8. A wind farm is connected to a power grid through a transmission system. A wind farm consists of a number of WTG units that are all exposed to the same wind regime. The rest of the power system is assumed to be composed of conventional generating units.

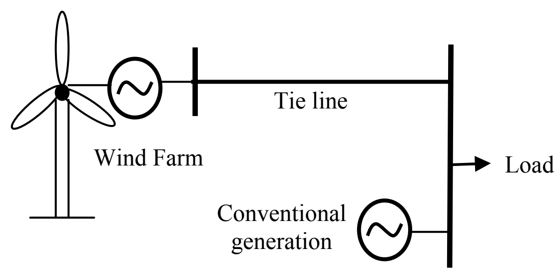

Figure 3.8: Basic system model

The overall methodology of the reliability/cost evaluation of the system in Figure 3.8 can be represented using a flow chart shown in Figure 3.9. It is very important to analyse the adequacy of the transmission system, evaluating its contribution to overall system reliability. The relevant reliability cost/worth analysis was conducted in this research according to the flow diagram in Figure 3.9. The basic indices obtained from the process and used in the research work are EPO, LOLE, LOEE and EES. These indices are used to derive other indices to assess wind power benefits.

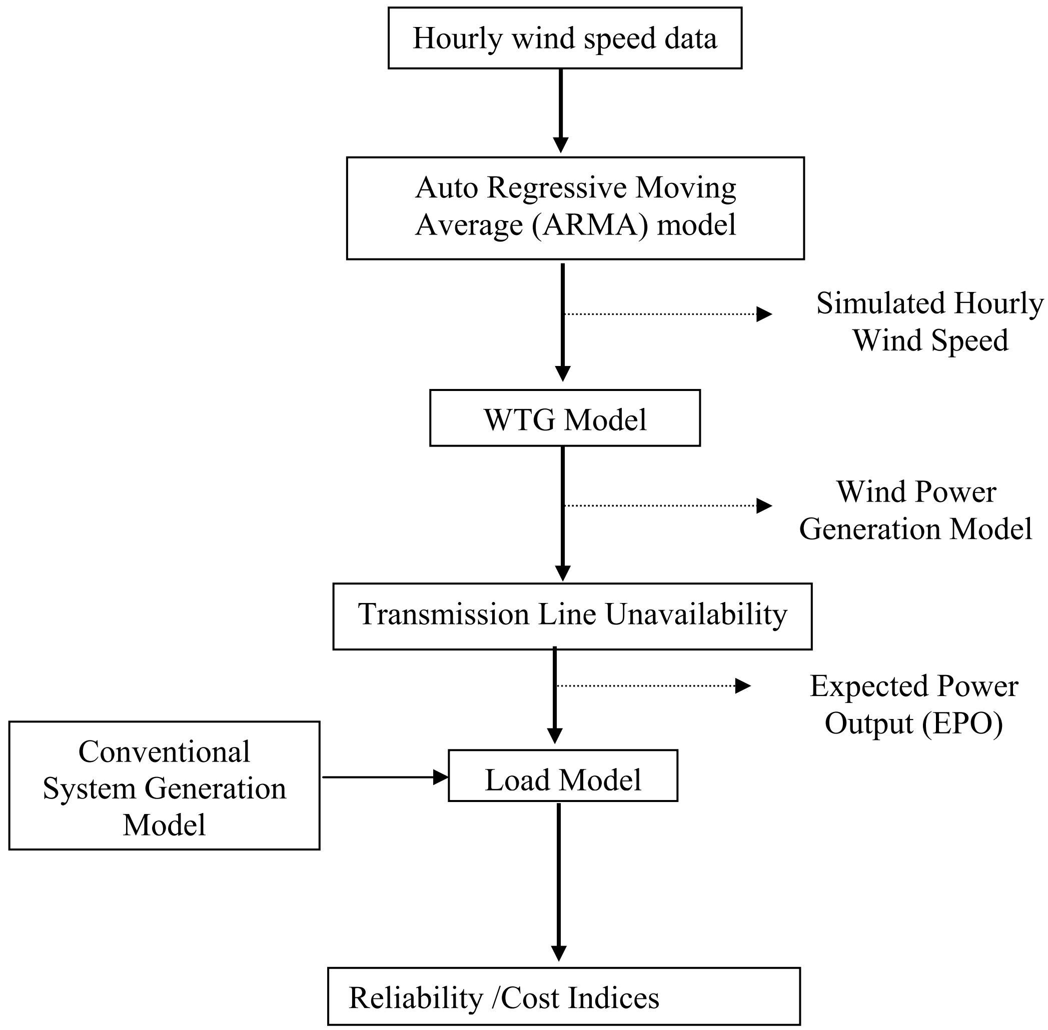

Figure 3.9: Flow chart of evaluation approach

3.7 Summary

Wind power application is growing steadily to meet the RPS targets put in place to reduce environmental degradation. Bulk wind power can be obtained from geographic sites with good wind resources. Wind farms installed at these sites need to be connected to the system grid. It becomes necessary to evaluate adequate transmission facility to deliver wind power from the remotely located wind farms. The system modeling and evaluation methods are explained for evaluating transmission system adequacy on wind power delivery.

The overall system modeling approach is presented in this chapter by dividing the entire process into three major tasks of wind speed modeling, WTG system modeling, and system risk modeling. A computer program was developed for wind speed modeling, WTG system modeling and for creating a wind generation model incorporating transmission system.

Wind generation model at grid access point can be combined with the conventional power generation system using SIPSREL software tool. SIPSREL can be used to obtain various risk indices by comparing the total system generation model with the system load model.

Reliability/cost indices are also introduced and explained in this chapter. There are numerous benefits associated with wind energy utilization in a conventional system. The benefits such as fuel offset, environmental benefit and reliability worth are described in this chapter. The cost savings due to these benefits are mathematically expressed.

The basic example system considered for this research is illustrated in this chapter. The overall system reliability/cost evaluation process for the system model under study is represented using a flow chart. System modeling and evaluation approach expressed in this chapter is used in analysis the effects of various system parameters on wind transmission system adequacy.

CHAPTER FOUR

RELIABILITY CONTRIBUTION OF WECS THROUGH A TRANSMISSION SYSTEM

4.1 Introduction

Wind power penetration in electric power systems is increasing significantly through out the world to meet the highly ambitious RPS targets set in many jurisdictions to reduce environmental degradation. Wind energy is recognized as the most promising source of renewable energy to meet the specified RPS targets. The number of remotely located wind farms that need to be connected to conventional power grid will continue to increase in the near future. Wind power integration to a main grid is becoming a challenging development in modern power systems. Transmission system planning for wind power delivery requires a realistic reliability/cost analysis in order to optimize the benefits from wind power application.

The basic reliability evaluation model is shown in Figure 3.8 in which a wind farm is connected to a conventional generation system through a transmission line. In order to analyze the impact of wind farm characteristics on the transmission line adequacy, the first part of the study considers a simple power generating system supplied by a wind farm. Section 4.3 presents the results and analysis of various system parameters considering a simple wind power generating system. Section 4.4 shows the results of the impact of various system parameters on transmission system adequacy evaluation considering wind power integration to a conventional power system.

4.2 System Data

The studies consider a test power generating system to which a wind farm is connected through a transmission line. The wind farm consists of a number of WTG units with cut-in, rated and cutout wind speeds of 14.4, 45 and 90 km/h respectively. Previous research work [25] has shown that WTG forced outage rate has insignificant impact on the overall system reliability. The forced outage rate of WTG was, therefore, not considered in the studies.

Historical hourly wind speed data were obtained from Environment Canada for different geographic locations in the province of Saskatchewan. Table 4.1 shows the mean wind speeds at six different sites. Case studies considering a test wind farm at the different sites were conducted to analyze the adequacy of transmission system for wind power delivery. The Swift Current location is home to large wind farms in Saskatchewan and is used as the wind farm site in the base case studies.

Table 4.1: Average Wind Speed for Saskatchewan Sites

Location	Swift Current	Regina	Saskatoon	Yorkton	North Battleford	Prince Albert
Wind Speed (km/h)	22.01	19.52	16.78	16.29	14.62	13.28

4.3 Reliability Evaluation of a Wind Power Delivery System

The basic system model shown in Figure 3.8 is reduced to a simple model by considering wind generation alone. The simplified system model is shown in Figure 4.1. The wind farm in Figure 4.1 has an installed capacity of 40 MW, which consist of 20 WTG units each rated at 2 MW. The wind farm is connected to the system load through a tie line.

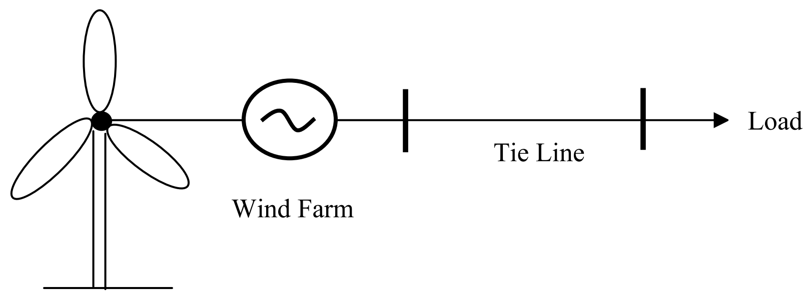

Figure 4.1: Simple example system

The approximate IEEE-RTS load model shown in Figure 3.6 was used in this study. The forced outage probability or unavailability of a transmission line is a function of line length. The distance from the wind farm to the load point is assumed to be such that the line unavailability is 1%. The effect on the overall system risk of varying the tie line capacity and the system peak loads were evaluated considering the wind farm to be located in Swift Current.

4.3.1 Effect of the System Peak Load

Previous reliability studies on conventional system have shown that the system peak load is one of the important parameters that have significant effect on the system reliability. Modern power system is growing continuously, and therefore system peak load also changes accordingly with new developments. This study was done to analyze the effect of system load growth considering a line capable of delivering the maximum power output from the wind farm. The effect of change in system peak load on example system is shown Figure 4.2.

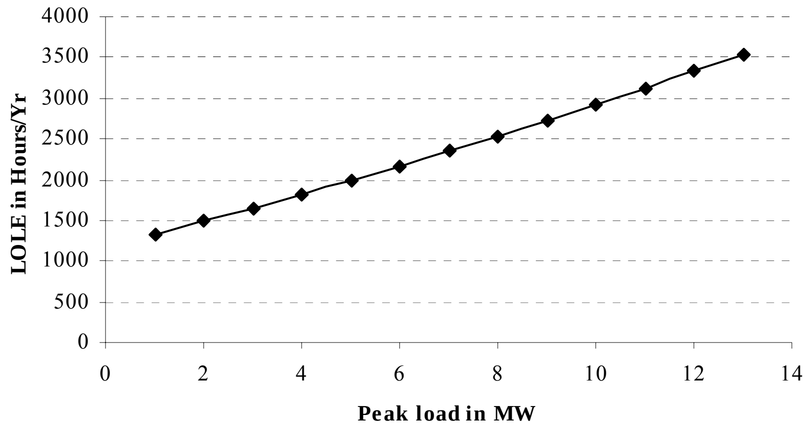

Figure 4.2: Variation in system LOLE with peak load

It can be seen from the figure that the system risk in LOLE increases significantly with the system peak load.

4.3.2 Effect of Transmission Line Capacity

It is necessary to analyze the effect of transmission line parameters on system reliability in deciding appropriate transmission line capacity connecting a particular wind farm to a power grid. The reliability indices obtained from reliability analysis can provide useful information in deciding the optimum transmission line.

The effect of varying line capacity on the system LOLE is shown in Figure 4.3. It can be seen from the figure that the system risk increases with increase in peak load for a given line capacity. The curves in the figure shift downwards as the system load decreases. The lowest curve shows the system LOLE for a peak load of 5 MW. At this peak load, the system reliability increases as the tie capacity is increased up to 5 MW. There is obviously no advantage in increasing the line capacity above the system peak load.

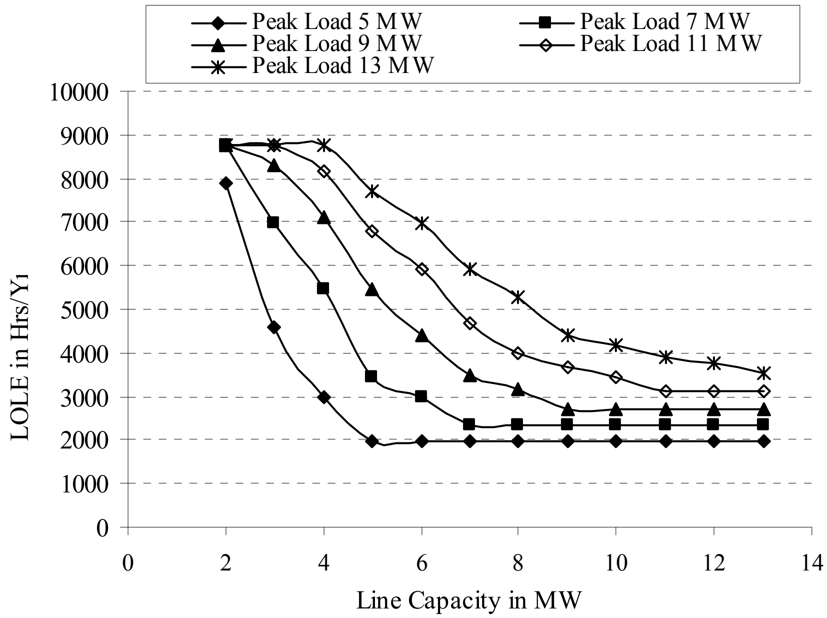

Figure 4.3: Variation in system LOLE with line capacity

The reliability benefit, however, decreases with increasing line capacity, and the incremental benefit reduces to zero when the line capacity exceeds the system peak load. The curves in Figure 4.3 tend to flatten out as they approach the corresponding system peak loads. It can be seen, for example, that the reliability benefits are greatly reduced when the line capacity exceeds 9 MW to supply a peak load of 13 MW. This study can be useful in transmission system planning for delivering wind power. The study can also be used to evaluate the reliability contribution of the combined wind generation and transmission systems. These studies can provide valuable input in capacity credit assessment of such systems.

Evaluation of the EPO at the grid access point is a useful method for assessing transmission line adequacy in delivering wind power to a power system grid. Figure 4.4 shows the variation in the EPO with line capacity. The EPO increases with the line capacity and reaches a saturation point. The horizontal line shows the EPO at infinite line capacity. There is no significant advantage in expanding the line capacity after a certain point. It can be seen from Figure 4.4 that the EPO for 20 MW line capacity is about 9.9 MW, and for twice that line capacity (i.e. 40 MW capacity) is only 10.5 MW.

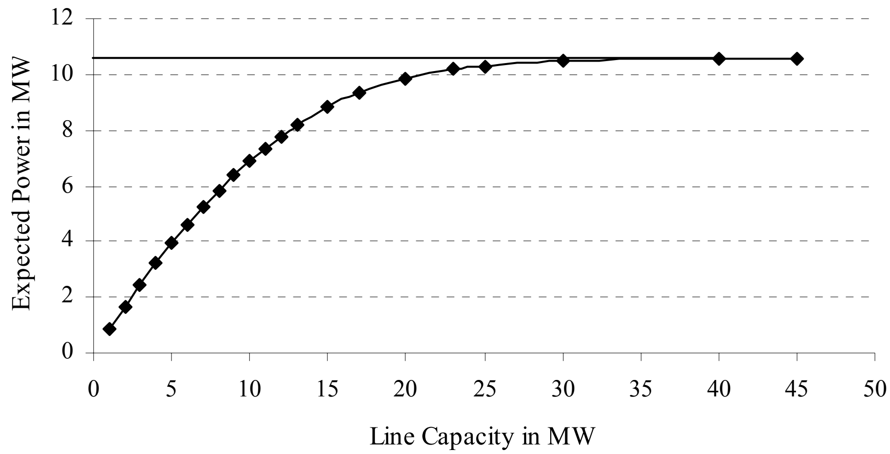

Figure 4.4: Variation in system EPO with line capacity

Figure 4.5 shows the variation in the incremental EPO with the transmission line capacity. This study can be useful in cost-benefit analysis of a transmission line. There is approximately a linear increase in investment cost with increasing line capacity. The benefits, however, decrease sharply beyond a certain point. It can be seen from Figure 4.5 that the incremental EPO decreases with increasing line capacity and tends to saturate at around 25 MW line capacity. It should be noted that the wind farm is rated at 40 MW.

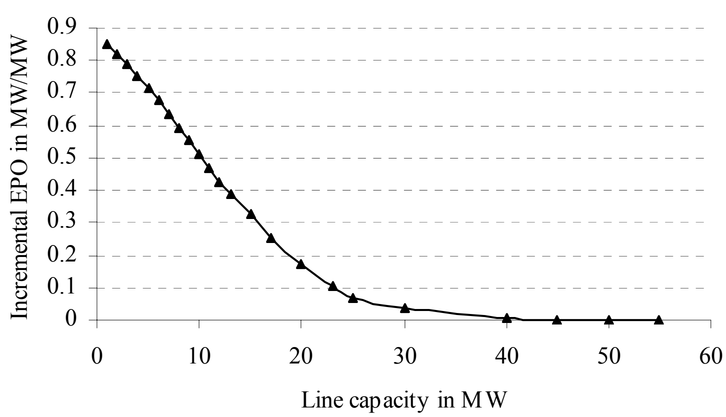

Figure 4.5: Incremental EPO versus line capacity

The reliability benefits from line capacity expansion can be compared with the corresponding investment cost in order to determine optimum line sizing. The cost analysis is presented in Chapter 5 of this thesis.

4.3.3 Effect of Wind Regime

The studies presented in the previous sections were done using the wind speed data for Swift Current, Saskatchewan. The effect of wind regime on system reliability indices was studied using wind data from different geographic sites shown in Table 4.1. An LOLE study was done considering the wind farm to be located at the different sites with the wind speed data given in Table 4.1. The EPO at the grid access point was calculated for each site using equations 3.10 to 3.12.

Figure 4.6 and 4.7 show the variation in system LOLE with increasing line capacity for a system peak load of 5 and 13 MW respectively.

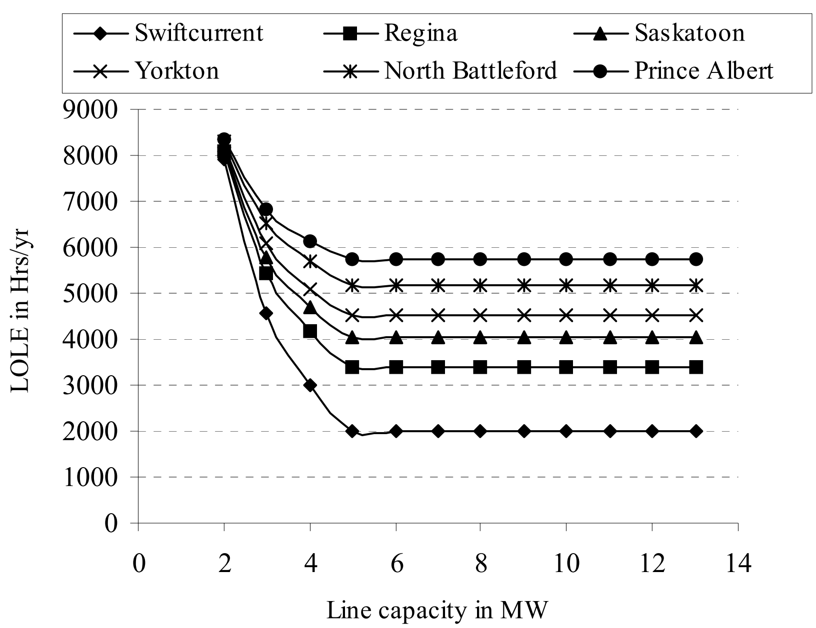

Figure 4.6: Variation in LOLE with line capacity for 5 MW peak load

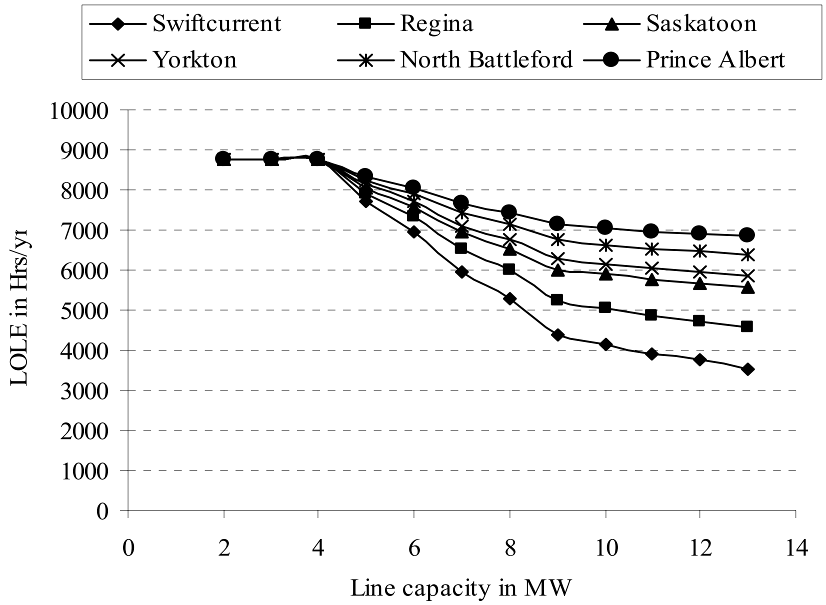

Figure 4.7: Variation in LOLE with line capacity for 13 MW peak load

It can be seen from Figure 4.6 that the system risks are similar for all of the six Saskatchewan sites when the line capacity is 2 MW. Similarly, Figure 4.7 shows that the system risks are similar for all the different sites when the tie capacity is less than 4 MW. The base load is calculated to be 3.9 MW from Figure 3.6 when the system peak load is 13 MW. The load is always curtailed when the line capacity is less than the base load, and this is shown in Figure 4.7 by a constant maximum risk.

The system peak load is 5 MW in the first case, and Figure 4.6 shows that there is a reliability benefit in increasing the line capacity to 5 MW in all the Saskatchewan sites. It can be seen from Figure 4.7 that there is significant reduction in system risk with line capacity increase of up to 9 MW for the Swift Current and Regina sites. The benefits tend to decrease for further line expansion.

Figure 4.6 and 4.7 also show that the reliability benefit of increasing the transmission line capacity is also greatly influenced by the site wind data. The wind farm in Swift Current provides a greater reliability improvement than the other wind farm sites when the transmission line capacity is increased. The system risk can be significantly reduced by increasing the tie capacity up to 9 MW for the Swift Current and Regina sites when the system peak load is 13 MW. The reliability benefits from line capacity expansion are relatively low for the other Saskatchewan sites.

It is obvious as seen from the figures that the reliability contribution of the wind generation and transmission system is greater when the wind farm is located at a geographic site with a better wind regime. Swift Current has the highest mean wind speed among the 6 Saskatchewan locations, and therefore, provides the greatest reliability benefit as shown by the lowest curve in Figures 4.6 and 4.7. The reliability benefits with capacity expansion are much less for the other Saskatchewan sites. An economic analysis can be done in conjunction with the above system reliability analysis to determine the optimum line capacity for different wind farms sites.

Studies were also done to evaluate the impact of site-specific wind regime and tie line capacity on the EPO at the grid access point. Figure 4.8 shows the increase in EPO with line capacity at the different locations. A relatively high EPO can be obtained from the Swift Current site when compared to the other sites. It can also be seen that there is a greater benefit in expanding the line capacity for the Swift Current site than for the other sites.

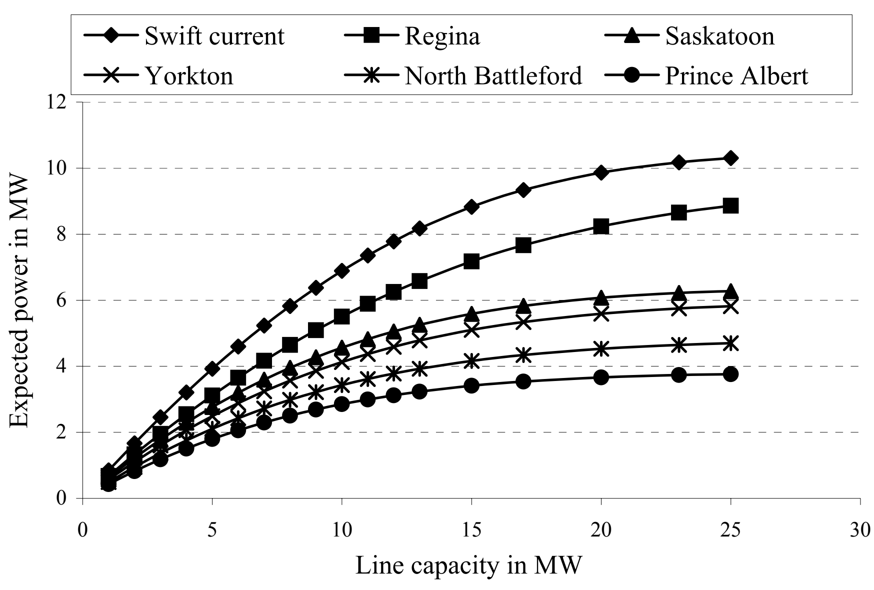

Figure 4.8: Variation in EPO with line capacity for different wind regime

4.4 Reliability Evaluation of a Wind Integrated Power System

This section presents the studies done to analyze the impacts of various system parameters on a conventional power system with wind power integration. The basic system model is shown in Figure 3.8. It is assumed that a wind farm is connected to the IEEE-RTS system through a transmission line. The effects of system peak load and transmission system capacity, its unavailability, redundancy and configuration on the reliability of the overall system are evaluated.

The IEEE Reliability Test System (RTS) [20] is used as the conventional system in the basic system model shown in Figure 3.8. The RTS consists of 32 conventional generating units with a total generating capacity of 3405 MW. The annual peak load is 2850 MW. The IEEE-RTS system load model shown in Figure 3.5 was used in this study. System data and relevant reliability data for the RTS are provided in [20]. The reliability data for all the generation units in the IEEE-RTS system is provided in Appendix-1. A wind power penetration of 8% was considered by assuming the integration of a 250 MW wind farm to the RTS through a transmission line. The wind farm consists of 100 WTG units, each rated at 2.5 MW, and is assumed at the Swift Current location. An unavailability of 2% is assumed for the transmission line.

4.4.1 Effect of Transmission Line Capacity

The generating system adequacy of the original RTS without considering wind power is measured to be an LOLE of 9.44 hours/year. The reliability of the RTS is improved by the integration of the 250 MW wind farm. The reliability contribution of the wind system, however, depends on the tie line connecting the wind farm to the RTS. Figure 4.9 shows the increase in system reliability with an increase in the tie line capacity.

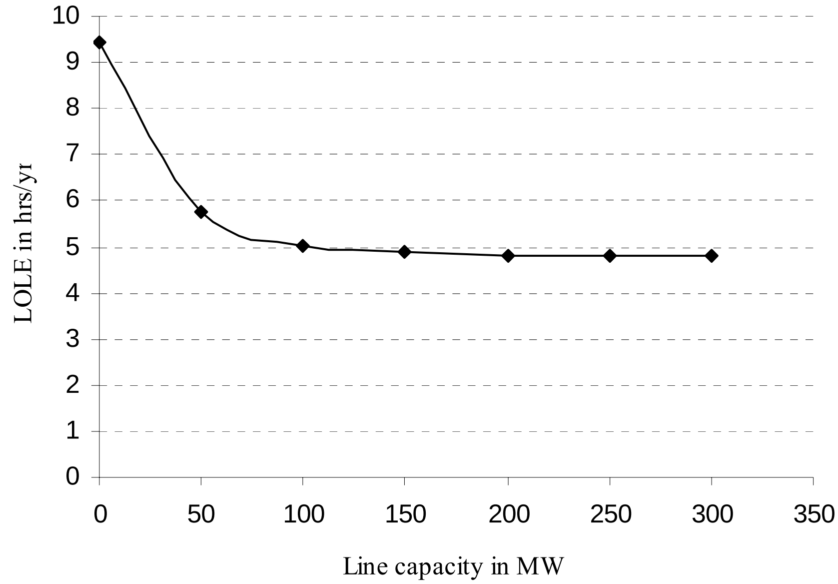

Figure 4.9: System risk versus line capacity

The zero line capacity in Figure 4.9 represents the system without any connection to the wind farm. The corresponding LOLE is the LOLE of the original RTS with no wind power. It can be seen that the system reliability increases significantly when line capacity is increased from a relatively low value. The incremental reliability, however, decreases with increase in line capacity. Figure 4.9 shows that increasing the tie line capacity beyond 70 MW capacity does not result in a significant increase in system reliability.

4.4.2 Effect of System Peak Load

Power system reliability is greatly influenced by the system peak load. The impact of the tie line capacity on system reliability was studied at different peak loads. The results are shown in Figure 4.10. It can be seen that the curves shift down indicating increasing reliability as the line capacity increases. The curves are very close to each other at high line capacities.

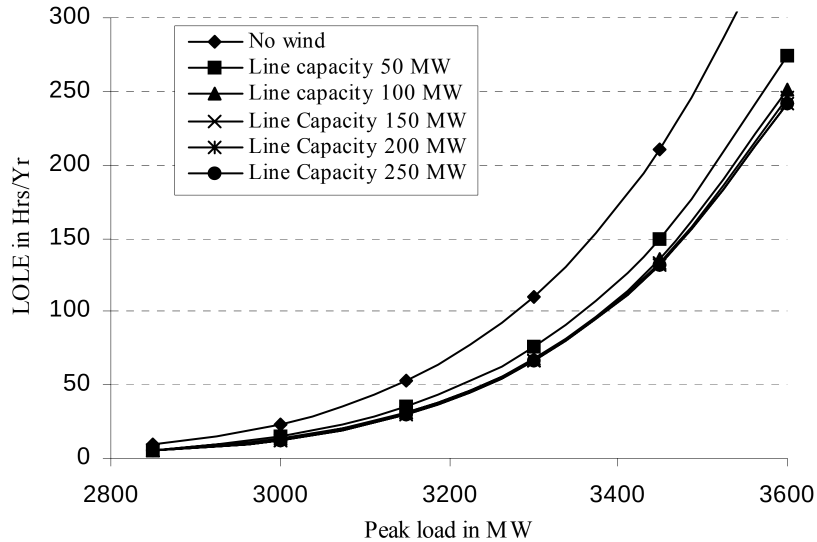

Figure 4.10: System risk versus peak load with varying line capacity

It can be seen that the system reliability decreases (or LOLE increases) sharply as the peak load increases for a given tie line capacity. Figure 4.10 also shows that the reliability benefit from the tie line capacity expansion increases as the system peak load is increased.

4.4.3 Effect of Transmission Line Unavailability

Transmission line unavailability largely affects the reliability of conventional power generating systems. The results presented here, were obtained considering the transmission line unavailability of 2%. The impact on system reliability of the unavailability of the line connecting the wind farm to the grid was studied. The studies were also done at different peak loads as the system reliability is greatly influenced by the system peak load. The results considering a 50 MW tie line connecting the wind farm to the RTS are shown in Figure 4.11.

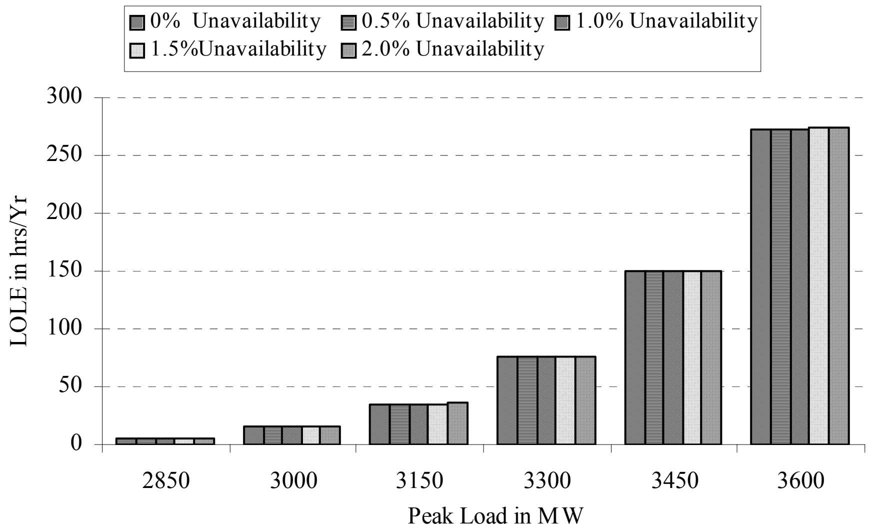

Figure 4.11: System risk versus peak load for 50 MW line capacity and varying transmission line availability

It can be seen that the impact of transmission line unavailability on the system reliability is insignificant. In order to determine whether the unavailability of a higher capacity line has any impact on the system reliability, similar studies were done using a 250 MW tie line capacity. It should be noted that the rated wind farm capacity is 250 MW. The results are shown in Figure 4.12.

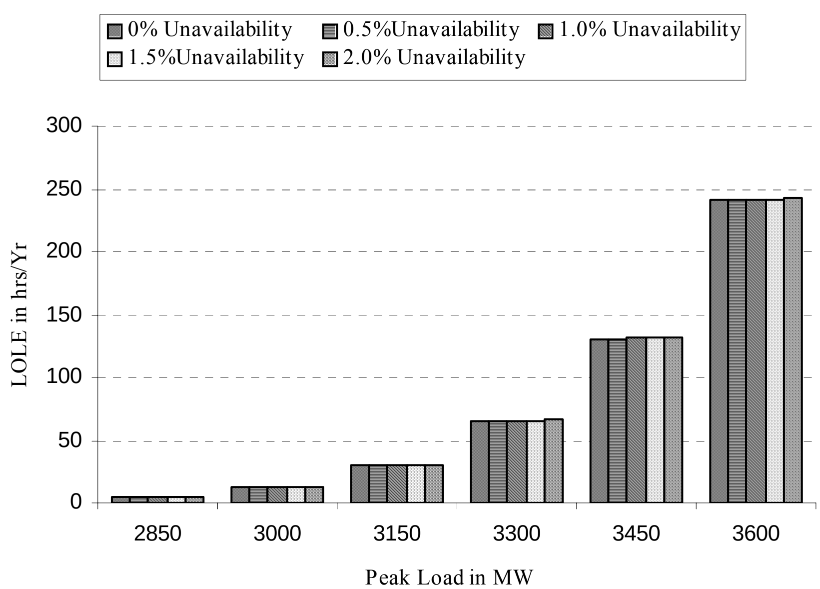

Figure 4.12: System risk versus peak load for 250 MW line capacity and varying transmission line availability

It can be seen from Figure 4.11 and 4.12 that the reliability contribution of wind generation and transmission system is dominated by the availability of wind at the wind farm site. The tie line availability has insignificant impact on the system reliability.

4.4.4 Effect of Transmission Line Redundancy

In order to design a system that can withstand the loss of any single element, an ‘n-1’ adequacy criterion is often used in transmission system planning. This criterion will require double transmission circuits from the wind farm to the grid access point. Studies were done to analyze the reliability contribution of single and double line circuits. The results are shown in Table 4.2 and Table 4.3.

Table 4.2 (a) shows the system LOLE as a function of the peak load for single and double circuit connections between the wind farm and the grid. The transmission line unavailability is assumed to be 0.5% and the individual line capacity is considered to be 200 MW. The second column in Table 4.2 (a) shows the system risks for a single 200 MW transmission line (single circuit) and the third column shows the system risks for two lines of same capacity (double circuit) each rated at 200 MW. It can be seen that the results in the two columns are very close.

Table 4.2 (b) shows results from similar studies considering 2% unavailability for transmission line. It can be seen from Table 4.2 (a) and (b) that there is no significant improvement in system reliability by providing full redundancy to the tie line connecting the wind farm to the RTS. The results show that the ‘n-1’ criterion is not very useful for wind power transmission from the system reliability point of view.

Table 4.2 (a): Risk Index for Transmission Line Redundancy for 0.5% Unavailability

Peak Load in MW	LOLE in hrs/yr	
	Single Circuit	Double Circuit
2850	4.7794	4.7656
3000	12.5499	12.5177
3150	29.998	29.9287
3300	65.616	65.479
3450	130.604	130.357
3600	241.026	240.627

Table 4.2 (b): Risk Index for Transmission Line Redundancy for 2% Unavailability

Peak Load in MW	LOLE in hrs/yr	
	Single Circuit	Double Circuit
2850	4.8211	4.7666
3000	12.6472	12.5201
3150	30.2069	29.9339
3300	66.0291	65.4894
3450	131.348	130.375
3600	242.232	240.657

Table 4.3 compares the LOLE results for three different transmission line configurations: a) single circuit line rated at 25 MW b) double circuit lines each rated at 25 MW and c) single circuit line rated at 50 MW. The table shows that two parallel 25 MW tie lines provide a higher system reliability than a single 25 MW tie line. The increase in reliability from the two parallel lines, however, is not due to redundancy, but due to increase in line transfer capability. The results in the last two columns are very close, which indicated that two 25 MW line provide similar reliability benefits as a single 50 MW line. The two line configurations in this case have an equal power transfer capacity. It should be realized that the installed wind farm capacity is 250 MW, and power available at the receiving end of a 25 MW tie line is greatly constrained by the tie capacity.

Table 4.3: Comparison of Risk Index for Transmission Line Size

Peak load in MW	LOLE in hrs/yr		
	1*25 MW	2*25 MW	50 MW
2850	6.3491	5.7496	5.7627
3000	16.2672	14.8909	14.9208
3150	38.0882	35.2924	35.3582
3300	82.1166	76.3541	76.4681
3450	159.9856	149.6378	149.8515
3600	288.9303	273.3001	273.6617

4.5 Conclusions

The growing application of wind power dictates the need to develop methods for assessing adequate transmission facility to deliver power from the remotely located wind farms to the system load through a main grid. The evaluation methods and techniques discussed in the previous chapter were used to analyse transmission line contribution to system reliability. The results are presented for a test system with wind power penetration. The effects of different parameters on the system reliability are analyzed using wind speed data for different Saskatchewan sites. The system risk in LOLE and the EPO are compared to analyze the effect of various parameters on transmission line adequacy.

The reliability of a power system decreases with increasing system load for a fixed line capacity. The system reliability improves as the capacity of the wind delivery system is increased. There is no benefit in increasing the line capacity greater than the system peak load. The incremental benefit, however, decreases with increasing line capacity. The optimum line capacity can, therefore, be much less than the peak load. The studies, for example, showed that the benefits are greatly reduced when the line capacity exceeds 9 MW to supply a peak load of 13 MW. A careful cost-benefit analysis should be done in deciding appropriate line capacity to serve a specified load level.

The evaluation of the expected power output at the load point is a useful method for assessing transmission line adequacy in delivering wind power. The expected power output increases with line capacity and saturates after a certain point. The incremental expected power output decreases with increasing line capacity. The wind regime at the wind farm site greatly influences the benefits from wind power.

The effect of various parameters on overall system risk has been evaluated for a wind integrated conventional power system. Reliability contribution of transmission line connecting wind farm to conventional system has been studied and presented in this chapter. System reliability improves with increasing transmission size up to a certain point. The incremental benefit, however, decreases with increasing transmission line size. A transmission line equal to the installed wind farm capacity is highly over rated based on risk analysis.

The benefits from wind power are greatly influenced by the system peak load and the wind regime at the wind farm site. The system risk sharply increases with the peak load for a given tie line capacity. The reliability benefit from the tie line capacity expansion increases as the system peak load is increased. The tie line unavailability has insignificant impact on system reliability. The 'n-1' adequacy criterion often used in transmission system planning is not very useful for transmission lines designed for wind power.

The impact of transmission line sizing on the system risk can be analyzed considering the different factors as presented in this chapter. The optimum sizing can be determined by conducting a cost analysis in conjunction with the risk analysis. The next chapter presents economic analysis of transmission line in determining optimum size for wind power delivery.

CHAPTER FIVE

ECONOMIC ASSESSMENT OF A TRANSMISSION SYSTEM DELIVERING WIND POWER

5.1 Introduction

Wind power is the most promising source of renewable energy, and its application in power generation is growing continuously. It is discussed earlier that renewable energy policies, such as the RPS, have set very ambitious targets for wind power penetration in electric power systems in many parts of the world. Many geographical locations with good wind resources become potential sites for large wind farms. It becomes extremely important to assess adequate transmission facility to deliver wind power from these wind farms to the power grid. Wind is a highly variable energy source, and therefore, transmission system planning for wind delivery is very different from conventional transmission planning.

The effect of different system parameters on the reliability of wind power delivery is discussed in the previous chapter. An economic assessment should be done in conjunction with the reliability assessment in deciding adequate transmission facility to transport wind power from the wind farms to a power grid system. The ultimate decision on the appropriate transmission system will require a trade off between the system cost and the system reliability. This chapter presents an analytical method to determine appropriate transmission line capacity based on its contribution to the overall system risk and associated transmission system cost. The effects of generation, transmission and load parameters on risk based transmission line sizing were studied using the basic system model shown in Figure 3.8. The system data used for the following studies are described in Section 4.4 of the previous chapter.

5.2 Reliability/Cost Indices

The investment in transmission line will generally increase linearly with the increase in transmission line capacity. The results from the studies presented in the previous chapter show that the resulting benefits, however, decrease with increasing line capacity. It was noted in Figure 4.9 that the incremental reliability decreases with an increase in the transmission line capacity. In other words, the benefits are costlier with increasing line capacity. A transmission system cost evaluation must be conducted in conjunction with the adequacy studies, presented in the previous chapter, in order to determine a cost effective line sizing for wind power delivery.

The monetary benefits from the wind delivery system are compared to the investment costs of the transmission system with different power transfer capabilities in order to determine appropriate sizing. All the costs are expressed in Canadian dollars in this chapter. The investment cost of 138 kV, 50 MW transmission line is assumed at 1.2 million (MM) $/km [26]. The investment costs of transmission lines are provided in Appendix-2. A linear interpolation was used to estimate the cost per km for transmission lines of various transfer capabilities in this study. The capital investment on the line is spread over an average life of 45 years to obtain annual investment costs.

The conventional fuel offset due to wind application was evaluated assuming the wind sources to be base loaded after the three largest conventional units in the IEEE-RTS system. The average fuel cost (FC) of 14.663 $/MWh [27] was used in the studies considering different types of conventional generating units in the system. The fuel cost data is provided in Appendix-3.

Many governments around the world recognize the environmental benefits and offer financial incentives in various forms to promote wind energy. This study considers a wind power production incentives of 0.01 $/kWh towards wind energy supplied by a wind farm. The value of IEAR for the IEEE–RTS system is 3.83$/kWh [1]. This value was used in this study to evaluate the reduction in the customer interruption costs due to wind application.

The overall cost benefits were calculated using Equation 3.19. The benefits from wind application were calculated in Canadian dollars considering various system alternatives to determine optimum line sizing.

5.2.1 Effect of Transmission Line Expansion

The amount of wind power delivered to a power system depends on the power transfer capability of the transmission line. There is a certain reliability benefit associated with each additional MW transfer capability in transmission line expansion. The marginal net benefit in expanding the transmission line above 50 MW capacity is shown in Figure 5.1 considering a line length of 100 km. The benefits of connecting wind power through a transmission line were calculated using Equation 3.19. The net benefit is obtained by subtracting the total investment costs from the total benefits from wind power.

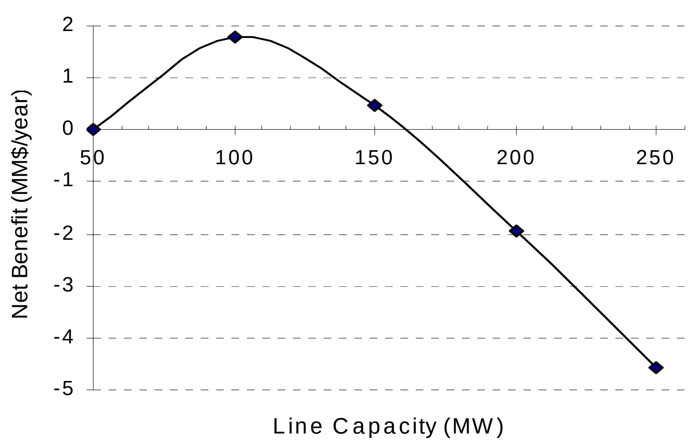

Figure 5.1: Net benefit with transmission line expansion

It can be seen from Figure 5.1 that the net benefit increases as the line capacity is increased from 50 MW. The benefit is maximized at about 100 MW line capacity. It was shown in Figure 4.9 that there was no reliability benefit in expanding the line above 100 MW capacity. It can be seen in Figure 5.1 that the net monetary benefit decreases rapidly as the line capacity is further increased. A line capacity of 160 MW provides the same net benefit as a 50 MW line. The net benefits become negative with further expansion of the tie line. The decision on a particular line capacity should also take into consideration future system expectations. Figure 5.1 shows that the optimum net benefit is obtained when the transmission line capacity is about 110 MW.

5.2.2 Effect of Transmission Line Cost

The effect of transmission line investment cost on optimum line sizing was studied by varying the transmission line costs within a certain range. The range of variation was estimated from the data obtained from the web site of PJM interconnection [26]. The transmission line investment cost for 50 MW capacity was varied in the range of 0.6 to 2.0 Million dollars (MM$) /km and the respective costs of different line sizes were calculated assuming linear interpolation. A sensitivity analysis was performed for five different line sizes taken in increments of 20% of the rated wind farm capacity. The wind farm is rated at 250 MW and the five different line capacities of 50,100,150,200 and 250 MW were used in the study. Figure 5.2 shows the variation in the net benefit with respect to varying transmission line costs at the different transmission line capacities.

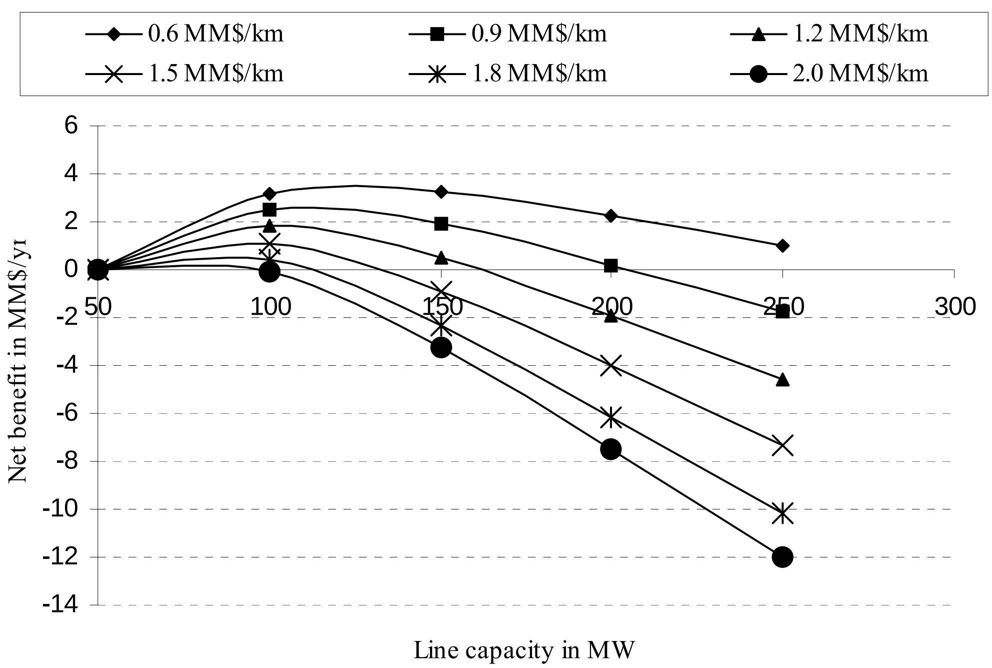

Figure 5.2: Variation in net benefit with transmission line cost

It is noticed from Figure 5.2 that the net marginal benefit associated with transmission line capacity expansion decreases with increase in transmission line cost. The curves shift downwards indicating less benefit as the line costs increase. The top curve is for the line cost of 0.6 MM$/km. At this value the net benefit is more than zero even when the transmission line capacity is equal to the total installed wind capacity. The net benefit becomes negative with increasing transmission line cost. The net benefits are positive when the transmission line capacity is somewhere between 50 and 100 MW at the entire range of investment costs. It can be estimated from Figure 5.2 that the line capacity for the maximum net benefits decrease from about 125 MW to about 80 MW as the line investment cost increases from 0.6 to 2.0 MM$/km. The negative benefits in Figure 5.2 indicate wind utilization that is not cost justified. Wind energy usage can be maximum and still cost effective as long as the investment costs are balanced by the benefits.

Figure 5.2 shows that the optimum line sizing is reduced from about 120 MW to about 80 MW as the line investment cost is increased from 0.6 to 2.0 MM$/km. This analysis can be useful in studying the effect of investment in deciding appropriate line sizing for wind farm integration to power systems.

5.2.3 Effect of Customer Interruption Cost

Studies from the previous chapter show that wind power contributes to the overall system reliability. The contribution, however, depends on the various system parameters as illustrated in Chapter 4. An increase in system reliability due to wind power application results in a decrease in the customer interruption cost. The effect on customer interruption costs due to wind application depends on the system IEAR and on the wind power delivered to the system load. The wind power delivery is however constrained by the transmission line capacity and unavailability. The effect of customer interruption cost in determining optimum transmission system can be evaluated by varying the system IEAR. The sensitivity analysis was performed by choosing a wide range of system IEAR. The system IEAR of more than 15 $/kWh has been noted in existing electric system in Canada.

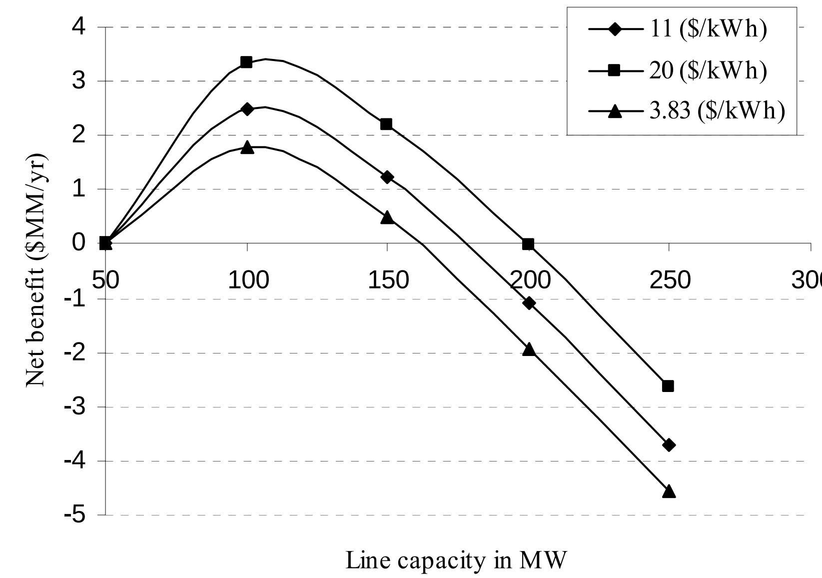

Figure 5.3: Variation in net benefit with system IEAR

Figure 5.3 shows the net marginal benefits in expanding the wind transmission capacity above 50 MW. Each curve represents a different system IEAR. The net benefits, therefore, increase with increasing IEAR, and the curves in Figure 5.3 shift upwards. It can be seen from Figure 5.3 that net benefit reaches to zero at approximately 180 MW line size for IEAR of 11$/kWh. The optimum line size for wind utilization is at about 110 MW capacity for all values of system IEAR.

5.2.4 Effect of Line Length

The benefits from integrating a remotely located wind farm to a power grid greatly depend on the distance of wind farm from the main grid system. The length of the transmission line is equal to the distance between the wind farm location and the grid access point. The investment cost attached to a transmission line normally varies linearly with the length. This section presents the results from studies done to evaluate the impact on the system reliability of the length of the transmission line connecting a wind farm to a power grid. Studies were done considering the 250 MW wind farm at five different distances i.e. 10, 50, 100, 150 and 200 km from the RTS access point. This analysis can be useful in selecting the proper transmission line capacity to connect wind farms at various distances from the main grid.

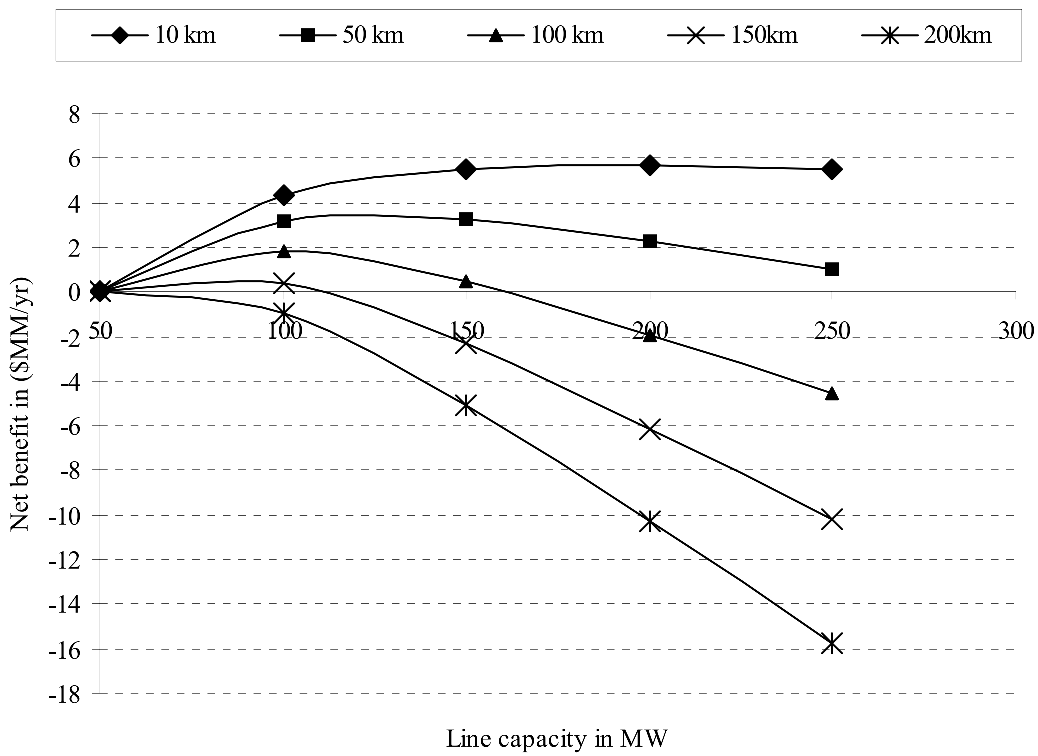

Figure 5.4: Variation of net benefit with transmission line length

Figure 5.4 shows the net marginal benefits with the variation in transmission line capacity at the five different line lengths. It can be seen from the figure that the net benefit decreases with the increase in the line length. The curves, therefore shift downwards with increase in the line length. The maximum net befits is reduced to about one fourth the amount as the wind site distance is increased from 100 km to 150 km from the grid connection point. For a given line capacity, the net benefits increase significantly as the distance between the wind farm and the grid connection point is decreased. It can be seen that there is no marginal net benefit in connecting a wind farm that is 200 km away. It can also be seen from the figure that the net benefit decreases more rapidly with increase in the line length for 250 MW line capacity than for a 100 MW line capacity. This rapid decrease in net benefit is observed because the wind farm seldom produces rated capacity output and hence the benefits obtained from wind energy is very small compared to the increase in investment cost of 250 MW line capacity.

A wind farm situated near a power system grid can be connected more economically than one that is located farther away. The net benefit becomes negative as the capacity of a 150 km line is increased above 110 MW. The line capacity for optimum benefits varies with the line length. The optimum line capacity is about 110 MW to connect wind farm located at a distance of 100 km from a power grid. The optimum line capacity is increased to about 200 MW to connect a wind farm that is 10 time closer to the grid. The results show that more benefits from wind energy is obtained by connecting a wind farm located closer to the main grid with a larger line capacity than connecting a wind farm that is located farther away.

5.2.5 Effect of Wind Regime

It is discussed in Chapter 4 that the wind regime at the wind farm site has significant effect on the reliability of the wind integrated system. The evaluation of benefits associated with power delivery from wind farms at installed locations with different wind variation pattern can be useful in deciding appropriate transmission line capacity for a particular wind site. Figure 5.5 compares the net marginal benefits from wind sources located at geographical sites with wind data from three Saskatchewan locations, Swift Current, Saskatoon and Prince Albert. The mean wind speeds at the three locations are given in Table 4.1.

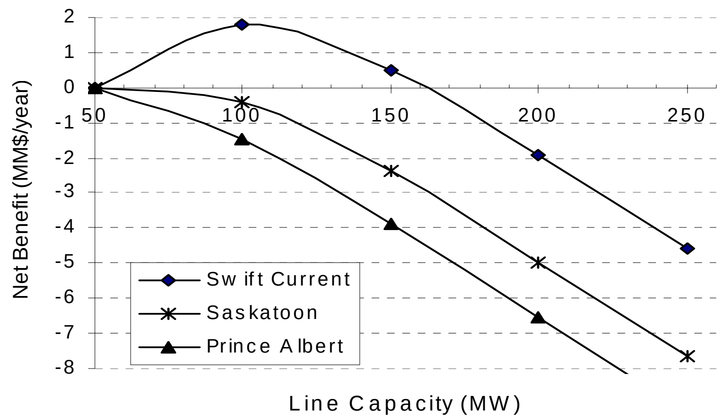

Figure 5.5: Variation of net benefit with wind regime

It can be seen from the Figure 5.5 that relatively high benefits are obtained from the Swift Current site when compared to the other two sites for any transmission line capacity. Swift Current has a better wind resource than the other two sites, and is the only site among the three that provides a monetary benefit in expanding the line capacity above 50 MW. Studies similar to these can be done for a wind farm location of interest to determine the actual benefit from wind sources in a power system.

5.2.6 Effect of Wind Penetration

Previous studies [7] have shown that the benefits from wind power application in electric power systems decrease and eventually become negligible as the wind penetration increases and reaches to a certain level. This section presents the results from the study done to evaluate the effect of wind penetration on the actual benefits from the wind. The results are then analyzed to determine the appropriate transmission line size for wind power delivery. Reliability cost/benefit analysis was carried out at three different levels of wind penetration.

The studies described in the previous sections consider a 8% wind penetration by integrating a 250 MW rated wind farm to the RTS. This study considers three different wind penetration levels at 8%, 15% and 20% (i.e. connecting 250 MW, 427 MW and

570 MW wind farms respectively) to the RTS. Each wind penetration case is studied separately considering various tie line capacities. Five different line sizes at 20%, 40%, 60%, 80% and 100% of the rated wind farm capacity were used in the study.

Table 5.1 shows the cost-effective line size for various wind power penetration levels. The wind farm in each case is assumed to be at a distance of 100 km from the main power grid. Columns 3 and 4 of the table show the cost-effective line size in MW and in percentage of wind farm rated capacity respectively. It can be seen that optimum line capacity varies with varying wind power penetration. It can be noticed from Column 4 that the cost-effective line capacity, expressed in percent of the rated wind farm capacity, reduces with the increase in wind power penetration. This reduction in the optimum line size is a result of the relative decrease in the wind benefits compared to the investment cost of the transmission line.

Table 5.1: Cost-Effective Line Sizing at Different Wind Power Penetration

Wind Farm		**Transmission Line**	
Penetration in Percentage	***Installed Capacity in MW***	***Capacity in MW***	***% of Wind Farm Rated Capacity***
8%	250	110	44%
15%	427	170	40%
20%	570	210	37%

The results shown in Table 5.1 were obtained considering IEAR of 3.83 $/kWh. The effect of IEAR for various wind penetration levels were studied using three various IEAR values. The results are shown in Figure 5.6.

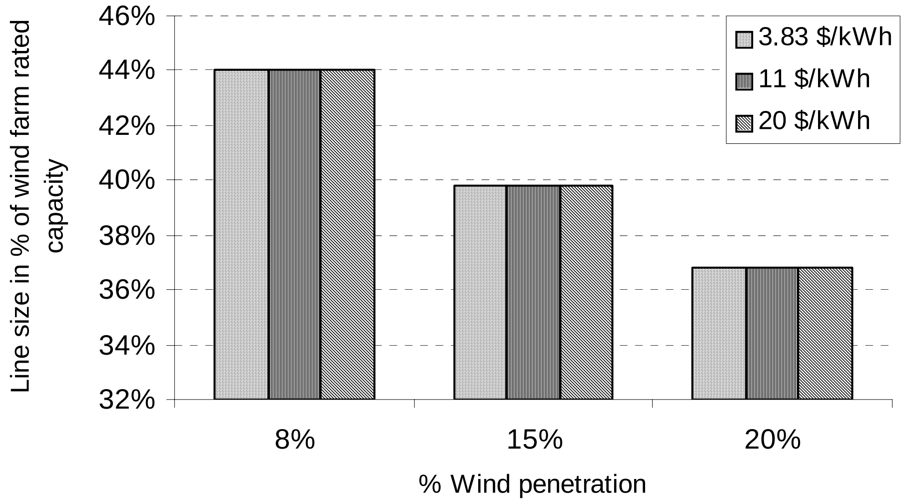

Figure 5.6: Cost-effective line sizing with varying IEAR

It can be seen from the Figure 5.6 that the cost effective line size is the same for all the values of IEAR for each level of wind penetration. This was also discussed in Section 5.2.3. It can be noticed from the figure that cost-effective line size decreases with increase in wind penetration for each IEAR value.

The results shown in Table 5.1 and Figure 5.6 were obtained considering the wind farm to be located 100 km away from the grid access point. The effect of transmission line length was studied for various wind power penetration level. Five different line lengths were used for the study. The variation in cost effective line size for various transmission line length on different wind power penetration levels are shown in Figure 5.7. The line sizes are expressed in percentage of the rated wind farm capacity.

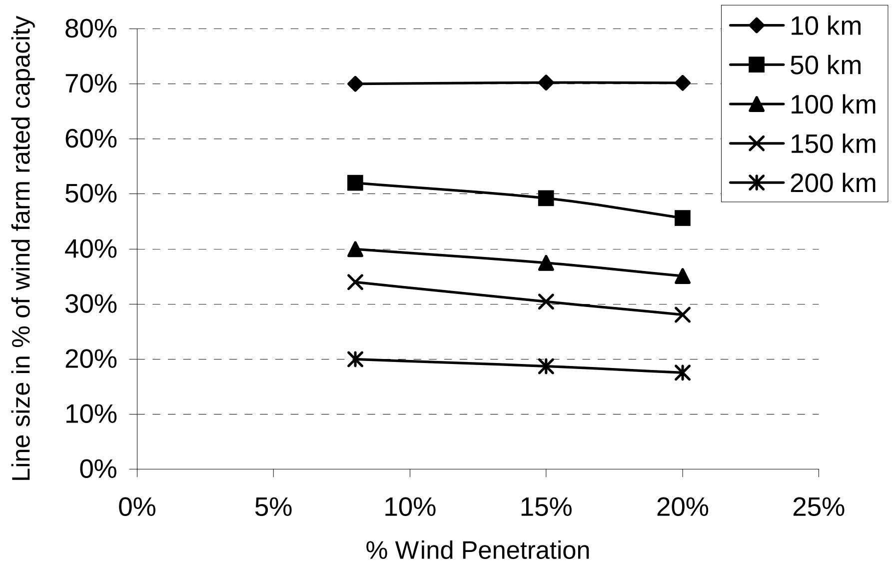

Figure 5.7: Cost-effective line size for varying line length

It can be seen from Figure 5.7 that the cost-effective line size varies with wind penetration for the different line lengths. The benefits from wind energy increases as the distance of the wind farm from the grid is decreased. The curves in Figure 5.7 shift upwards to indicate that the optimum line capacity to connect a wind farm increases as the line length decreases. The result is also shown in Figure 5.4. The top curve in Figure 5.7 shows that the optimum line sizing to connect a wind farm 10 km away, increases with increasing wind penetration. On the other hand, the optimum line capacity decreases with increasing wind penetration for wind farms located at large distance from the grid. It can be noticed that the optimum line size decreases with increase in the wind power penetration for the line length of 100, 150 and 200 km.

5.3 Conclusions

The prime objective of power system planner is to design reliable and economical system facilities. This objective becomes more challenging when considering transmission system facility to deliver wind power. An analytical approach for reliability/cost analysis is presented in this chapter for determining cost-effective transmission line size for wind power delivery.

The benefits associated with wind power integration to a conventional system were analyzed for various case studies. The benefits are significantly limited by the power transmission capacity. The benefits associated with wind power delivery were compared with the investment cost of the respective line expansion. The marginal net benefit, which is the total benefit less the investment cost in line expansion above 50 MW rating, varies with different system parameters.

The results show that the net benefits normally increase when line capacity is increased from a relatively small capacity rating, and reach an optimum level. Further increase in line capacity results in a decrease of the net benefit. Studies with different transmission line investment cost show that the optimum transmission line size reduces with increase in line cost. The length of the transmission system increases with the increase in distance between the wind farm and the grid access point. The optimum line capacity for wind farm integration decreases with an increase in the line length. In other words, a wind farm situated near a power system grid can be connected more economically than one that is located farther away.

Wind regime at the wind farm location has great influence in the benefits that can be obtained from wind power generation and therefore greatly influences the economic line sizing for transporting the wind power to a grid system. Studies were conducted on different wind farm locations in the Canadian province of Saskatchewan. The results show that the optimum line size is relatively large for a wind site with good wind resources. The effect of wind power penetration on the optimum line sizing was also analyzed in the studies. The cost-effective transmission line size reduces with increase in wind penetration. The effect of line length and system IEAR were also studied for each level of wind penetration.

The relatively benefits from wind transmission system expansion are evaluated from the resulting reduction in the customer interruption costs. An increase in system IEAR results in a higher reduction in the customer interruption costs and therefore the net benefits from increasing line size increases with system IEAR. The optimum line capacity, however, does not vary with the system IEAR.

Reliability cost/benefit analysis presented in this chapter was carried out on a base system with various sensitivity studies. The method illustrated in this chapter can be used for any wind site located at any distance from a grid system, and for any level of wind power penetration in a power system. Reliability/cost analysis as presented in this chapter can be useful for evaluation of wind integrated power system for optimizing benefits available from wind. The analysis presented in this chapter can provide valuable guidelines to the system planner in determining optimum transmission system for wind power.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

The application of wind power in electric power system is growing rapidly around the globe due to increasing environmental concerns and public awareness. Many governments have committed or are in the process of making commitments to the RPS energy policy, which ensures a certain percentage of power generated from renewable energy sources in electric power systems within a certain period of time. Wind power is the most mature and capable source of renewable energy, which can be useful in meeting RPS targets. Many large wind farms for bulk power generation are expected to be added to power systems in near future. These wind power plants require good wind resources to generate bulk power and can be away from the main grid access point. It becomes extremely important to determine an appropriate transmission facility to connect remotely located wind farms to a power grid. Wind power varies randomly with the available wind speed at the wind farm site. Transmission system planning for wind power integration requires different evaluation approach compared to a conventional system. Many utilities around the world use the 'n-1' deterministic criterion for transmission system planning. Deterministic techniques, however, cannot recognize the random variation in wind power generation, and therefore are not suitable for power system planning considering wind power. This thesis presents probabilistic methods for evaluating the contribution of wind transmission system to overall system reliability. The application of the developed reliability and cost evaluation techniques are illustrated with various sensitivity studies.

A number of various evaluation techniques are available for power system reliability studies. These methods are categorized as deterministic and probabilistic techniques. Both of these approaches are used in various aspects of power system planning. These techniques are explained briefly in Chapter 2. Probabilistic techniques can be mainly divided in analytical and simulation techniques. The simulation techniques are generally used when direct analytical techniques are not available. This research work was done using analytical techniques to obtain direct numerical solutions for system reliability evaluation. The prominent system reliability indices such as LOLE and LOEE are explained. Limited transmission line can be added in HL-I reliability evaluation. The system model and techniques are presented for incorporating limited transmission line in the HL-I study. The tie line constraint equivalent unit approach was used to incorporate limited transmission line in HL-I study. This approach is very useful in order to study the effect of transmission line on wind power integration to a conventional system.

System modeling and evaluation techniques developed for this research work are presented in Chapter 3. The overall modeling process is divided into three major tasks of wind speed modeling, wind system modeling, and system risk modeling. A computer program was developed to construct a wind generation model at the grid access point. This model incorporates the effect of the transmission line. Evaluation techniques were used on an example system to illustrate the evaluation method. Wind generation model at grid access point was integrated with a conventional system using a software tool SIPSREL. The benefits associated with wind power application to a conventional system are introduced with mathematical expressions in Chapter 3. The basic system model and a flow chart for the system evaluation are presented. The EPO is a useful power index that can provide useful information on adequate transmission line size for wind power delivery.

Reliability evaluation techniques developed and presented in Chapter 3 were used for evaluating system indices for a simple wind system. The impact of various system parameters on system reliability was first studied without considering a conventional system in the basic system model. The effect of the system peak load, transmission line capacity and wind regime was studied evaluating the system risk index LOLE and power index EPO. It was noticed that the system reliability decreases with increasing peak load. The increasing line capacity helps in improving system reliability. However, the incremental benefit decreases with increase in transmission line capacity. The EPO also increases with transmission line size and reaches to a saturation point after a certain line capacity addition. The incremental EPO decreases with transmission line capacity. The effects of wind regime on the system reliability are also presented. It is shown that wind site with good wind resources provides higher reliability benefits.

The effect of transmission line size on the over all system reliability is presented in Chapter 4 considering a wind farm connected to the IEEE-RTS system. The effect of the system peak load and the capacity and unavailability of the transmission line on the overall system risk indices are presented. It is shown that system reliability increases with the transmission line size when wind power is integrated to a conventional system. The incremental reliability benefits are however decreased with increasing line capacity. The important conclusion regarding the impact of transmission line unavailability was drawn in this research. The unavailability of transmission line delivering wind power has very insignificant impact on over all system reliability. The usefulness of the conventional 'n-1' deterministic criterion was studied for the transmission system delivering wind power to a conventional system. It is shown that the 'n-1' criterion cannot recognize the system risks, and is not useful in transmission system planning for delivering wind power.

Reliability evaluation should be conducted in conjunction with appropriate economic analysis in system planning. Reliability cost/benefit techniques were developed and presented in Chapter 5. The results in Chapter 4 show that the incremental benefit associated with transmission system expansion decreases with an increase in transmission line capacity. The benefits are justified up to a certain limit of transmission line capacity. This optimum line capacity can be evaluated using reliability/cost evaluation techniques. The effects of transmission line investment cost, transmission line length, wind regime, and wind penetration levels on the optimum line sizing were studied using the basic system model. It is shown that the optimum line capacity decreases with an increase in line cost. The transmission line length depends on the distance between wind farm and the grid access point. A wind farm located near the grid access point can be connected by a transmission line of a relatively large capacity for optimum benefits. The optimum line capacity decreases with an increase in transmission system length. The wind resource at the wind farm site has significant affect on the optimum line sizing. There is a high net benefit in connecting a wind farm, located at a site with good wind resource, with a transmission line of relatively large capacity. The effect of wind penetration on optimum line sizing was studied in this research. It was observed that the optimum line size decreases with increasing wind penetration. The wind penetration level after a certain point can not fully contribute to the system load, and therefore the relative benefits tend to decrease with further increase in wind penetration in the system.

The methodology and techniques presented in this thesis should be useful in transmission system planning for wind power delivery from a wind farm to a power system. This work can also be used in capacity credit assessment combining wind generation and transmission system. The results presented in this thesis provide useful information on the benefits obtained from a wind generation and transmission system. The effect on the benefits of various system parameters, such as, wind power penetration in a power system, distance of the wind farm from the grid, capacity and unavailability of the tie line connecting wind farm, the wind regime at the wind farm location can also be estimated based on the presented results. The general conclusions obtained from this study can also be useful in practical wind transmission system planning.

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APPENDIX ONE

IEEE RELIABILITY TEST SYSTEM

(A) Generating System Reliability Data

Unit size in MW	Number of units	Forced outage rate	*MTTF in hours	**MTTR in hours
12	5	0.02	2940	60
20	4	0.10	450	50
50	6	0.01	1980	20
76	4	0.02	1960	40
100	3	0.04	1200	50
155	4	0.04	960	40
197	3	0.05	950	50
350	1	0.08	1150	100
400	2	0.12	1100	150

*   *MTTF: Mean Time To Failure*
** *MTTR: Mean Time To Repair*

(B) Weekly Peak Load as a Percentage of Annual Peak

Week	Peak Load (%)	Week	Peak Load (%)
1	86.2	27	75.5
2	90	28	81.6
3	87.8	29	80.1
4	83.4	30	88
5	88	31	72.2
6	84.1	32	77.6
7	83.2	33	80
8	80.6	34	72.9
9	74	35	72.6
10	73.7	36	70.5
11	71.5	37	78
12	72.7	38	69.5
13	70.4	39	72.4
14	75	40	72.4
15	72.1	41	74.3
16	80	42	74.4
17	75.4	43	80
18	83.7	44	88.1
19	87	45	88.5
20	88	46	90.9
21	85.6	47	94
22	81.1	48	89
23	90	49	94.2
24	88.7	50	97
25	89.6	51	100
26	86.1	52	95.2

(C) Daily Peak Load as a Percentage of Weekly Peak

Day	Peak Load (%)
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

(D) Hourly Peak Load as a Percentage of Daily Peak

	Winter Weeks 1-8 & 44-52 Weeks		Summer Weeks 18-30		Spring/Fall Weeks 9-17 & 31-43	
Hours	**Wkdy**	**Wknd**	**Wkdy**	**Wknd**	**Wkdy**	**Wknd**
12-1am	67	78	64	74	63	75
1--2	63	72	60	70	62	73
2--3	60	68	58	66	60	69
3--4	59	66	56	65	58	66
4--5	59	64	56	64	59	65
5--6	60	65	58	62	65	65
6--7	74	66	64	62	72	68
7--8	86	70	76	66	85	74
8--9	95	80	87	81	95	83
9--10	96	88	95	86	99	89
10--11	96	90	99	91	100	92
11-Noon	95	91	100	93	99	94
Noon-1pm	95	90	99	93	93	91
1--2	95	88	100	92	92	90
2--3	93	87	100	91	90	90
3--4	94	87	97	91	88	86
4--5	99	91	96	92	90	85
5--6	100	100	96	94	92	88
6--7	100	99	93	95	96	92
7--8	96	97	92	95	98	100
8--9	91	94	92	100	96	97
9--10	83	92	93	93	90	95
10--11	73	87	87	88	80	90
11--12	63	81	72	80	70	85

Wkdy= Weekday, Wknd=Weekend

APPENDIX TWO

TRANSMISSION SYSTEM COST

Typical Costs and Capacity of New Transmission Lines (1995 Dollars)

Voltage	Type of Supporting Tower and Number of Circuits	Size of Power Line	Normal Rating MW	Cost per Circuit per Mile[a]
	Above Ground			
60 kV	Wood pole, single	4/0 AWG	32	$120,000
60 kV	Wood pole, single	397.5 kcmil	56	$125,000
60 kV	Wood pole, single	715.5 kcmil	79	$130,000
115 kV	Wood pole, single	4/0 AWG	64	$130,000
115 kV	Wood pole, single	397.5 kcmil	108	$135,000
115 kV	Wood pole, single	715.5 kcmil	151	$140,000
115 kV	Steel pole, single	715.5 kcmil	151	$250,000
115 kV	Steel pole, single	715.5 kcmil, bundled	302	$400,000
115 kV	Steel pole, double	715.5 kcmil	151	$160,000
115 kV	Steel pole, double	715.5 kcmil, bundled	302	$250,000
230 kV	Steel pole, single	1,113 kcmil	398	$360,000
230 kV	Steel pole, single	1,113 kcmil, bundled	796	$530,000
230 kV	Steel pole, single	2,300 kcmil, bundled	1,060	$840,000
230 kV	Steel pole, double	1,113 kcmil	398	$230,000
230 kV	Steel pole, double	1,113 kcmil, bundled	796	$350,000
230 kV	Steel pole, double	2,300 kcmil, bundled	1,060	$550,000
	Underground			
115 kV	Underground cable	200 MVA	180	$3,300,000
230 kV	Underground cable	400 MVA	360	$3,700,000

[a]These costs do not include right-of-way costs.
AWG = American wire gauge.
kcmil = One kcmil is 1,000 circular mils, a measure of wire cross-area.
kV = Kilovolts.
MVA = Megavolt amperes.
MW = Megawatts.
Source: CSA Energy Consultants, "Existing Electric Transmission and Distribution Upgrade Possibilities, "(Arlington, VA, July 18, 1995), p. 9.

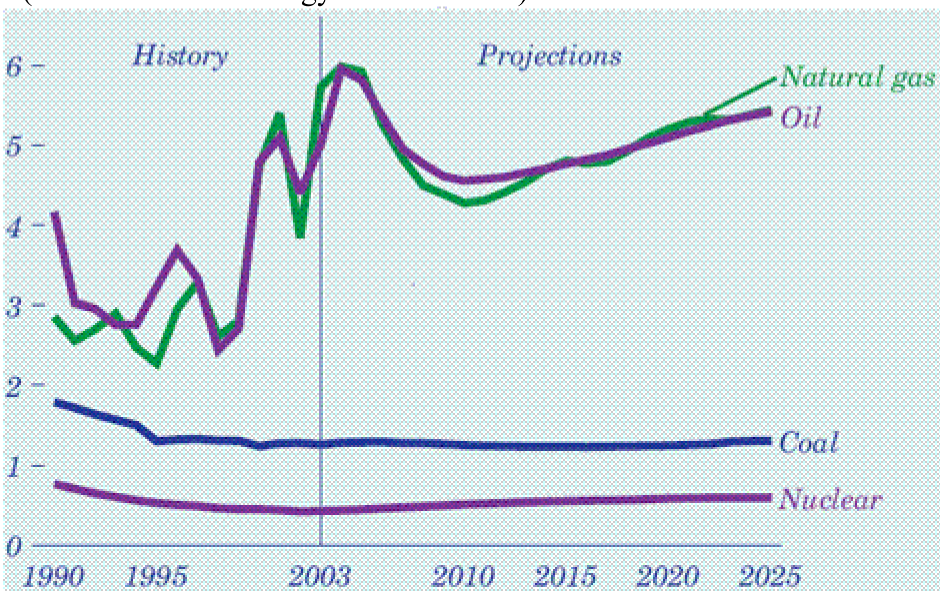
(Source: Energy Information Administration, Department of Energy USA)

APPENDIX THREE

FUEL COST DATA

A. Fuel prices to electricity generator 1990-2025 (2003 dollars per million btu)

(Source: Annual Energy Outlook 2005)



(Figure reference: History: Energy Information Administration, Annual Energy Review 2003, DOE/EIA-0384 (2003) (Washington, DC, September 2004). Projections: Table A3.)

B. Fuel cost for electricity generation in 2005

Type of Fuel	Price (US$/Million btu)
Oil	5.814591
Natural Gas	5.921783
Coal	1.289429
Nuclear	0.445984