# Adequacy Assessment of a Combined Generating System Containing Wind Energy Conversion Systems

A Thesis

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by

Xiaoming Cao

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**University of Saskatchewan**

Electrical Engineering Abstract 93A390

# Adequacy Assessment of a Combined Generating System Containing Wind Energy Conversion Systems

Student: Xiaoming Cao Supervisor: Dr. Roy Billinton

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## ABSTRACT

Dwindling energy resources and the potential impact on the environment of conventional energy systems have resulted in serious consideration of the utilization of wind energy for satisfying electrical energy demands. It is, therefore, both necessary and important to study the characteristics of wind power and its effects in a combined generating system. Modeling wind energy conversion systems is more complex than conventional unit modeling in that wind energy conversion systems consist of small size units in the KW range and the wind energy is both intermittent and weather dependent. This thesis examines the adequacy of combined generating systems containing conventional units and wind energy conversion systems. The analysis is conducted using Monte Carlo simulation and multi-state analytical approaches. A systematic procedure for wind modeling is presented using time-series analysis. The two methods are used to investigate the effects of some important factors, such as, the number of wind turbine generating units added to the system, the forced outage rate of wind turbine generating units, the wind speed, the penetration level and the load profile on the adequacy of the combined system. The wind is modeled using a time-series analysis which incorporates the randomness and the chronological order of the wind speed. In this thesis, practical multi-state and Monte Carlo simulation techniques for adequacy evaluation of electric power systems containing wind energy conversion systems are developed and applied to a hypothetical test system. The basic multi-state approach is improved using simulated wind speeds from the time-series model. The calculated results from the multi-state approach are compared with those from the simulation results to determine the applicability of the multi-state approach.

The developed models and methods are relatively easy to use and can be applied to practical combined generating systems containing wind energy conversion systems .

# TABLE OF CONTENTS

COPYRIGHT i

ACKNOWLEDGMENTS ii

ABSTRACT iii

TABLE OF CONTENTS v

LIST OF FIGURES ix

LIST OF TABLES xiv

LIST OF ABBREVIATION xvii

**1. Introduction** 1

1.1 Power System Reliability Evaluation 1

1.2 The Advantages of Using Wind Power 5

1.3 The Characteristics of Wind Power 6

1.4 History of Development of Wind Energy Conversion Systems (WECS) 7

1.5 Method Development for Reliability Modeling of Generating System Containing WECS 9

1.5.1 Introduction 9

1.5.2 Analytical Methods 12

1.5.3 Monte Carlo Simulation Methods 16

1.6 The Scope of the Thesis 18

**2. Conventional Generating Capacity Adequacy Assessment** 19

2.1 Introduction

2.2 Analytical Method 21

2.2.1 Capacity Outage Probability Table 21

2.2.2 Loss of Load Expectation and Loss of Energy Expectation Indices 23

2.2.2.1 Loss of Load Expectation (LOLE) 23

2.2.2.2 Loss of Energy Expectation (LOEE) 26

2.3 Monte Carlo Simulation Method 27

2.3.1 General Steps in the Monte Carlo Simulation Method 29

2.3.1.1 Modeling Base Load Generating Units 29

2.3.1.2 Modeling Peaking Units 33

2.3.2 Stopping Rule 36

2.4 Case Studies 38

2.4.1 RBTS 38

2.4.1.1 Brief Description of the RBTS 38

2.4.1.2 Load Model 38

2.4.1.3 Generating System 40

2.4.2 Calculated Study Results 40

2.4.2.1 Analytical Method 41

2.4.2.2 Monte Carlo Simulation 41

2.5 Summary 44

**3. Monte Carlo Simulation Method for Adequacy Assessment of Generating System Containing WECS** 45

3.1 Introduction 45

3.2 Time-Series Model 46

3.3 Simulation Procedure for the Adequacy Assessment of Generating System Containing WECS 48

3.4 Stopping Rule 48

3.5 Case Studies 54

3.6 Two Wind Farm Case 65

3.7 The Effect of Wind Penetration on the Combined System Reliability 71

3.8 Conclusions 73

**4. Adequacy Assessment for the Combined Generating System Containing WECS Using Multi-State Approach** 75
4.1 Introduction 75
4.2 Routine Multi-State Approach 76
4.2.1 WECS Capacity Probability Table in the Routine Multi-State Approach 76
4.2.2 Routine Technique in the Combined Generating System Containing WECS 84
4.2.3 Calculation Results from the Routine Multi-State Approach 86
4.3 Improved Multi-State Approach 93
4.4 Two Wind Farm Case 106
4.5 Comparisons between Monte Carlo Simulation and Multi-State Approach 109
4.6 Conclusions 115

**5. Alternative Wind Model** 117
5.1 Introduction 117
5.2 Modeling 118
5.3 Checks of Adequacy 119
5.4 Modeling Procedure with the Illustrative Example 121
5.6 Simulation Results from the New Wind Model 127
5.7 Multi-State Results from the New Wind Model 129
5.8 Conclusions 134

**6. Summary and Conclusions** 135

References 140

Appendices

Appendix A Some Variables, Arrays and Subroutines in the GRASS Program 144

Appendix B WECS Capacity Probability Table for Different Wind Speed Multiplication Factors Using Time-Series Model in Chapter 3 146

Appendix C Wind Data at a Site in Saskatchewan 157

Appendix D Estimation of Parameters of An Autoregressive Moving Average (ARMA) Model 165

Appendix E WECS Capacity Probability Table for Different Wind Speed Multiplication Factors Using Time-Series Model in Chapter 5 168

Appendix F Results from the Multi-State Approach Using the New Wind Model in Chapter 5 179

## LIST OF FIGURES


Figure 1.1: Subdivision of System Reliability 1

Figure 1.2: Hierarchical Level Structure 3

Figure 1.3: Linearized Power Output Characteristics of a WTG 11

Figure 2.1: Conceptual Tasks in Generating Capacity Reliability Evaluation 19

Figure 2.2: Generation System Model 20

Figure 2.3: Relationship Between Load, Capacity and Reserve 25

Figure 2.4: Energy Curtailment due to a Given Capacity Outage Condition 28

Figure 2.5: Two-State Model for a Base Load Unit 30

Figure 2.6: Three-State Model for a Base Load Unit 31

Figure 2.7: Outage History of a Base Load Generating Unit with Two-States 32

Figure 2.8: Outage History of a Base Load Generating Unit with Three-States 32

Figure 2.9: Four-State Markov Model for a Peaking Unit 33

Figure 2.10: Superimposition of the System Capacity and Load Cycles 35

Figure 2.11: Single Line Diagram of the RBTS 39

Figure 3.1: Simulated Wind Speed in a Sample Year (Year = 1) 49

Figure 3.2: Simulated Wind Speed in a Sample Year (Year = 30,000) 49

Figure 3.3: Simulated Wind Speed for the First 4 Days in a Sample Year (Year = 10,000) 50

Figure 3.4: Simulated Wind Speed for the Last 4 Days in a Sample Year (Year = 10,000) 50

Figure 3.5: Stopping Rule Methodology 51

Figure 3.6: The Simulation Procedure for Reliability Evaluation of a Generating System Containing WECS 53
Figure 3.7: LOLE vs. Number of Replications 55
Figure 3.8: LOEE vs. Number of Replications 55
Figure 3.9: LOLE vs. Annual Peak Load - MCS 58
Figure 3.10: LOEE vs. Annual Peak Load - MCS 58
Figure 3.11: LOLE vs. Number of WTGs Added to the RBTS -MCS 59
Figure 3.12: LOEE vs. Number of WTGs Added to the RBTS - MCS 60
Figure 3.13: PLCC vs. Number of WTGs Added to the RBTS - MCS 61
Figure 3.14: LOLE vs. Multiplication Factor of Wind Speed - MCS 62
Figure 3.15: LOEE vs. Multiplication Factor of Wind Speed - MCS 63
Figure 3.16: PLCC vs. Multiplication Factor of Wind Speed - MCS 63
Figure 3.17: LCBR vs. Wind Speed Multiplication Factor - MCS 64
Figure 3.18: LOLE vs. Number of WTGs Added to the RBTS (Two Wind Farms) - MCS 67
Figure 3.19: LOEE vs. Number of WTGs Added to the RBTS (Two Wind Farms) - MCS 68
Figure 3.20: LOLE vs. Number of WTG Units Added to the RBTS (Two Wind Farms with Different Wind Data) - MCS 70
Figure 3.21: LOEE vs. Number of WTG Units Added to the RBTS (Two Wind Farms with Different Wind Data) - MCS 70
Figure 3.22: PLCC vs. Penetration due to Replacing Different Units in the RBTS - MCS 73
Figure 4.1: LOLE vs. Annual Peak Load - Basic Analytical 87
Figure 4.2: LOEE vs. Annual Peak Load - Basic Analytical 88
Figure 4.3: LOLE vs. Number of WTGs Added to the RBTS - Basic Analytical 88

Figure 4.4: LOLE vs. Number of WTGs Added to the RBTS - Basic Analytical 89
Figure 4.5: PLCC vs. Number of WTGs Added to the RBTS - Basic Analytical 90
Figure 4.6: LOLE vs. Multiplication Factor of Wind Speed - Basic Analytical 91
Figure 4.7: LOEE vs. Multiplication Factor of Wind Speed - Basic Analytical 92
Figure 4.8: PLCC vs. Multiplication Factor of Wind Speed - Basic Analytical 92
Figure 4.9: LCBR vs. Wind Speed Multiplication Factor - Basic Analytical 93
Figure 4.10: LOLE vs. Annual Peak Load for the RBTS - Modified Analytical 98
Figure 4.11: LOEE vs. Annual Peak Load for the RBTS - Modified Analytical 98
Figure 4.12: LOLE vs. Number of WTGs Added to the RBTS - Modified Analytical 99
Figure 4.13: LOLE vs. Number of WTGs Added to the RBTS - Modified Analytical 100
Figure 4.14: PLCC vs. Number of WTGs Added to the RBTS - Modified Analytical 101
Figure 4.15: LOLE vs. Multiplication Factor of Wind Speed - Modified Analytical 101
Figure 4.16: LOEE vs. Multiplication Factor of Wind Speed - Modified Analytical 102
Figure 4.17: PLCC vs. Multiplication Factor of Wind Speed - Modified Analytical 103

Figure 4.18: LCBR vs. Wind Speed Multiplication Factor - Modified Analytical 104
Figure 4.19: LOLE vs. Annual Peak Load for the RBTS - Two Wind Farms 106
Figure 4.20: LOEE vs. Annual Peak Load for the RBTS - Two Wind Farms 107
Figure 4.21: LOLE vs. Number of WTGs Added to the RBTS - Two Wind Farms 107
Figure 4.22: LOLE vs. Number of WTGs Added to the RBTS - Two Wind Farms 108
Figure 4.23: PLCC vs. Number of WTGs Added to the RBTS - Two Wind Farms 108
Figure 4.24: PLCC vs. Penetration due to Replacing Different Units in the RBTS - Modified Analytical 114
Figure 5.1: Simulated Wind Speed in a Sample Year (Year = 30,000) 124
Figure 5.2: Simulated Wind Speed for the First 4 Days in a Sample Year from the New Wind Model (Year = 30,000) 125
Figure 5.3: Simulated Wind Speed for the Last 4 Days in a Sample Year from the New Wind Model (Year = 30,000) 125
Figure 5.4: Simulated Wind Speed for the First 4 Days in a Sample Year from the Old Wind Model (Year = 30,000) 126
Figure 5.5: Simulated Wind Speed for the Last 4 Days in a Sample Year from the Old Wind Model (Year = 30,000) 126
Figure 5.6: LOLE vs. Number of WTGs--Results from Different Wind Models 128
Figure 5.7: LOLE vs. Number of WTGs--Results from Different Wind Models 129
Figure C.1: Hourly Mean Wind Speed in January 159

Figure C.2: Hourly Mean Wind Speed in February 159
Figure C.3: Hourly Mean Wind Speed in March 160
Figure C.4: Hourly Mean Wind Speed in April 160
Figure C.5: Hourly Mean Wind Speed in May 161
Figure C.6: Hourly Mean Wind Speed in June 161
Figure C.7: Hourly Mean Wind Speed in July 162
Figure C.8: Hourly Mean Wind Speed in August 162
Figure C.9: Hourly Mean Wind Speed in September 163
Figure C.10: Hourly Mean Wind Speed in October 163
Figure C.11: Hourly Mean Wind Speed in November 164
Figure C.12: Hourly Mean Wind Speed in December 164
Figure F.1: LOLE vs. Annual Peak Load - Modified Analytical (ARMA) 179
Figure F.2: LOEE vs. Annual Peak Load - Modified Analytical (ARMA) 180
Figure F.3: LOLE vs. Number of WTGs Added to the RBTS - Modified Analytical (ARMA) 180
Figure F.4: LOLE vs. Number of WTGs Added to the RBTS - Modified Analytical (ARMA) 181
Figure F.5: PLCC vs. Number of WTGs Added to the RBTS - Modified Analytical (ARMA) 181
Figure F.6: LOLE vs. Multiplication Factor of Wind Speed - Modified Analytical (ARMA) 182
Figure F.7: LOEE vs. Multiplication Factor of Wind Speed - Modified Analytical (ARMA) 182
Figure F.8: PLCC vs. Multiplication Factor of Wind Speed - Modified Analytical (ARMA) 183
Figure F.9: LCBR vs. Wind Speed Multiplication Factor - Modified Analytical (ARMA) 183

# LIST OF TABLES


Table 2.1: Generating Unit Reliability Data 40

Table 2.2: LOLE and LOEE for the RBTS 40

Table 2.3: Capacity Outage Probability Table for the RBTS 42

Table 3.1: Reliability Indices for the RBTS before and after Adding 100 WTGs 56

Table 3.2: Reliability Indices of RBTS with the Addition of Different Units 57

Table 3.3: LOLE for the RBTS Containing Two WECS 66

Table 3.4: LOEE for the RBTS Containing Two WECS 66

Table 3.5: LOLE for the RBTS Containing Two Wind Farms with Different Wind Speed Data for Replacing Different Units 69

Table 3.6: LOEE for the RBTS Containing Two Wind Farms with Different Wind Speed Data for Each Wind Farm 69

Table 3.7: PLCC vs. the Penetration for Table 2.2: LOLE and LOEE for the RBTS 72

Table 4.1: WECS Unit Capacity Probability Table 77

Table 4.2: Modified Capacity Probability Table for a 0.225 MW WECS with a FOR 0.05 78

Table 4.3: Wind Speed Multiplication Factor = 0.7 78

Table 4.4: Wind Speed Multiplication Factor = 0.9 79

Table 4.5: Wind Speed Multiplication Factor = 1.1 79

Table 4.6: Wind Speed Multiplication Factor = 1.3 80

Table 4.7: Wind Speed Multiplication Factor = 1.5 80

Table 4.8: Wind Speed Multiplication Factor = 1.7 81

Table 4.9: Wind Speed Multiplication Factor = 1.9 81

Table 4.10: Wind Speed Multiplication Factor = 2.1 82

Table 4.11: Wind Speed Multiplication Factor = 2.3 82
Table 4.12: Wind Speed Multiplication Factor = 2.5 83
Table 4.13: Wind Speed Multiplication Factor = 2.7 83
Table 4.14: WECS Capacity Probability Table
(Number of Replications = 6,000 years) 94
Table 4.15: WECS Capacity Probability Table
(Number of Replications = 6,000 years) 95
Table 4.16: WECS Capacity Probability Table
(Number of Replications = 60,000 years) 96
Table 4.17: LOLE vs. Annual Peak Load for Different Approaches 104
Table 4.18: LOEE vs. Annual Peak Load for Different Approaches 104
Table 4.20: LOLE vs. Annual Peak Load for Different Approaches 110
Table 4.21: LOEE vs. Annual Peak Load for Different Approaches 110
Table 4.22: LOLE vs. Number of WTGs Added for Different Approaches 111
Table 4.23: LOEE vs. Number of WTGs Added for Different Approaches 111
Table 4.24: PLCC vs. Number of WTGs Added for Different Approaches 112
Table 4.25: PLCC vs. Wind Speed Multiplication Factor for Different
Approaches 113
Table 4.26: Comparisons of PLCC vs. Penetration (Fewer Unit Case) 114
Table 4.27: Comparisons of PLCC vs. Penetration (Fewer Unit Case) 115
Table 5.1: A Comparison of the LOLE Using the Two Wind Models 127
Table 5.2: A Comparison of the LOEE Using the Two Wind Models 128
Table 5.3: WECS Capacity Probability Table Using the New Wind Model 129
Table 5.4: LOLE vs. Annual Peak Load for Different Approaches 131
Table 5.5: LOEE vs. Annual Peak Load for Different Approaches 131
Table 5.6: LOLE vs. Annual Peak Load for Different Approaches 132
Table 5.7: LOEE vs. Annual Peak Load for Different Approaches 132

Table 5.8: PLCC vs. Number of WTGs Added for Different Approaches 133

Table 5.9: PLCC vs. Wind Speed Multiplication Factor for Different Approaches 133

Table B.1: Wind Speed Multiplication Factor = 0.7 146

Table B.2: Wind Speed Multiplication Factor = 0.9 147

Table B.3: Wind Speed Multiplication Factor = 1.1 148

Table B.4: Wind Speed Multiplication Factor = 1.3 149

Table B.5: Wind Speed Multiplication Factor = 1.5 150

Table B.6: Wind Speed Multiplication Factor = 1.7 151

Table B.7: Wind Speed Multiplication Factor = 1.9 152

Table B.8: Wind Speed Multiplication Factor = 2.1 153

Table B.9: Wind Speed Multiplication Factor = 2.3 154

Table B.10: Wind Speed Multiplication Factor = 2.5 155

Table B.11: Wind Speed Multiplication Factor = 2.7 156

Table C.1: Hourly Mean Wind Speed in a Day for Each Month 158

Table E.1: Wind Speed Multiplication Factor = 0.7 168

Table E.2: Wind Speed Multiplication Factor = 0.9 169

Table E.3: Wind Speed Multiplication Factor = 1.1 170

Table E.4: Wind Speed Multiplication Factor = 1.3 171

Table E.5: Wind Speed Multiplication Factor = 1.5 172

Table E.6: Wind Speed Multiplication Factor = 1.7 173

Table E.7: Wind Speed Multiplication Factor = 1.9 174

Table E.8: Wind Speed Multiplication Factor = 2.1 175

Table E.9: Wind Speed Multiplication Factor = 2.3 176

Table E.10: Wind Speed Multiplication Factor = 2.5 177

Table E.11: Wind Speed Multiplication Factor = 2.7 178

# LIST OF ABBREVIATION

| | |
|---|---|
| ARMA | Autoregressive Moving Average |
| CPU | Central Processing Unit |
| DPLVC | Daily Peak Load Variation Curve |
| ENS | Energy Not Supplied |
| FOR | Forced Outage Rate |
| HLI | Hierarchical Level I |
| HLII | Hierarchical Level II |
| HLIII | Hierarchical Level III |
| IEEE | Institute of Electrical and Electronics Engineers |
| KW | Kilo Watt |
| KWh | Kilo Watt Hours |
| LCBR | Load Capacity Benefit Ratio |
| LDC | Load Duration Curve |
| LLD | Loss of Load Duration |
| LOEE | Loss of Energy Expectation |
| LOLE | Loss of Load Expectation |
| MCS | Monte Carlo Simulation |
| MW | Mega Watt |
| MWh | Mega Watt Hour |
| MTTF | Mean Time To Failure |
| MTTR | Mean Time To Repair |
| NWTG | Number of Wind Turbine Generator |
| PLCC | Peak Load Carrying Capability |
| RBTS | Roy Billinton Test System |
| TTF | Time To Failure |

| | |
|---|---|
| TTR | Time To Repair |
| WECS | Wind Energy Conversion Systems |
| WTG | Wind Turbine Generator |

# 1. Introduction

## 1.1 Power System Reliability Evaluation

The basic function of a modern electric power system is to supply customers, both large and small, with electrical energy as economically as possible and with a reasonable level of reliability. Modern society, because of its pattern of social and working habits, demands that the supply be continuously available. This degree of expectation requires utilities to provide uninterrupted power supply to their customers. It is not feasible economically and technically, however, to attempt to design a power system with one hundred percent reliability and power system engineers have always attempted to achieve the highest possible reliability within their socioeconomic constraints.

The reliability associated with a power system is a measure of the ability of the system to supply electrical energy. System reliability can be divided into the two distinct categories of system security and system adequacy, as shown in Figure 1.1.

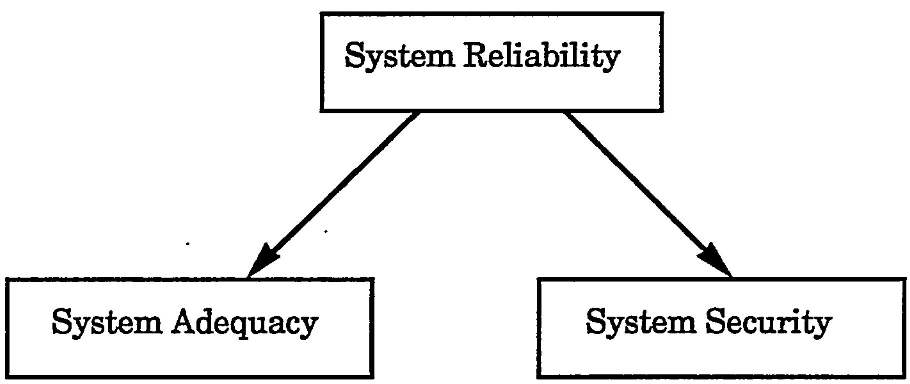


Figure 1.1: Subdivision of System Reliability

The concept of security is related to the ability of the system to respond to disturbances arising within the system. Security is therefore associated with the response of the system to whatever perturbations it is subjected to. These include the conditions associated with both local and widespread disturbances and the loss of major generation and transmission facilities. Dynamic studies such as transient stability analysis may have to be performed when system security is examined. System adequacy relates to static system conditions and the existence of sufficient facilities within the system to meet the system load demand. Adequacy evaluation is therefore associated with static conditions which do not include system disturbances.

The basic techniques for power system adequacy assessment can be categorized in terms of their application to segments of a complete power system. These segments are shown in Figure 1.2. and are defined as the functional zones of generation, transmission and distribution. Three hierarchical levels can be structured by combining these functional zones.

Hierarchical level I (HLI) is concerned only with the generation facilities. The effects of both the transmission network and the distribution facilities are neglected. The main concern in an HLI study is to estimate the generating capacity required to satisfy the perceived system demand and to have sufficient capacity to perform corrective and preventive maintenance on the generation facilities. Conceptually, a capacity model and a load model are created and then convolved to obtain the risk indices. Hierarchical level II (HLII) assessment considers both generation and transmission facilities. HLII adequacy evaluation techniques are concerned with the composite problem of assessing the generation and transmission facilities in regard to their ability to supply adequate, dependable and suitable electrical energy at the bulk load points. The inclusion of the transmission network usually results in a sharp increase in computational effort and analysis complexity. Hierarchical level III (HLIII) includes all three functional zones and is not normally conducted in a practical system due to the computational complexity involved in this assessment. The analysis is usually performed only in the distribution functional zone, in which the input points may or may not be considered to be fully reliable.

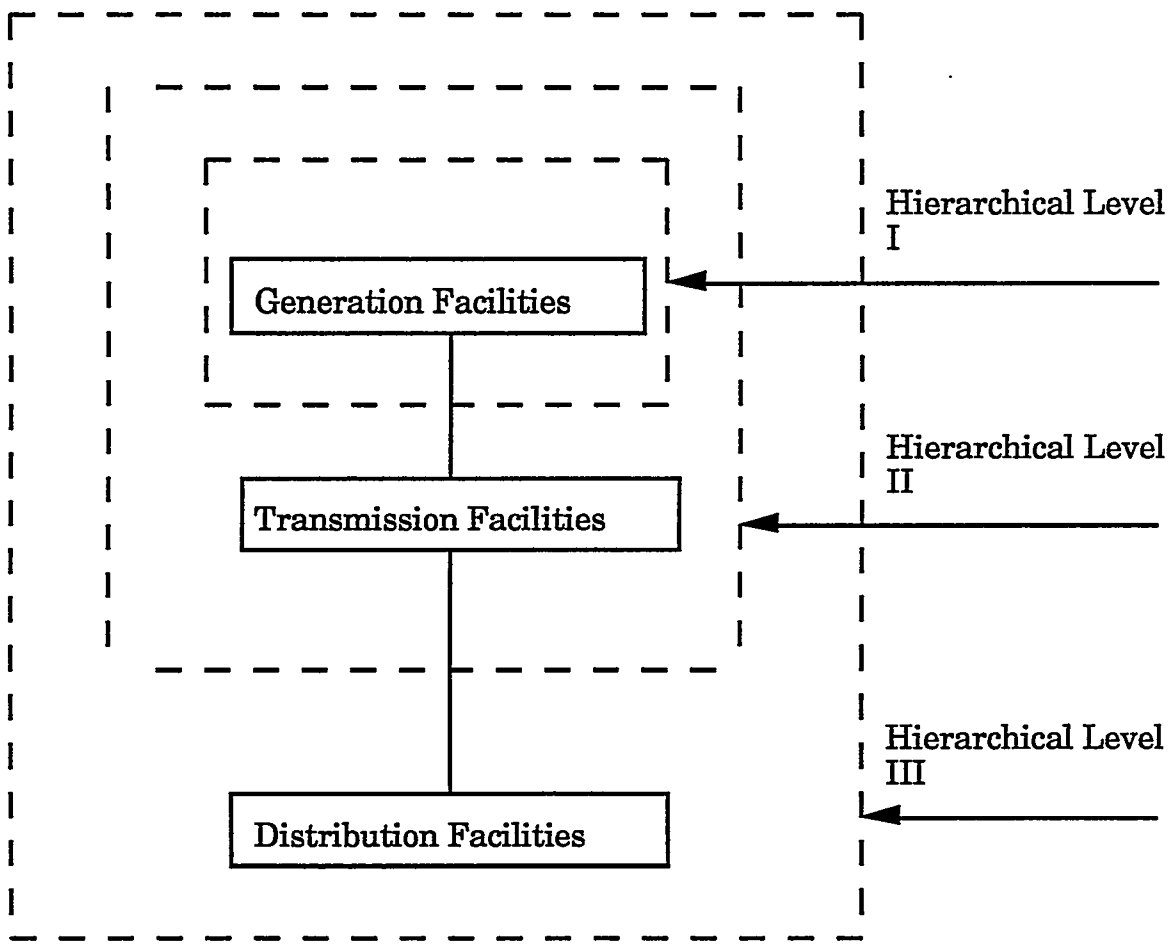


Figure 1.2: Hierarchical Level Structure

This thesis is concerned with adequacy assessment at Hierarchical Level I (HLI). At HLI, the total system generation is examined to determine its adequacy to meet the total system load demand. This is normally defined as generating capacity adequacy evaluation.

Considerable work has been done in the area of generating capacity adequacy assessment [1-6]. The most widely used technique is the loss of load approach [7]. The basic method has been extended to create a loss of energy approach [7]. Both of these techniques involve the evaluation of mathematical expectation using basic probability methods. The conventional applications are based on analytical approaches in which models of the system are analyzed using mathematical equations and direct numerical solutions. An alternative approach is to utilize Monte Carlo simulation.

Generating capacity reliability evaluation is normally done assuming that there are no basic energy limitations. Energy limitations often occur in hydro systems and in unconventional energy systems. Thermal generating units are normally assumed to be energy limited only when their capacity is limited by equipment failure. Energy limitations, however, can play an important role in capacity adequacy evaluation. In order to include them in an analytical approach it is usually necessary to make some simplifying assumptions [8-10]. Generating unit energy limitations are, however, relatively easy to include in a simulation approach.

Generating units can be categorized into two basic groups, namely, conventional generating units and unconventional generating units. Conventional generating sources include thermal, nuclear and hydro capacity while unconventional units include wind, solar, battery, and fuel cell systems [11]. As the cost of conventional electrical energy production continues to rise, the use of non-conventional energy sources is attracting and will continue to attract more attention.

## 1.2 The Advantages of Using Wind Power

The development and utilization of feasible sources of renewable energy for satisfying electrical demand is being given very serious consideration due to the concern expressed in recent years about dwindling energy resources and enhanced public awareness of the potential impact of conventional energy systems on the environment. The possibility of harnessing energy from the wind on a large scale has been seriously considered by many utilities. The windmill, which is one of the oldest means of producing mechanical power, might by now have become a curiosity but for the energy crisis of the 1970's. Because of this interest in alternatives to petroleum as a source of energy, the windmill has received a considerable technological improvement. As a result, individual windmills and windmill farms or arrays of windmills, are contributing to electric power systems in several countries. The contribution is relatively small at the present time, but it can be suggested that it will become significant with the inevitable eventual tightening in petroleum supplies and improving technology of wind mills.

The annual energy available in the winds over the earth's surface amounts to many trillions of kilowatt-hours (Parker gives 13 trillion Kwh [15]) although it is only possible to envisage the utilization of a fraction of this enormous total. Nevertheless, it might prove possible in a windy country to develop wind power to provide installed capacity of some ten to twenty percent of the total requirement.

There is approximately 2,000 MW of installed generating capacity using wind energy worldwide. Most of this (approximately 1,600 MW) is in California. In 1990, wind energy supplied utilities in California with 2.5

billion kilowatt hours of electricity generated from more than 17,000 wind turbines. U.S. Wind Power, the world's largest wind energy company, has manufactured, installed and is operating more than 4,100 wind turbines in California. The majority of these have a rated generating capacity of 100 kilowatts.

The use of the wind for electric power generation is considered to be an attractive generation alternative, due to increased interest in sources of energy that are renewable and environmentally-friendly. The obvious attraction is that the wind itself is free. Private and government sponsored organizations have been established to examine and promote the potential of the sun and wind as alternative sources of energy. The obvious basic attraction for this is the realization that coal and oil resources are limited and are being used up at an increasingly rapid rate. Furthermore, difficult global economic and political conditions are tending to make countries depend upon their own resources for the generation of power rather than upon imported fuels [12-14].

## 1.3 The Characteristics of Wind Power

Energy from the wind is a form of solar energy. Winds are turbulent masses of air resulting from evening out the differences in atmospheric pressure created by the sun. Wind is, therefore, highly variable, site-specific and also terrain specific. It has instantaneous, minute-by-minute, hourly, diurnal and seasonal variations. Wind force varies with the square of wind speed whereas the power in the wind varies with the cube of the wind speed. As an example, if the power (P) in the wind is known at a wind speed of 10 miles per hour(mph), and the wind speed increases to 11 mph, the increase in the power in the wind is as follows [15]:

$$P\times\left(\frac{11}{10}\right)^3 = P\times 1.331 \qquad (1.1)$$

The example shows that an increase in wind speed from 10 to 11 mph, just one mph, or 10 percent, causes a 33 percent increase in the power in the wind. A small increase in wind speed produces a large increase in power.

Besides variability, wind has the characteristic of diffusness and is not a concentrated source of energy. In order to generate a significant amount of power, a windmill must harvest a large cross-sectional area of wind. The wind at any point in time may be insufficient to operate a wind system, as wind power is dependent upon climatic and weather conditions. Wind energy therefore is a non-dispatchable or intermittent resource.

## 1.4 History of Development of Wind Energy Conversion Systems (WECS)

Windmills have existed since earliest antiquity in Apersia, in Iraq, in Egypt and in China. In the seventeenth century B. C., it is said that Hammurabi, king of Babylonia, conceived a plan to irrigate the rich plain of Mesopotamia with the aid of wind energy. The windmills used at that time and in that country, probably included vertical-axis machines similar to those whose ruins have been found on the Iranian plateau. It was only during the Middle Ages that windmills appeared in Italy, France, Spain, and Portugal and later in Great Britain, Holland, and Germany. By A. D. 1100, Crusaders and travelers found windmill technology well established in the Middle East. The slow multibladed wind turbine appeared later during the nineteenth century. This development did not occur on the old continent but in the

United States of America and from 1870, it dominated the development and came back to Europe under the name of the " American Windmill".

The first modern fast wind turbines driving electric generators, appeared in France at the dawn of the 20th century and subsequently spread all over the world. This invention was attributed to the French Academician Darrieus.

With the invention of the steam engine, the internal combustion engine, and the development of electricity, emphasis on wind power development declined and could be said to have been abandoned. Due to concerns regarding decreases in the world stock of hydrocarbons and the fear of expanding pollution, wind energy has, however, again become important.

Although wind energy has been exploited for thousands of years, by windmills and sailors and the principles of wind--generated electricity are well known, the actual development of grid--connected, efficient and reliable wind turbines has proved to be a major challenge. Many technological developments have occurred over the late twenty years and a range of commercial wind turbines is now available from about 30 manufacturers worldwide. The most dramatic rise in wind energy applications occurred in the U.S.A. during the 1980s, when favorable tax credits and energy rates for independent power producers resulted in 1500 MW of installed capacity. About 500 MW of wind turbines were operational in Europe in 1991, most of it in Denmark. By taking advantage of its vigorous home market, Denmark has developed a successful industry, which during the five years of peak production in the California boom of the 1980s earned an average of £130 million per annum.