A PROBABILISTIC STUDY OF WIND-ELECTRIC CONVERSION SYSTEMS FROM THE POINT OF VIEW OF RELIABILITY AND CAPACITY CREDIT

By

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TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

Table		Page

LIST OF FIGURES

LIST OF SYMBOLS

$A_1, A_2, \ldots, A_n$ - availability of states 1, 2,....., n of the n-state Markov model

A_c - availability of rated output capacity of a conventional generating unit

$\bar{A}_c$ - unavailability of rated output capacity of a conventional generating unit

A_{c1}, A_{c2}, A_{c3} - availabilities of states 1, 2, and 3 of the ternary model of a conventional generating unit

A_{gi} - availability of the i^{th} state of a combined (WECS plus conventional generating units) system

A_{mk} - availability of the k^{th} state in the reserve margin states

A_T - availability of the transmission line up state

$\bar{A}_T$ - unavailability of the transmission line up state

A_{wk} - availability of the k^{th} state in the WECS model

A_{wkt} - availability of the k^{th} state in the combined WECS and transmission line system

C_{gi} - capacity output of the i^{th} state of combined (WECS plus conventional generating units) system

C_w - rated capacity output of a WECS

C_{wk} - capacity output of the k^{th} state of WECS

C_{wkt} - capacity output of the k^{th} state of combined WECS and transmission line system

Den - value of the denominator

$\frac{d}{dt}$ - mathematical operator derivative

f_c - frequency of encounter of up state of a conventional generating unit

f_{gk}	- frequency of encounter of state k of the combined (WECS plus conventional) system
f_{mk}	- frequency of encounter of state k of the reserve margin states
f(v)	- density (function) of the random variable wind speed
$F_v(V)$	- distribution function (or distribution) of the random variable wind speed
i, j, k	- variable used to represent the states of a system or model
m	- reserve margin capacity
$m_1, m_2, \ldots$	- capacity of reserve margin states, 1, 2,.....
N	- number of conventional generating units in the system
N1	- number of identical capacity states in a system
$O_{g1}, O_{g2}, \ldots$	- outage capacity of states 1, 2,..... in the combined (WECS plus conventional generating units) system
P	- probability of outage of a state in a system
Q	- probability of the occurrence of a state in a system
$Q_c(t)$	- probability of finding the conventional generating unit in the up state at time t
$S_1, S_2, \ldots$	- states 1, 2,.....in the model of the multistate system
T	- total duration under consideration
$t_1, t_2, \ldots$	- duration of time that output stayed in states 1, 2, ...in the multistate system
T_k	- total time of residence in output capacity C_k
Δt	- small interval of time
v	- hourly wind speed
α	- parameter in the Weibull density function
β	- parameter in the Weibull density function
$\Gamma(\ )$	- mathematical gamma function

λ_c - rate of departure to a down state in a conventional generating unit (binary) model

λ_{gi} - total rate of departure to down states from state i in the combined (WECS plus conventional generating units) system

λ_{Lj} - total rate of departure to down states from state j in the load model

λ_{mk} - total rate of departure to down states from state k in the reserve margin states

μ_c - rate of departure to up state in a conventional generating unit (binary) model

μ_{gi} - total rate of departure to up states from down state i in the combined (WECS plus conventional generating units) system

μ_{mk} - total rate of departure to up states from state k in the reserve margin states

μ_{Lj} - total rate of departure to up states from state j in the load model

τ_{gk} - residence time of state k in the combined (WECS plus conventional generating units) system

ρ - rate of departure from a state in a multistate Markov model

CHAPTER I

INTRODUCTION

1.1 Past Developments and Future of Wind Energy Systems

Harnessing power from wind has been known to mankind for centuries. However, only during the turn of the 19th century, windmills were used for the generation of electricity. Early developments in this area took place mostly in European countries, notably in Denmark, France, Germany, and Holland. In Denmark, during the first and the second world wars, due to a cutoff of 95 percent of their fuel supply, generation of power from wind became a necessity. Seeing the early successes, the neighboring countries of England, France, and Germany undertook the development of small and large wind systems for the generation of electricity. In almost all cases the projects had to be abandoned due to frequent technical problems and the high cost involved in their repair.

Among the large windmills built and successfully operated in Europe in the past are the "Gedser mill" (200 kW) in Denmark (1956-1957),(1), the 800 kW "BEST Romani" near Paris (1958-1963), (2), the 100 kW unit in Okney, U.K. (1952-1956), (3, 4), and Hütter's 100 kW system in Germany (1958), (5, 6).

The early significant works in this area in the United States were initiated by Palmer Putnam in 1934 (7). The 1250 kW Smith-Putnam wind plant was built and commissioned on October 19, 1941. It experienced problems frequently and the project was discontinued after one of its blades broke off in March, 1945, and due to the subsequent preoccupation of the country with World War II (8).

The brief oil embargo of 1973, the sharp rise in the energy consumption in the decade of the seventies, the rising cost of fossil fuels and their dwindling supply and the public awareness of the environmental impacts of unrestricted consumption of fossil fuels have rekindled the interest in wind power in the United States. In early 1973, the National Science Foundation (NSF) was given the responsibility for planning and executing a program whose objective was to develop the technology to build reliable, cost competitive wind energy conversion systems for commercial implementation. The National Aeronautics and Space Administration (NASA) and other governmental agencies cooperated with NSF in developing the program. By January, 1975, the responsibility was transferred to the then newly formed Energy Research and Development Administration (now the Department of Energy) which, along with NASA, initiated a number of parallel activities under 45 different projects on wind energy conversion systems research development and design (9).

The future of wind energy utilization appears to be in two major areas (10):

1) Refinement of current designs to develop inexpensive, durable, small and medium size systems for use in homes and farms in rural areas.

2) Development, fabrication and testing of large experimental Mega Watt scale wind-electric systems for operating in parallel with existing utility systems.

Integration of large WECS with utility grids raises questions regarding the reliability of the overall system and the capacity credit (if any) that can be assigned to wind systems and how these are influenced by factors such as the wind regime, amount of penetration, load model, and the like.

1.2 Reliability Concepts Applied to Power Systems

The term "reliability" is defined in the aerospace industry as "the probability that an item will perform the intended function for a specified interval under stated conditions." The period of time is defined as the "mission time," and the component has to function successfully not only at the end of the mission time but also during the entire mission (11).

The definition of reliability for power system apparatus as contained in the Federal Power Commission Report Vol. II (June, 1967) on "Prevention of Power Failures" reads as follows: "Reliability is the degree of assurance of bulk power supply in delivering electricity to major points of distribution" (12).

This definition reveals the probabilistic nature of reliability by the inclusion of the phrase "degree of assurance" and it does not precisely state anything about the specific measure of the reliability. Thus the term "reliability" as applied to Power Systems is general and broad-based. It is related to actual phenomena in an inexact manner.

Probability models and approaches are useful in describing and analyzing situations wherein uncertainty is an important factor. Successful planning, design and operation of electrical power systems with a high degree of reliability requires the consideration of several sources of uncertainties. Some of the major sources of uncertainties are the time of occurrence of failures or forced outages, the time to repair the failed components, the magnitude of the peak load demand, the date of installation of new facilities and the frequency and duration of weather extremes (13).

1.3 Literature Survey

Most of the probabilistic approaches in the power systems area have been in the planning of generation capacity requirements for conventional generation systems (14 - 20). Generating capacity reliability evaluation is broadly divided into the areas of static and spinning requirements. Both of these are considered at the planning level. Static requirement is the installed capacity which is planned and constructed in advance of the system load growth. The static reserve must be sufficient to take care of the overhaul of generating equipment, outages that are not scheduled and the error in the forecasted load growth. Too low a reserve capacity may lead to excessive interruptions while too high a value results in excessive costs. The greater the uncertainty regarding the actual reliability of any installation, the greater the investment wasted.

In the typical case of system generating capacity reserve, the problem not only concerns the risk of outage but also the economic balance between the generation reserve and tie capacity in providing against local outage concentrations. The complexity of the problem, in general, makes it difficult to find an answer by rule of thumb. One such rule that was in use had been to provide a total generation capacity (planned and installed) in excess of the expected demand by some fixed percentage. The main drawback of this type of procedure is that it does not take into consideration the differences in the load characteristics and the unit sizes of installed and planned generating Capacity. A slightly better reserve criterion that followed was to provide a reserve equivalent to the capacity of the largest unit in the system plus some fixed percentage of the maximum demand. Application of probability methods to the static generation capacity problem provides an analytical approach to planning the generation. Further, it is possible to incorporate the effects of partial and complete integration of systems, capacity interconnections, difference in sizes, scheduled maintenance, and the economic aspects based on reliability standards (21).

A probabilistic approach to conventional generation studies was initiated as early as in the early thirties of this century. The first such paper ever to appear was in 1933 (22). Pioneering works in this area were published by Calabrese (23), Seelye (24, 25), and Loan and Watchorn (26). They suggested some basic concepts upon which present methods of reliability of conventional generation systems are based. A subcommittee of the AIEE on the application of probability methods prepared a report in 1949 giving precise comprehensive definitions for equipment outages and equipment expectancies. The group of papers published in 1947 has evolved, with some modifications, into the well known "Loss of Load Probability Approach" and the "Frequency and Duration Approach" for generation capacity reliability evaluation. Important papers on interconnection, and determination and allocation of capacity benefits resulting from interconnection by Watchorn (27) and Calabrese

(28) appeared in 1950 and 1953. With the advent of high speed digital computers, Kirchmayer and his associates (29) published a paper on the evaluation of economic unit additions in system expansion studies. All of these papers and three AIEE committee reports on equipment forced outages experience published in 1949, 1954, and 1957 (except for a small section of the 1949 report) deal with information on thermal units. Brown, Dean and Caprez (30) published results in 1960 on statistical studies using five years of data on 387 hydro-electric generating units. A large number of excellent papers on static generation capacity reliability (31, 32), spinning generating capacity evaluation (33, 34), reliability of transmission and distribution (35), composite system reliability (36, 37), etc., appeared in the late sixties and in the early seventies. The bulk of the publications on power systems reliability evaluation pertain to generation capacity requirements. However, publications on reliability studies of transmission and distribution systems and on spinning generating capacity evaluation, composite systems and interconnected systems are relatively fewer in number.

A survey of all of the publications shows that the "Loss of Load Probability" method with simple load model with assumed daily peak loads is preferred above any other method. This method is relatively simple and can incorporate changes in load characteristics, load forecast uncertainty, and the reliability aspects of multiple interconnection facilities.

The duration and the interval of an outage is given by the "frequency and duration approach," and this method is suitable to link the generation and transmission systems to permit the evaluation of bus reliability at any point in the utility network.

All of the works on the reliability of power systems discussed so far involved conventional generation units. With the expected entry of large wind-electric conversion systems (WECS) into the utility grids of the future, interest in similar works on WECS is recently gaining importance. Melton's work (38) on loss of load probability and capacity credit calculations for WECS deals with WECS operating in parallel with the conventional generators of the Hawaiian Electric Company. It is based on hourly wind speed data for a period of over fifteen years. WECS is modeled in terms of a number of preselected capacity (full capacity, zero capacity, and a number of partial capacity) states and the availabilities of each of the states for each hour of the day are computed. Further, the loss of load approach has been followed to evaluate the reliability of WECS assisted conventional generation system. A new term, "capacity credit for WECS," indicating the conventional capacity displacement due to the addition of WECS, has been introduced. The results derived are fairly accurate but the approach requires the availability and processing of a large amount of wind data.

1.4 Problem Description

Since the input to a WECS is the kinetic energy in wind, the behavior of a WECS depends considerably on the characteristics of the wind regime. Wind characteristics depend strongly on the nature of the region where the WECS is located, plain mainland, mountainous or hilly areas, coastal areas, etc. As such, the behaviors of the same WECS at different sites would differ widely. Further, it is influenced by gusty winds. In addition, the behavior of a WECS depends upon factors such as the size, number and characteristic of conventional generating units operating in parallel, the amount of reserve provided and the nature of the load demand. Influence of transmission system is also important since, by nature, WECS will be located in remote areas, connected to other conventional units and/or other WECS via transmission lines.

The first step in the study is to develop an understanding of WECS from the point of view of generation. Once a suitable model is developed, it can be used to study the overall system reliability and the potential capacity credit. Obviously, the model will be probabilistic because of the inherent variability of the wind.

It is required to develop a procedure to predetermine the behavior of a WECS operating alone or along with other conventional generating units. This behavior should be modeled from readily available information and if available, using detailed information about the wind regime at the site of installation of WECS. Further, since the location of WECS would normally be in remote areas, integration of WECS with conventional generation system requires the use of primary feeders. With increasing number of WECS installed in the near future, their interconnection and operation in parallel with utility grids will involve a number of transmission lines in the system. Thus, the procedure evolved should incorporate transmission system also. Such studies and ensuing results can be used for planning to meet a specific reliability level or to make comparison of alternate expansion schemes when they include WECS as a component.

1.5 Method of Analysis

In order to develop an understanding of a WECS operating in parallel with other conventional generators in a power system, the following steps will be undertaken:

(i) Develop probability models for an individual WECS operating alone or in parallel with conventional generating units.

(ii) Employ the models in reliability analysis with an assumed load model.

(iii) Compute reliability indices or reliability index range that are valid for an assumed study period.

(iv) Study the influence of changes in key parameters on the reliability index. The parameters of interest are the number of conventional units, the system load and the wind regime.

(v) Study the influence of transmission system on the overall reliability when WECS are present.

The results will be presented in the form of tables and families of curves. Further, these tables and curves would be interpreted and some useful conclusions would be drawn which can be used for planning studies and reserve evaluations. This study will also form a good foundation for further work and refinements that are yet to come.

1.6 Organization of the Thesis

Chapter II presents an approach to develop capacity outage probability tables for WECS using mathematical models for the wind-speed distribution at a site and compares the results obtained with the results using actual hourly wind data. These tables have been utilized to compute the reliability of WECS assisted conventional generation systems using the loss of load probability approach with a simple load model.

Chapter III develops a Markov model for WECS using the actual wind data for a site. This model, combined with one or more conventional generating units, is used to evaluate the overall system reliability using the frequency and duration approach for a typical load model based on the Markov chain.

Chapter IV studies the influence of transmission system on the generation reliability evaluation of WECS alone and of WECS assisted conventional generation systems. These reliability studies are based on frequency and duration approach involving Markov models for hourly peak loads. Generation reliability studies of two WECS connected through a transmission line have also been discussed in this chapter.

Chapter V summarizes the conclusions and limitations of this work and outlines some suggestions for future research work.

CHAPTER II

PROBABILITY MODELS FOR WIND ELECTRIC CONVERSION SYSTEMS AND THEIR APPLICATION TO RELIABILITY STUDIES

2.1 Introduction

Over the past decade, many attempts have been made to analyze and model wind in connection with the development of wind power (39 - 42). However, very little literature is available on the application of these results to model WECS and on the use of such models in reliability studies. Melton (38), in his recent work, utilized detailed wind characteristics (extended over a period of fifteen years) of the Hawaiian Islands to study the loss of load probability and capacity credit of WECS operating in parallel with the conventional generators of the Hawaiian Electric Company. Though the results derived are fairly accurate for the system studied, the procedure requires the availability and processing of a significant amount of wind data, extending over long periods of time.

This chapter discusses the development of a probability approach for modeling the loss of generation capacity due to the inherent variability of the wind input. It is based on readily available parameters such as the mean and/or variance of the wind speed. The model is then applied to the study of the wind generation availability and the reliability of WECS operating in parallel with conventional generators, supplying a common load. The results obtained are discussed and some conclusions are drawn regarding the reliability of wind-assisted utility systems.

2.2 Types of Wind Data and Probability Models

Wind is highly variable and site specific. Complete information on the nature of the wind regime at any given site requires continuous plots of wind speed and direction as functions of time. A typical plot of wind speed is shown in Figure 1 for a site in Albuquerque, New Mexico (39). However, such information is not available for any extended periods of time, and designers of wind energy systems have to base their calculations on far less information.

Hourly wind speed and direction measurements are the most commonly available data for potential sites. These hourly measurements are obtained by taking the average over one minute, five minutes, or ten minutes every hour on the hour, and are recorded as the values for the entire hour. Generally, wind speed values are given up to the first decimal place accuracy (see Table I), but sometimes the data are rounded off to the nearest integer (see Table II).

The accuracy of the results of the generation reserve capacity and reliability studies for WECS depends on the type of wind data available and on the validity of the assumptions made. In this thesis, hourly (averaged over one minute duration) wind speed data obtained over a two-year period for a typical site (Kahuku Upper) on the Hawaiian Island of Oahu (43) and for a period of two (low and high mean wind speed) months for a site (Livermore) in California (44) are used as

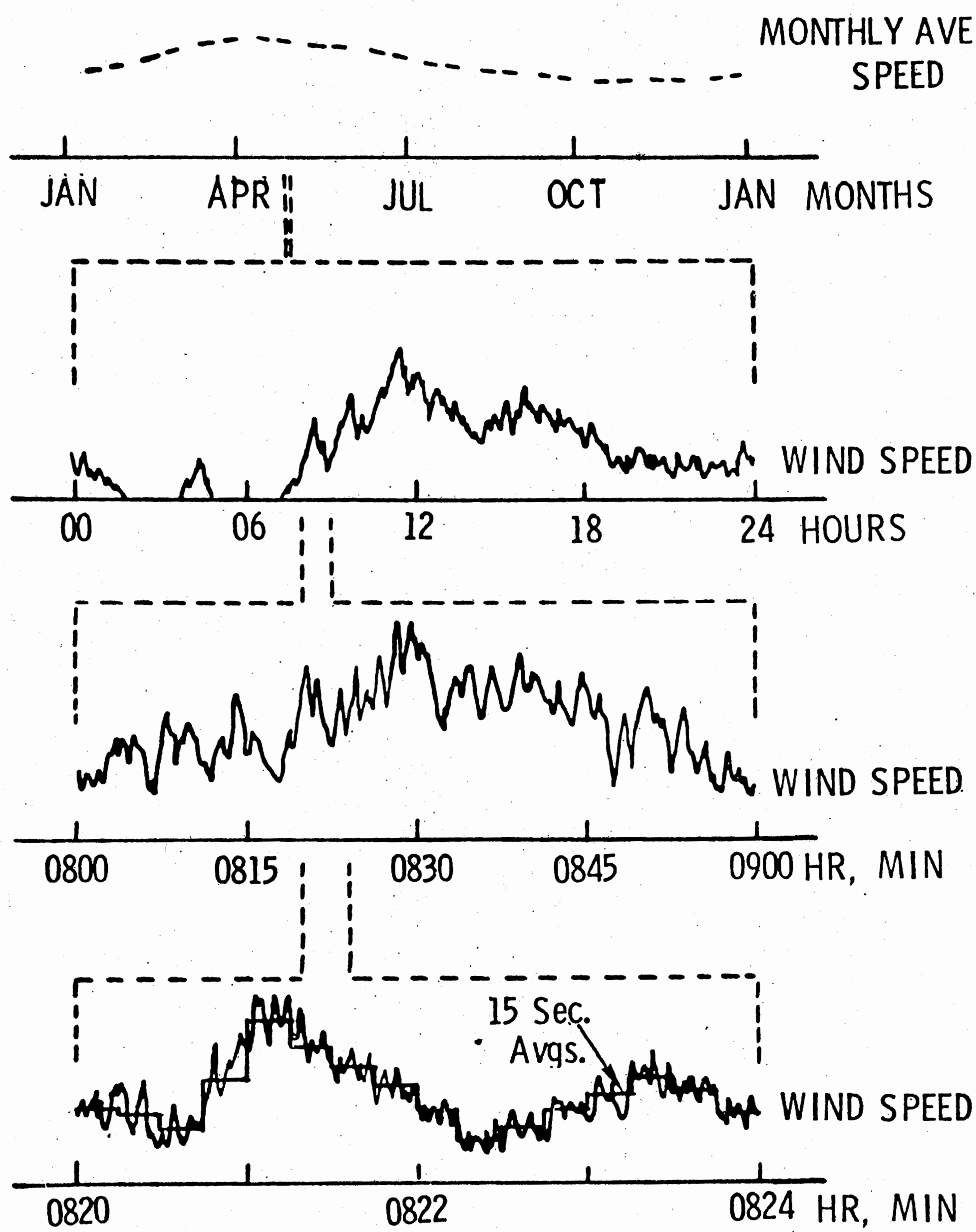


Figure 1. Wind Speed Records on Expanding Time Scale

TABLE I

TYPICAL WIND SPEED DATA FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

	HOUR OF DAY																							
DAY	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	27.9	25.7	26.1	26.5	29.6	32.8	31.1	28.7	32.1	29.7	30.1	27.3	27.5	31.6	30.1	27.9	28.4	26.7	26.5	27.8	28.2	26.3	26.3	29.0
2	32.2	28.6	26.7	25.8	25.4	26.8	25.8	24.8	25.8	27.0	28.0	32.2	30.0	29.7	30.3	29.2	29.3	29.5	27.8	28.3	28.0	26.8	27.4	26.7
3	28.6	27.4	27.0	26.2	26.3	26.8	28.8	27.1	27.6	29.0	29.8	31.3	33.7	30.8	24.4	24.7	23.9	26.7	28.2	28.5	26.8	26.5	26.9	26.6
4	26.6	29.3	29.5	27.3	24.4	27.8	29.1	29.1	27.7	29.0	28.2	28.1	28.2	25.2	28.5	28.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
5	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
6	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
7	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	32.6	31.6	31.9	31.2	34.0	32.9	29.7	28.9	26.9	29.0	29.0
8	28.7	30.0	30.1	29.5	26.6	26.8	27.5	26.0	27.8	30.1	28.8	33.6	32.6	36.7	36.6	31.5	31.0	30.3	30.3	30.2	29.8	30.9	27.1	26.7
9	28.5	28.3	26.1	28.2	30.7	29.6	29.9	24.8	24.3	25.0	23.7	23.5	20.2	23.1	28.3	28.2	26.6	26.5	21.2	20.3	18.3	17.9	17.4	18.7
10	19.9	14.4	14.4	18.8	23.6	26.5	24.6	23.3	24.3	26.2	26.2	25.2	23.9	25.6	28.3	29.0	25.9	26.6	25.6	25.8	26.2	24.7	26.7	27.1
11	27.5	25.0	24.4	27.5	28.5	30.5	31.0	29.6	27.5	29.3	30.6	29.3	20.3	28.1	31.7	29.5	31.8	26.2	33.9	32.1	25.7	29.9	34.6	32.7
12	34.3	35.0	38.5	36.6	37.8	38.6	36.8	34.0	38.3	35.4	33.0	35.9	31.4	29.7	31.8	29.9	28.2	31.3	24.0	23.3	19.0	22.3	21.5	24.3
13	27.5	28.1	27.2	25.9	24.0	25.6	26.4	28.8	30.9	29.0	33.9	37.9	36.8	36.8	39.4	39.1	39.4	37.7	38.7	39.4	37.5	36.7	36.4	35.4
14	36.2	38.0	36.2	34.7	33.8	34.2	33.8	36.1	35.4	36.6	35.0	34.9	33.7	34.3	31.9	28.2	30.2	29.6	33.9	33.8	33.5	31.8	34.8	30.7
15	29.2	29.6	27.2	31.8	29.1	25.8	30.7	30.0	28.7	28.4	32.9	31.5	29.2	28.6	30.3	31.2	30.3	31.0	30.9	32.7	29.5	31.0	35.0	35.0
16	33.7	33.0	31.3	36.7	36.4	31.6	33.3	29.0	32.8	32.1	32.3	31.8	28.1	28.4	30.4	31.3	33.1	35.8	37.1	37.5	35.7	37.3	34.4	33.8
17	36.1	33.8	32.9	31.6	30.7	27.4	29.6	31.8	35.8	32.9	31.6	36.7	30.4	27.6	30.9	38.0	32.9	33.7	30.6	27.0	26.0	26.3	27.4	33.1
18	33.8	31.1	30.9	29.1	28.2	27.6	29.3	27.6	28.0	26.7	27.8	27.1	25.6	26.4	25.4	25.0	26.1	24.3	25.9	26.0	25.3	27.3	27.6	26.5
19	27.3	27.7	27.3	26.1	26.3	27.1	28.9	28.7	27.2	28.6	28.0	27.5	25.6	23.9	27.6	28.9	26.8	24.4	24.9	25.1	26.4	24.9	24.7	27.2
20	26.0	25.4	26.0	28.2	29.6	32.7	33.6	33.6	30.1	35.5	32.8	29.7	29.1	27.2	27.0	24.9	24.4	25.4	26.6	28.6	30.4	28.0	26.8	26.6
21	27.4	26.2	27.5	25.7	27.8	28.7	27.7	25.5	26.6	28.2	28.8	27.6	29.4	28.1	28.2	26.8	30.2	29.6	29.9	29.9	30.1	30.4	32.0	29.8
22	31.1	26.1	24.0	25.2	23.2	25.5	29.7	30.8	31.1	29.4	28.8	30.1	28.4	28.3	21.1	27.3	27.7	25.4	25.6	29.1	32.7	33.8	29.3	28.6
23	25.5	22.9	25.6	26.0	24.9	26.4	26.0	27.9	31.3	28.8	29.1	28.5	30.0	32.8	29.8	31.5	30.0	30.6	31.3	32.8	28.6	29.1	29.6	28.6
24	28.9	24.7	23.0	22.7	22.0	24.5	23.1	22.8	21.8	22.9	24.8	25.8	24.6	24.3	23.1	22.1	23.6	24.0	22.6	27.1	22.7	20.9	23.4	27.5
25	30.0	30.3	29.0	32.6	37.7	31.9	31.6	38.2	33.6	30.2	26.1	26.7	24.7	27.7	27.6	23.9	21.1	24.1	25.2	27.1	27.1	26.2	26.8	22.6
26	21.1	13.9	10.7	14.3	9.0	3.7	6.0	4.3	8.0	6.6	11.0	13.7	15.7	12.5	12.2	8.6	1.4	0.5	1.3	5.7	14.3	13.2	15.5	21.5
27	20.9	18.7	15.9	11.1	13.3	10.2	12.7	16.1	5.4	5.9	16.8	18.5	21.6	21.2	21.1	16.1	13.7	13.7	14.7	11.7	10.1	12.7	11.5	5.4
28	14.0	10.0	8.1	10.3	13.1	11.3	9.6	6.4	17.6	17.5	13.3	13.5	9.3	9.4	6.3	9.3	11.2	7.4	6.4	10.8	12.3	4.7	6.6	12.4
29	14.3	16.3	14.4	4.8	0.8	4.4	14.9	12.8	10.7	13.0	11.9	6.3	12.1	13.9	19.3	15.6	12.6	9.7	11.7	11.1	11.8	15.0	13.1	13.3
30	11.3	13.9	13.1	11.0	11.7	12.3	20.4	19.9	15.5	13.2	7.4	14.4	21.9	13.9	14.6	13.7	2.8	2.3	1.9	0.6	0.7	0.7	0.8	8.4
31	9.6	13.1	7.4	5.5	6.8	11.2	11.7	7.6	3.5	0.6	3.2	1.7	2.8	2.9	4.7	2.1	0.6	0.7	0.6	1.9	2.9	5.6	5.3	11.8

-1.0 indicates data not collected.

TABLE II

TYPICAL WIND SPEED DATA FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

	Hour of day																							
Day	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	36	31	30	30	34	36	36	33	36	36	46	40	42	42	42	40	40	42	38	44	44	38	34	32
2	32	36	34	38	38	38	30	20	20	15	14	14	14	20	20	20	28	27	24	30	36	30	28	28
3	20	22	20	18	18	16	21	14	10	6	4	10	10	20	10	16	20	22	22	22	24	28	30	30
4	28	30	30	26	29	21	18	14	16	16	12	12	14	12	10	12	18	20	21	26	32	28	24	22
5	24	26	33	30	20	12	12	13	6	11	4	10	14	10	12	12	18	22	26	30	30	20	12	2
6	10	18	20	18	9	15	8	14	8	10	6	12	10	15	12	14	14	18	24	25	24	22	16	18
7	16	18	12	18	2	6	7	8	8	6	10	10	8	10	14	14	16	12	14	21	22	24	22	24
8	20	18	16	11	6	10	4	0	0	0	8	12	10	15	22	24	22	26	30	34	38	42	40	36
9	40	40	32	30	25	25	28	36	28	30	30	22	36	38	32	34	38	42	46	44	40	50	50	50
10	42	42	38	28	23	18	16	14	20	14	12	20	14	8	16	14	26	28	28	30	28	28	28	24
11	24	24	25	28	20	10	4	7	6	10	16	12	10	16	16	20	24	34	32	40	36	36	38	40
12	38	38	42	40	44	15	40	42	37	10	28	28	36	40	38	36	46	44	48	47	42	44	40	32
13	26	22	30	20	20	21	24	22	24	23	20	20	20	14	22	26	34	37	42	38	34	35	36	38
14	38	33	30	24	18	20	20	18	20	20	18	24	20	30	38	32	34	34	10	56	55	60	60	55
15	24	46	44	34	34	32	34	40	30	28	32	30	24	21	40	40	42	48	42	46	48	38	36	36
16	38	42	40	36	42	30	26	32	26	26	20	20	18	14	26	28	35	32	32	22	20	36	32	14
17	24	20	22	20	30	30	1	12	20	20	22	20	20	20	30	32	30	34	30	30	22	28	30	22
18	12	12	15	20	8	15	20	20	20	20	14	10	18	20	20	24	20	30	25	30	28	30	30	32
19	30	30	30	38	30	30	24	25	28	22	20	20	30	20	34	30	36	34	42	37	38	40	44	36
20	32	34	32	36	34	36	26	22	24	20	18	20	20	18	20	22	20	22	22	26	30	22	22	24
21	18	18	18	20	10	8	12	8	0	6	8	10	10	10	10	14	18	16	24	27	27	26	26	20
22	20	18	18	10	18	18	14	14	18	12	10	12	14	8	10	14	16	25	30	28	28	26	26	30
23	24	28	24	24	22	22	14	12	10	20	19	14	15	14	14	24	28	26	24	21	28	30	26	28
24	26	24	24	20	12	12	10	3	6	8	14	14	10	14	18	26	30	30	38	36	30	30	30	30
25	30	28	20	16	10	5	4	2	4	14	12	14	14	10	10	10	18	16	15	14	13	14	10	12
26	10	11	12	12	10	14	16	18	24	27	26	23	18	18	14	15	13	12	14	20	24	22	14	14
27	16	14	18	16	16	22	24	12	14	18	22	20	20	26	32	32	40	36	40	50	50	44	50	50
28	42	48	50	50	50	40	30	37	32	24	28	28	22	24	30	32	34	48	50	42	50	50	50	50
29	46	50	48	46	40	38	32	28	20	14	10	6	10	16	20	26	24	23	20	30	34	35	30	20
30	18	14	9	10	12	13	9	11	16	18	18	16	16	12	12	6	20	21	28	26	30	36	36	30
31	20	22	20	10	14	18	18	0	12	6	8	16	20	18	16	18	24	24	20	22	22	22	28	30

inputs. The anemometer at the Hawaiian site is located 30 feet above ground and is on a lookout tower approximately 30 feet above the ground at the California site.

Several probability models have been suggested (45, 46) to model wind speed distributions. Even at a particular site, different models may be required to approximate the wind behavior during different seasons. The Chi-square (Rayleigh) distribution given by the density function

$$f(v) = \frac{\pi}{2} \frac{v}{m_v^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{m_v}\right)^2\right] \qquad (2.1)$$

has been found to be a reasonable fit to the observed velocity magnitude distribution by several workers (46, 47) including Corotis et al.

The Chi-square distribution is a single parameter (mean speed 'm_v') distribution and is fairly easy to use since it requires only one quantity, namely, the mean wind speed.

The Weibull distribution given by the density

$$f(v) = \beta \frac{v^{\beta-1}}{\alpha^{\beta}} \exp\left[-\left(\frac{v}{\alpha}\right)^{\beta}\right] \qquad (2.2)$$

is an improvement over the Chi-square distribution, but it requires two parameters (α and β) to be evaluated from the values of the mean wind speed and the vaiance. When $\beta = 2$ and $\alpha = 2m_v/\sqrt{\pi}$, the Weibull distribution reduces to the Chi-square distribution.

Using the hourly wind speed data at the Hawaiian site, 'Kahuku Upper,' and at the California site 'Livermore,' values of mean and variance were computed for each month of the year for the Hawaiian site and for two months for the California site. The parameters α and β for the Weibull distribution were determined from the sample mean and variance using the following well known relations:

$$m_v = \alpha\, \Gamma\left(1 + \frac{1}{\beta}\right) \tag{2.3}$$

$$\left(\frac{\sigma_v}{m_v}\right)^2 = \frac{\Gamma\left(1 + \frac{2}{\beta}\right)}{\Gamma^2\left(1 + \frac{1}{\beta}\right)} - 1 \tag{2.4}$$

The values are tabulated in Tables III and IV. An examination of Table III shows that there is a wide variation in the value of the parameter β at the site 'Kahuku Upper.' This variation and its influence on the value of the parameter α complicate the approach to WECS reliability studies. In general, the parameter β has a low value (2 to 3) for low mean wind speed (less than 13 mi/h) months with low variance (less than 40) or for high mean wind speeds (above 13 mi/h) months with high variance (above 40). The β value is high (3 to 7) for high mean wind speed months with low variance. A good compromise value appears to be around 4. If the mean wind speed is very low, or very high with extremely large variations, the β value necessary for good representation may be even lower (as low as 1.5). A wind regime with high mean wind speed and low variance requires a β value of larger than 4. The wind speed value of 13 mi/h separating the different wind regimes is not rigorous. A slight variation is possible depending on the site. The values of the parameter β for the months of January and May, 1974, for the Livermore site are 1.41 and 2.22, respectively. Both low mean wind speed and high mean wind speed months have low values for the

TABLE III

WIND STATISTICS AND VALUES OF α AND β FOR THE SITE 'KAHUKU UPPER'

Month and Year	Mean m_v mi/h	Variance σ_v^2	β	α
Apr 76	20.34	28.19	4.33	22.34
May 76	18.59	10.15	6.85	19.89
Jun 76	17.12	22.52	4.05	18.87
Jul 76	18.86	12.80	6.13	20.30
Aug 76	17.86	18.41	4.74	19.51
Sep 76	14.94	20.99	3.62	16.57
Oct 76	15.60	22.38	3.67	17.29
Nov 76	16.78	31.77	3.27	18.72
Dec 76	18.12	31.54	3.58	20.11
Jan 77	13.78	28.04	2.81	15.47
Feb 77	16.91	65.17	2.20	19.09
Mar 77	24.96	77.40	3.10	27.90
Apr 77	19.58	68.48	2.53	22.06
May 77	18.93	49.77	2.91	21.23
Jun 77	19.37	19.71	4.99	21.10
Jul 77	22.34	19.43	5.88	24.10
Aug 77	18.38	17.42	5.04	20.01
Sep 77	15.97	19.43	4.07	17.60
Oct 77	14.41	17.06	3.91	15.92
Nov 77	10.31	21.80	2.35	11.64
Dec 77	11.43	23.60	2.51	12.88
Jan 78	10.97	17.55	2.83	12.31
Feb 78	12.28	22.56	2.80	13.80

parameter β because of very high values for the variance (97.21 and 130.35). It is encouraging to note that the discussion regarding the parameter β for the Hawaiian site holds good for the California site also.

TABLE IV

WIND STATISTICS AND VALUES OF α AND β FOR THE SITE 'LIVERMORE'

Month and Year	Mean m_v mi/h	Variance σ_v^2	β	α
January 1974	13.71	97.21	1.41	15.05
May 1974	24.06	130.35	2.22	27.17

To illustrate the fitness of the various mathematical models to the actual data, three distributions are plotted in Figure 2 for the month of August, 1976, for the Hawaiian site ('Kahuku Upper'), and in Figure 3 for the month of May, 1974, for the California site ('Livermore'). Each figure has three curves: a) actual distribution obtained from measured data; b) Weibull distribution using a β value 4 and the corresponding α computed from the mean wind speed and Equation (2.3), and c) Weibull distribution with values of α and β computed from the mean wind speed and variance using Equations (2.3) and (2.4).

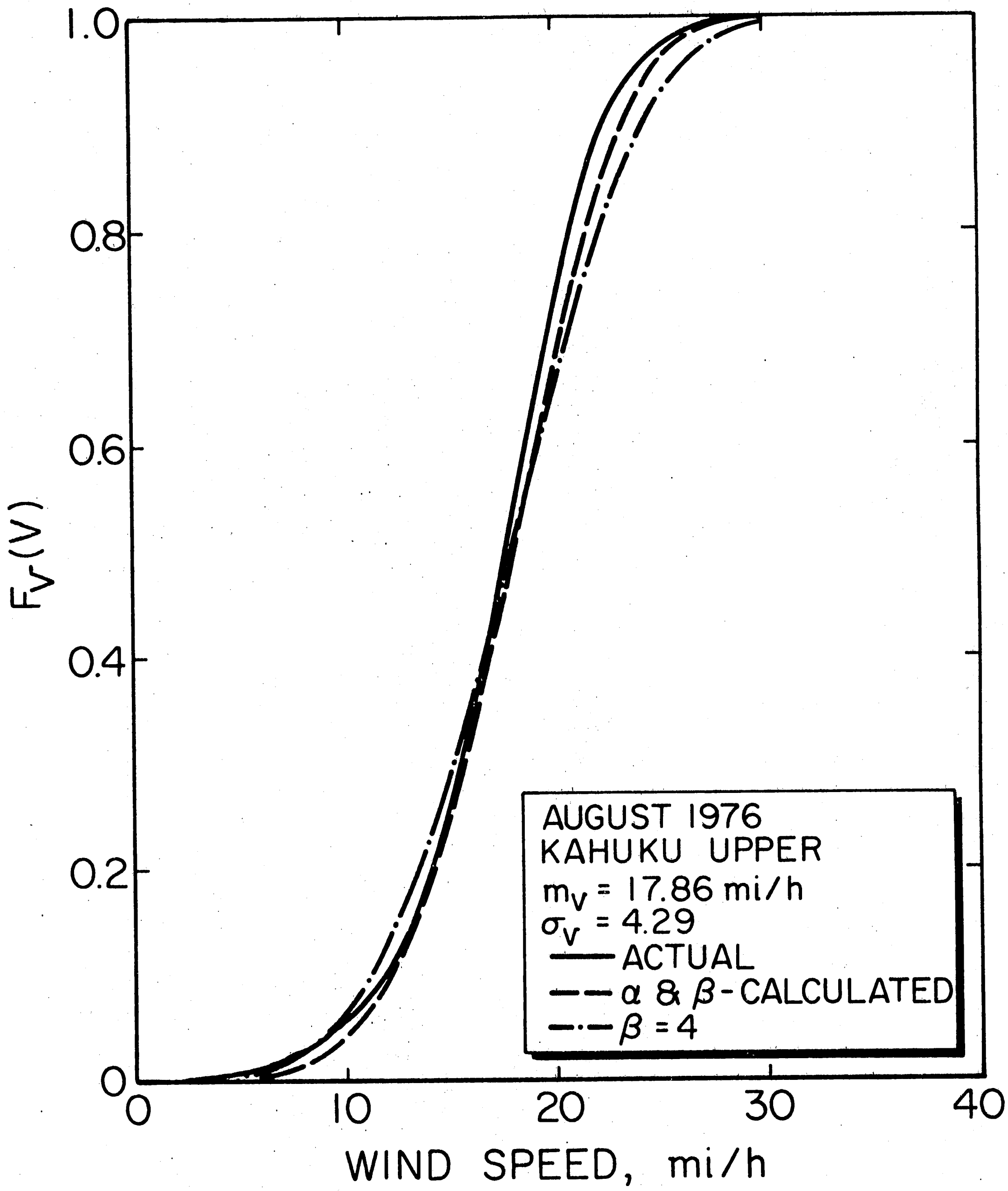


Figure 2. Actual and Calculated Distributions of Wind Speed for the Month of August, 1976, for the Site 'Kahuku Upper'

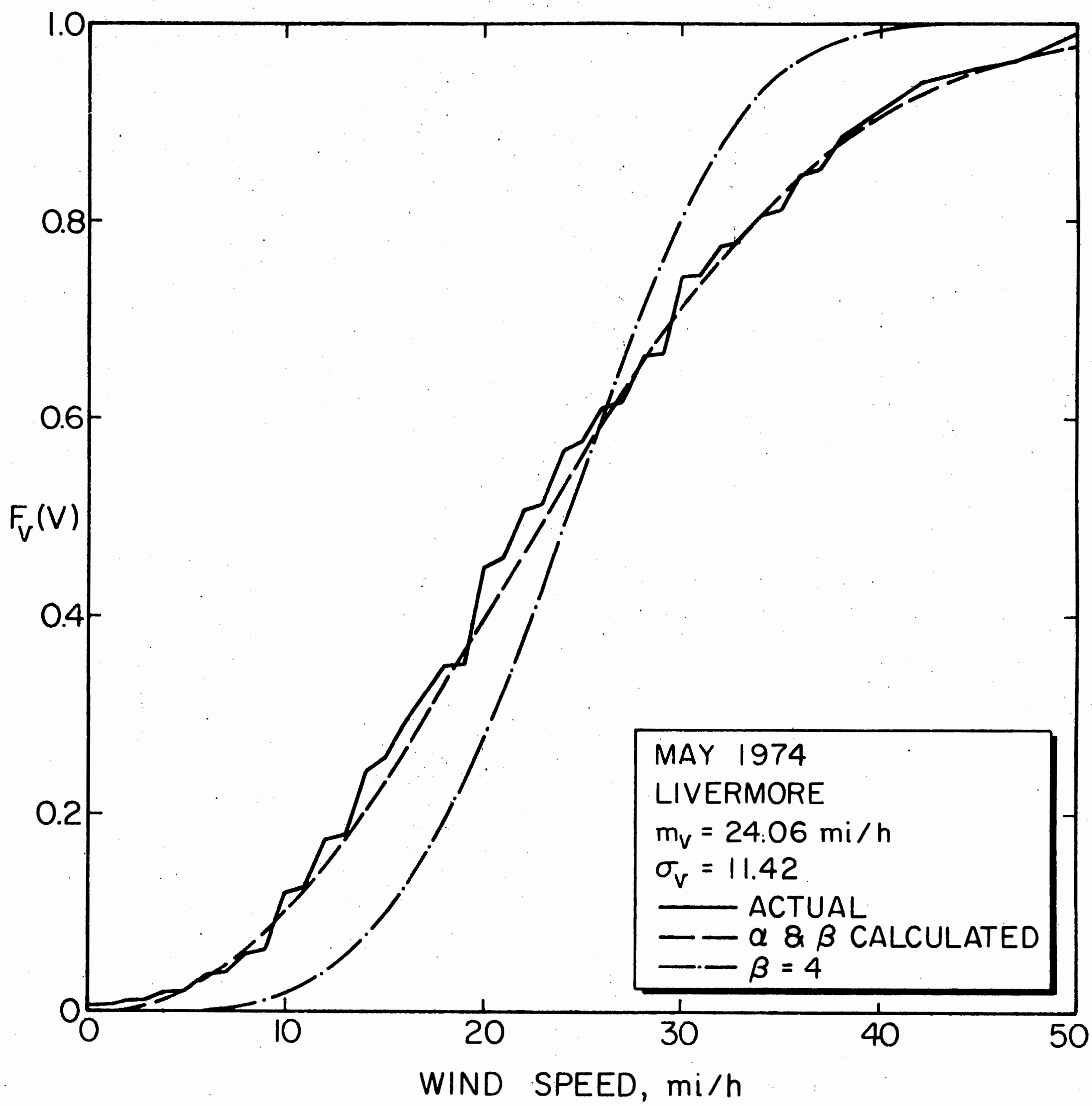


Figure 3. Actual and Calculated Distributions of Wind Speed for the Month of May, 1974, for the Site 'Livermore'

The actual distribution of the measured hourly wind speed is obtained by first calculating the total number of hours each of the speeds occurred during the study period (usually one month). These numbers are then expressed as fractions of the study period and plotted in a cumulative fashion, starting with the lowest wind speed of interest.

The Weibull distribution corresponding to a chosen value of β and a known mean wind speed (m_V) is simply the plot of the distribution function, $F_V(V)$, given by

$$F_V(V) = 1 - \exp\left[-\left(\frac{V}{\alpha}\right)^{\beta}\right] \tag{2.5}$$

in which the value of α is found from Equation (2.3).

If both the mean and variance of wind speed are known, then the parameters α and β can be computed using Equations (2.3) and (2.4), and Equation (2.5) is replotted.

Figures 4 and 5 show plots similar to Figure 2 for the months of March and November, 1977, for the Hawaiian site, and Figure 6 shows the plots for the month of January, 1974, for the California site. The three months selected for the study of the Hawaiian site represent typical average (August, 1976), maximum (March, 1977), and minimum (November, 1977) values of mean wind speed and the two months selected for the study of the California site represent the maximum (May, 1974) and the minimum (January, 1974) values of mean wind speed.

An examination of Figures 2 through 6 shows that the mathematical models fit reasonably well with the actual distributions except when the variance is very high (the month of March, 1977, for the Hawaiian site and the months of May and January, 1974, for the California site).

Corotis et al. (46) showed that the Weibull model used in modeling wind speed distribution passes the Kolmogorov-Smirnov fitness test in most cases. Hence, it is believed that in all cases, the models are adequate for reliability calculations.

The most commonly used characteristics in the design and study of WECS, however, is the wind speed-duration curve. This is a plot of wind speed versus time (usually hours)--the speed greater than or equal to the value in question. The procedure for obtaining the wind speed-duration curve is outlined below.

From the measured hourly wind speed data, different values of wind speeds and the total number of hours each of the speeds occurred during the study period are collected and rearranged in the descending order of wind speeds. Corresponding to each of the wind speed values, a cumulative sum indicating the number of hours that particular speed was greater than or equal to the value in question is calculated. The required wind speed-duration curve is obtained by plotting the wind speed versus the cumulative time.

The procedure to calculate the data for use in the plot of wind speed-duration curve based on the Weibull distribution function is given below.

The distribution function gives the probability of occurrence of speeds less than or equal to the speed used in the distribution function. The value of this function corresponding to each wind speed is multiplied by the total duration (hours) under consideration, and the numbers obtained are tabulated first. From this table, the total number of hours each of the wind speeds occurred during the study period is computed. Then a procedure similar to the one used in the case of

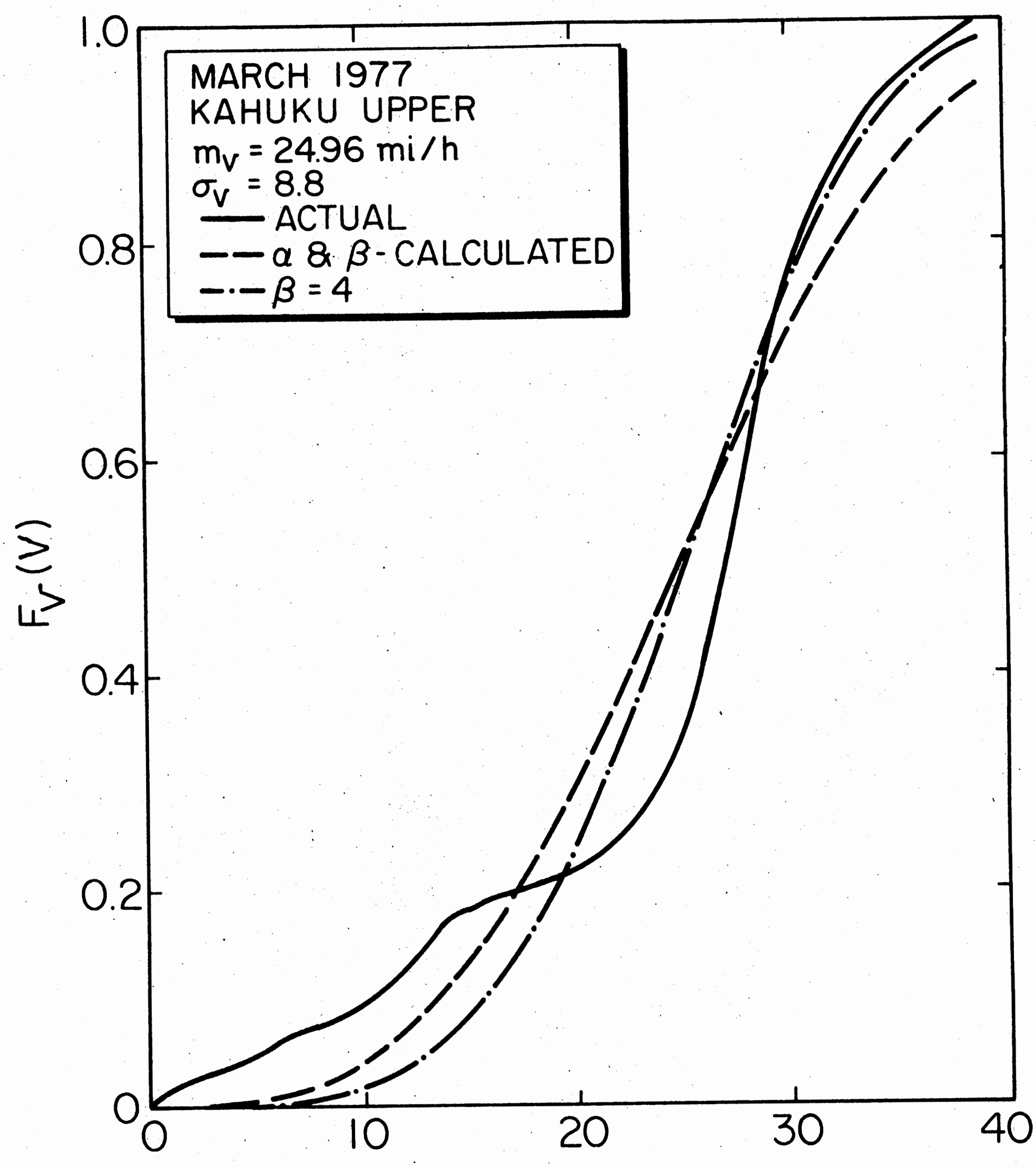


Figure 4. Actual and Calculated Distributions of Wind Speed for the Month of March, 1977, for the Site 'Kahuku Upper'

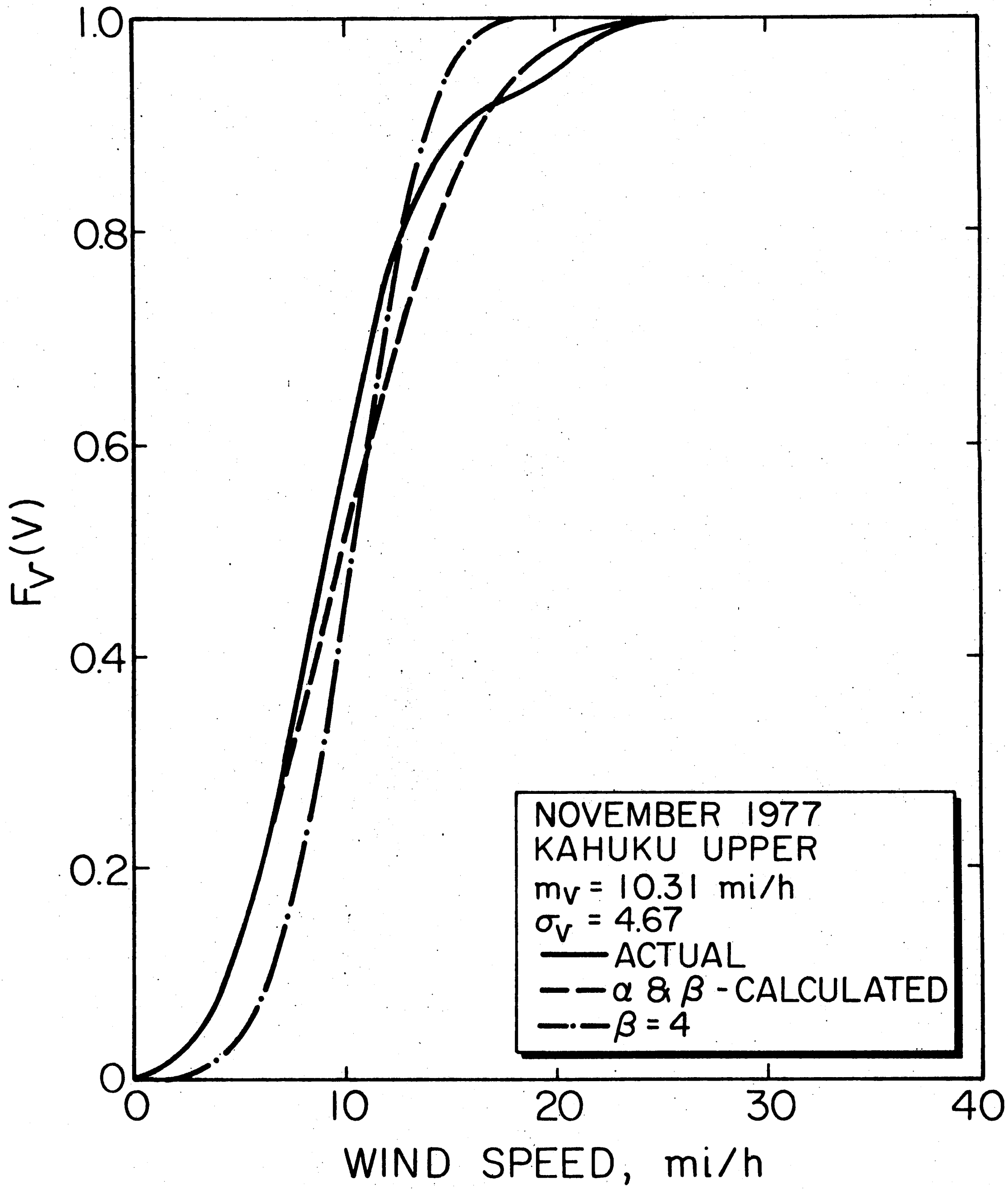


Figure 5. Actual and Calculated Distributions of Wind Speed for the Month of November, 1977, for the Site 'Kahuku Upper'

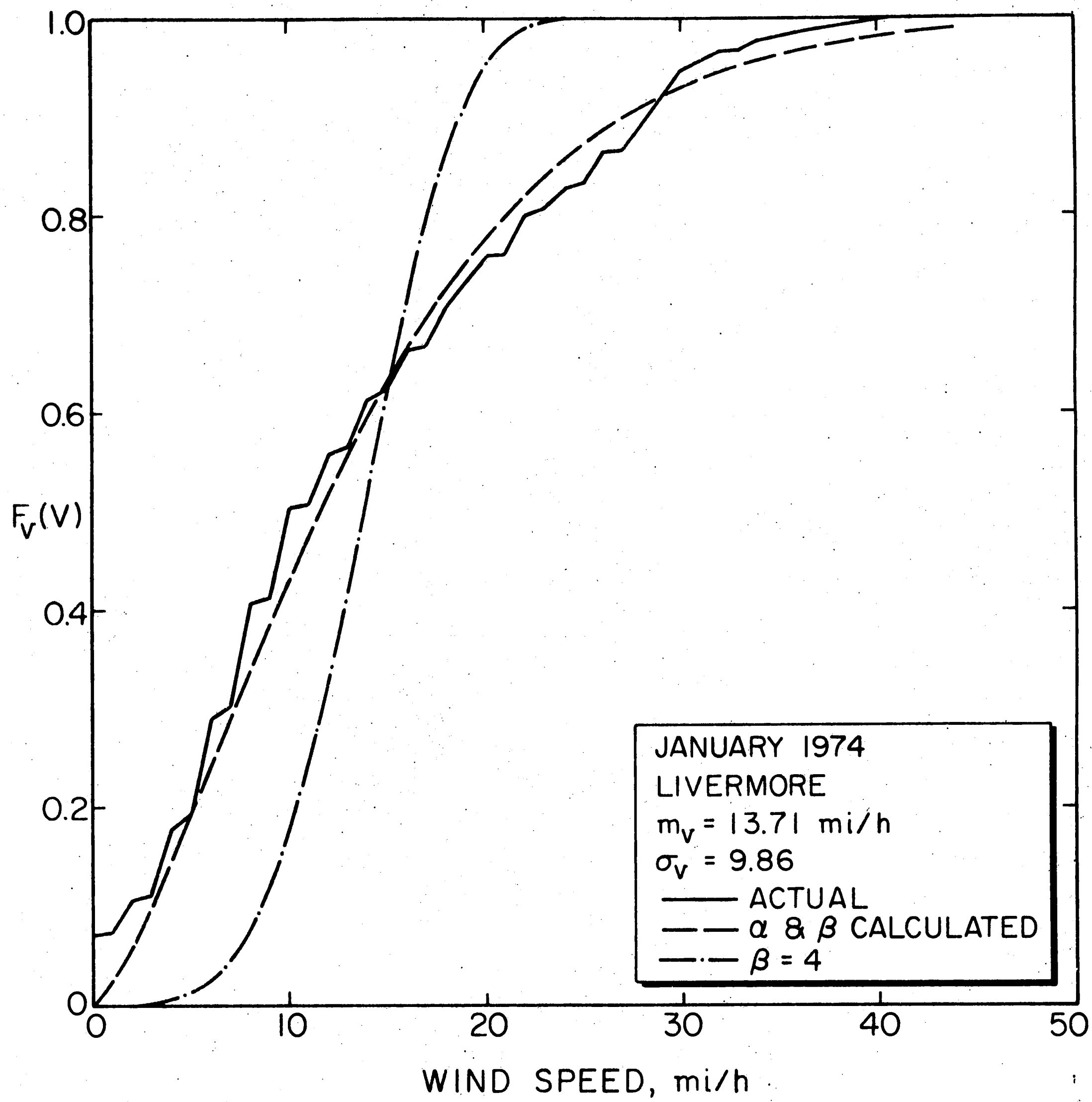


Figure 6. Actual and Calculated Distributions of Wind Speed for the Month of January, 1974, for the Site 'Livermore'

measured hourly wind speed data yields the required wind speed-duration curve. Typical wind speed-duration curves are shown in Figures 7, 8, and 9 for the Hawaiian site, and in Figures 10 and 11 for the California site. Since the wind speed-duration curves are derived from the wind speed distribution curves, the discussion regarding the actual distribution and the models is valid.

2.3 WECS Capacity Outage Probabilities

The electrical output of a WECS depends mainly on the wind characteristics. It also depends on the aeroturbine performance and the efficiency of the electric generator. These three factors must be combined to obtain a probabilistic profile (capacity outage probability) of the WECS output.

2.3.1 Aeroturbine and Generator Characteristics

The present trend in large WECS design and development is to employ the constant (or nearly constant) -speed constant-frequency approach (48). The aeroturbine is operated at a constant speed and a synchronous machine converts the mechanical input to constant-frequency electrical output. When induction generators are employed, the aeroturbines must slip a little and consequently operate at a nearly constant speed. In either case, the unit starts delivering electrical output at a wind speed called the cut-in speed and reaches the rated electrical output at a wind speed called the rated speed. The electrical output is maintained constant (at the rated value) for further increases in wind speed (by appropriate blade pitch control) up to the cutout (furling) speed, beyond which the unit is shut down for safety

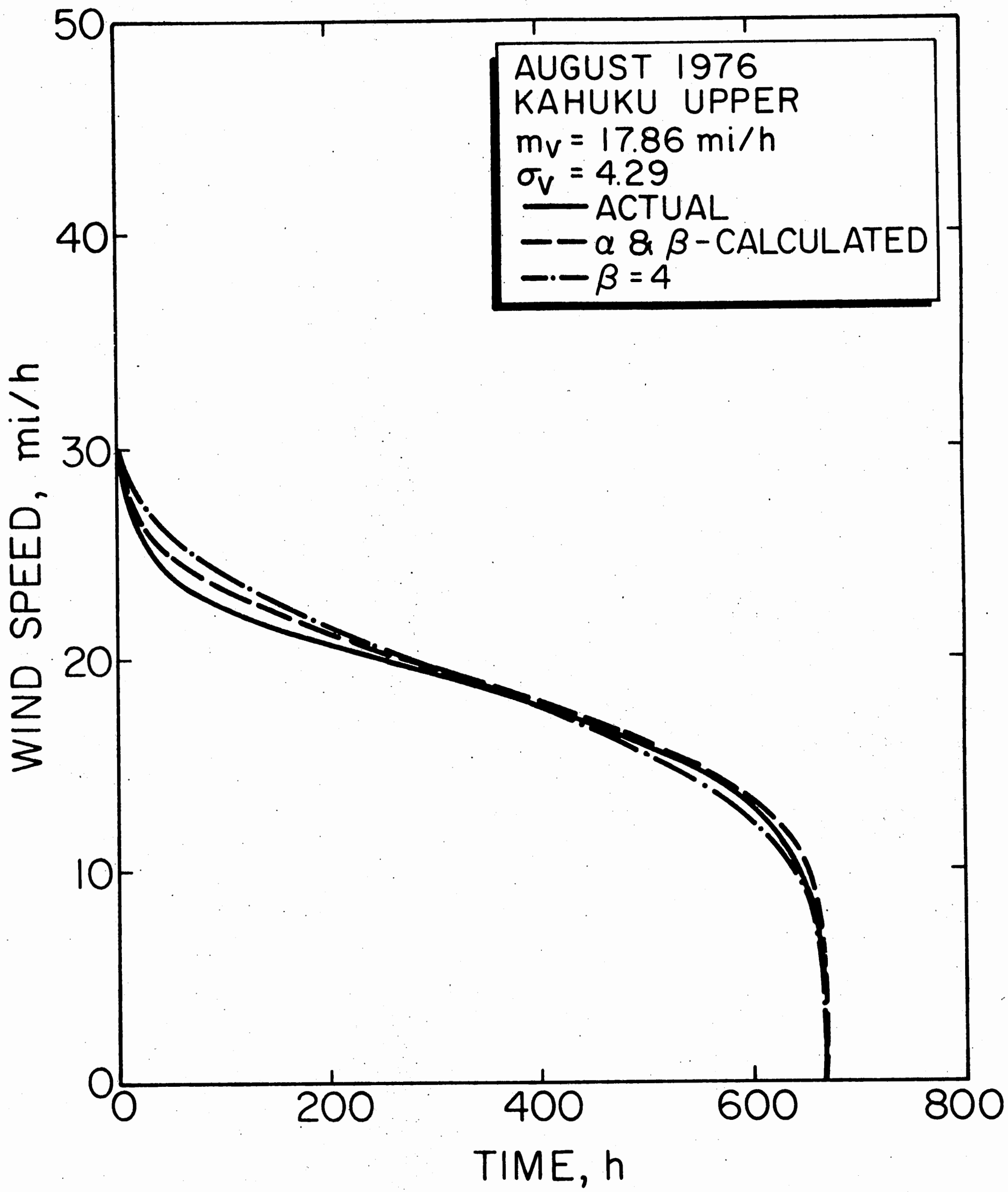


Figure 7. Wind Speed-Duration Curves for the Month of August, 1976, for the Site 'Kahuku Upper'

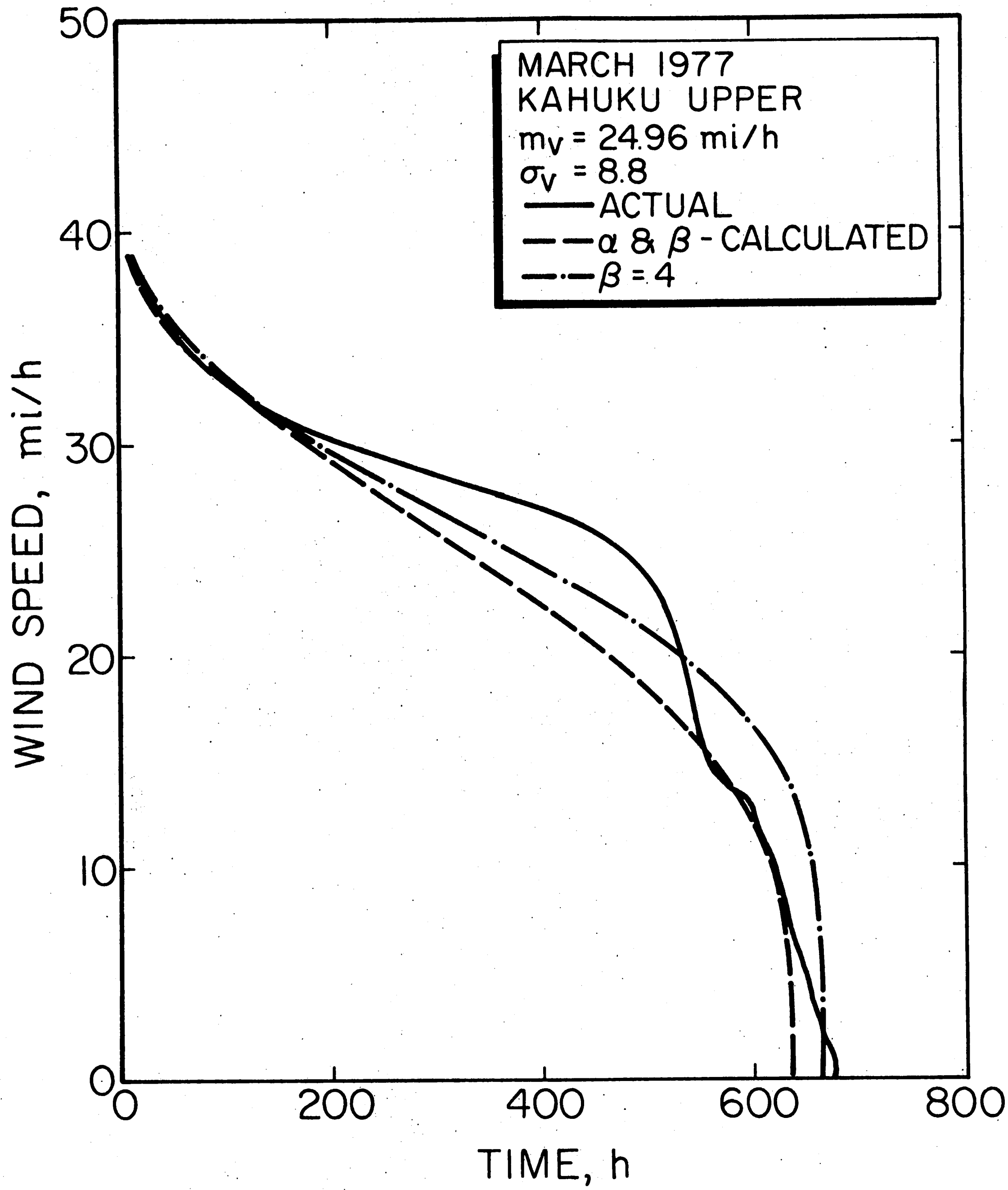


Figure 8. Wind Speed-Duration Curves for the Month of March, 1977, for the Site 'Kahuku Upper'

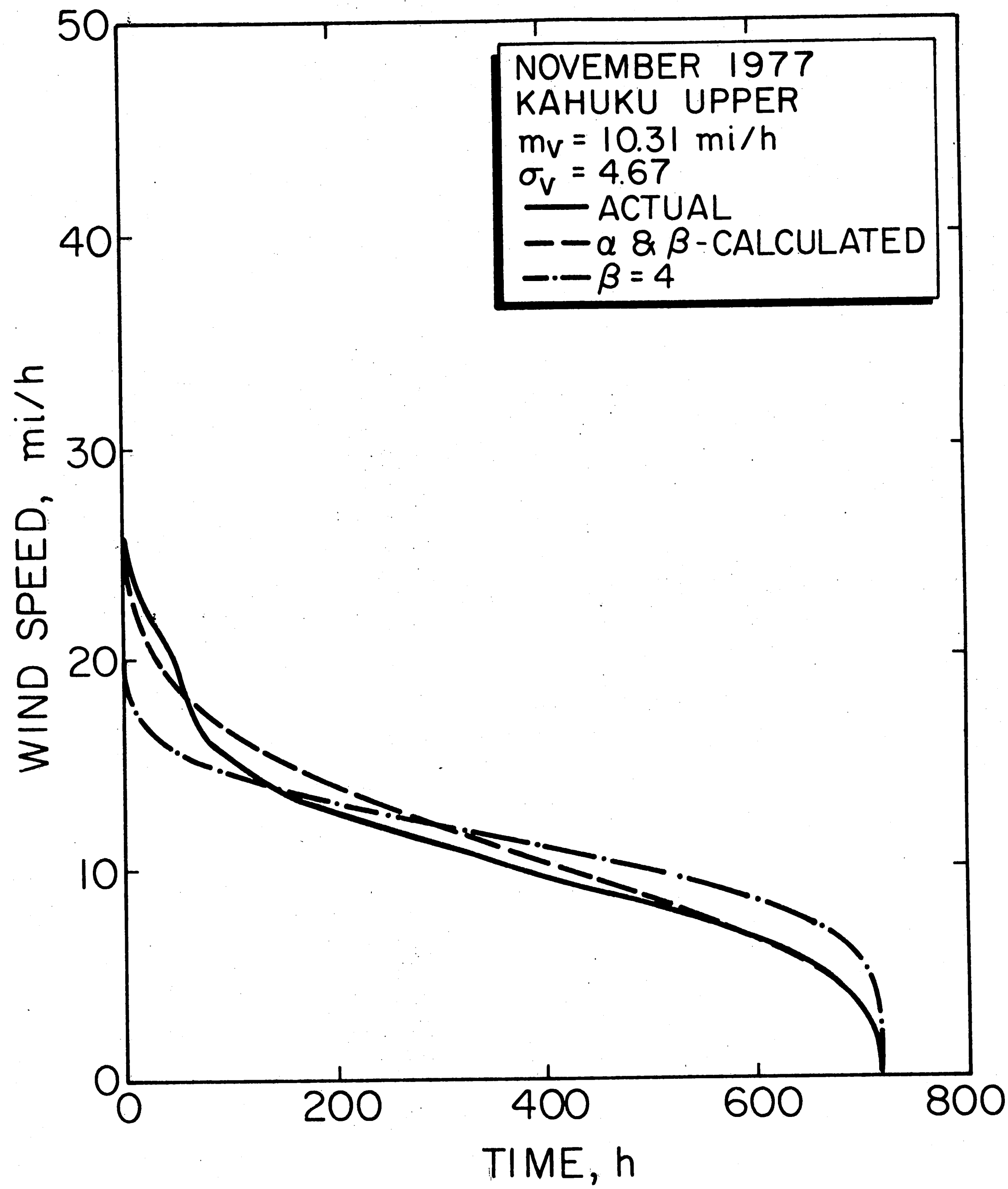


Figure 9. Wind Speed-Duration Curves for the Month of November, 1977, for the Site 'Kahuku Upper'

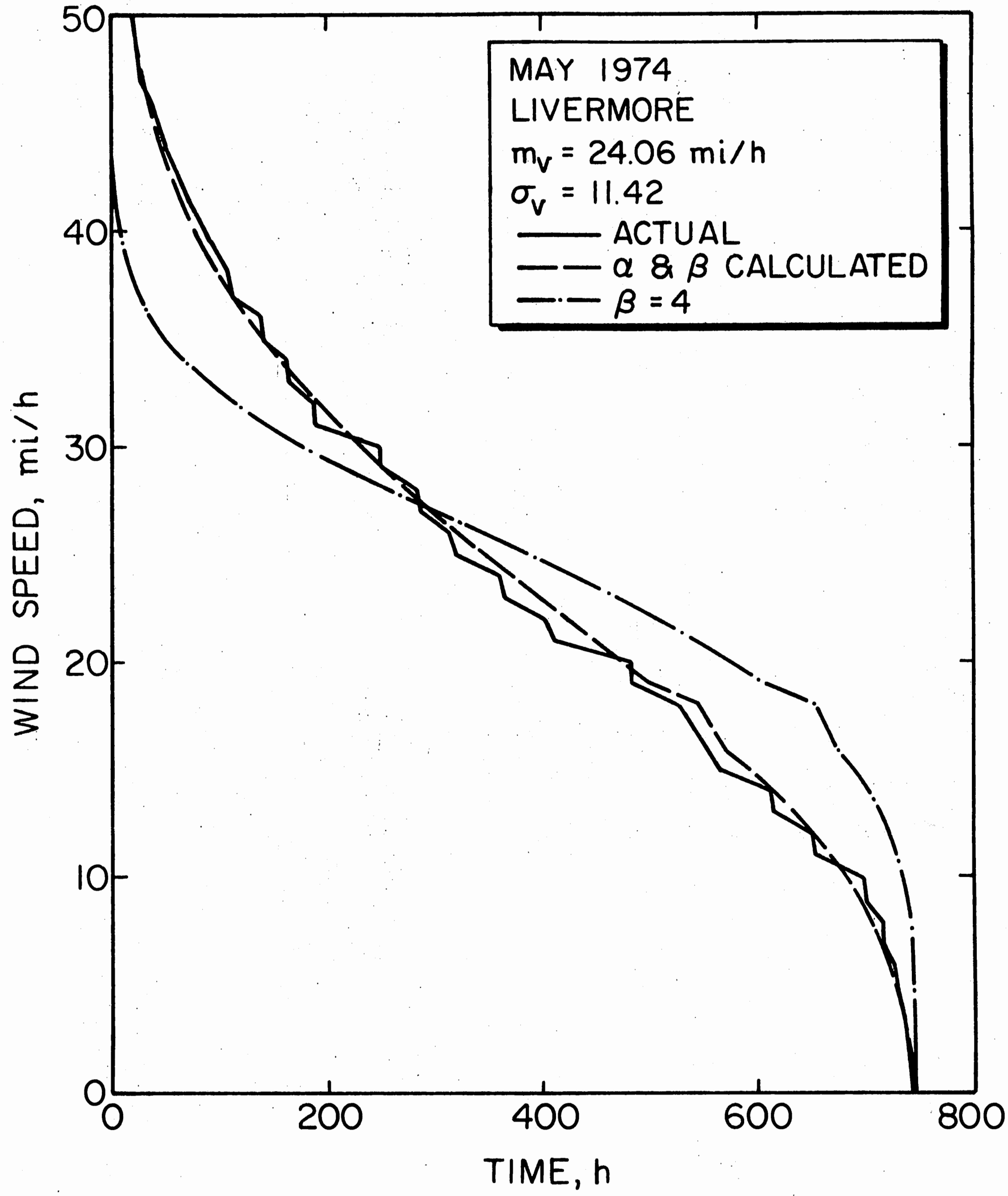


Figure 10. Wind Speed-Duration Curves for the Month of May, 1974, for the Site 'Livermore'

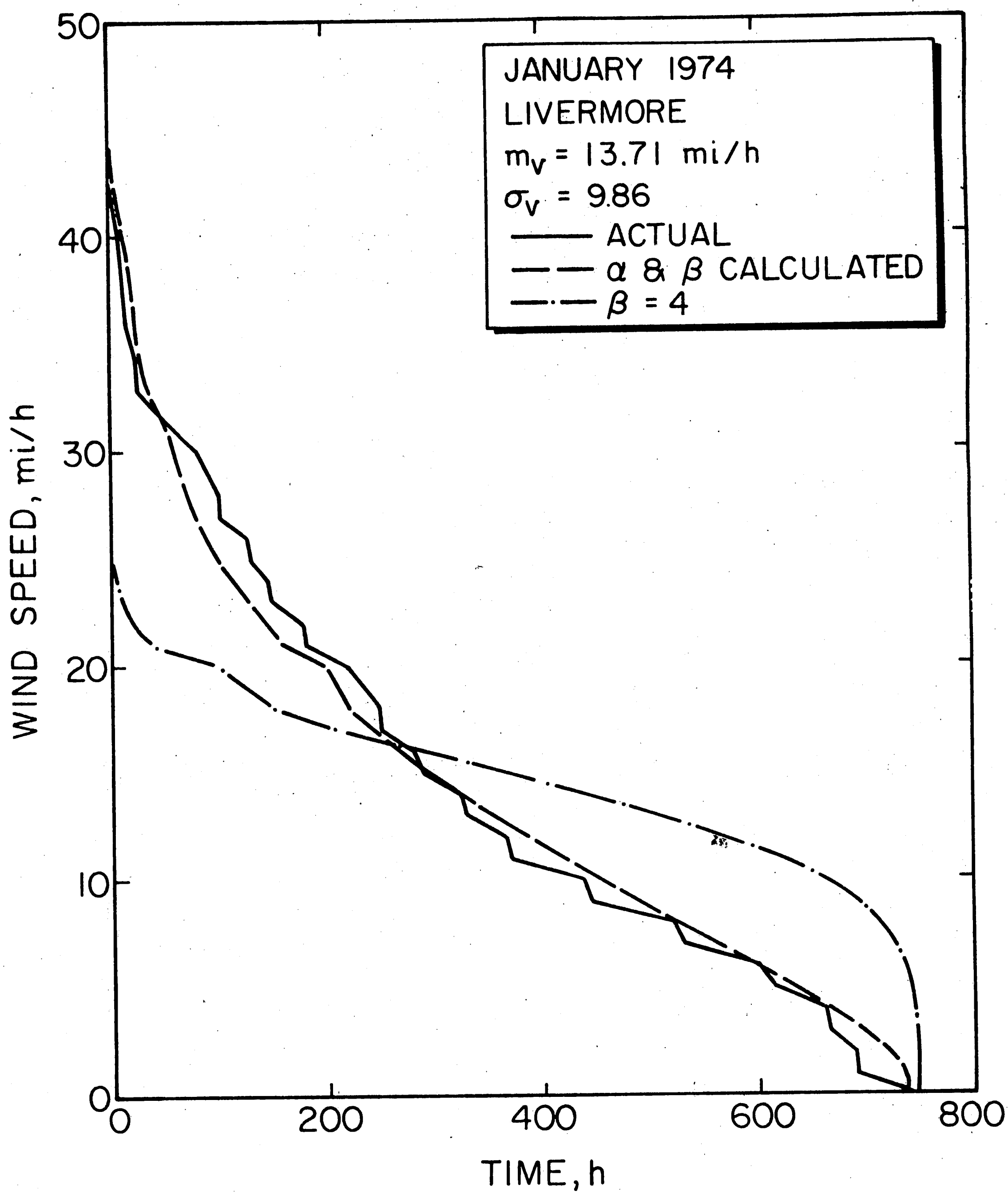


Figure 11. Wind Speed-Duration Curves for the Month of January, 1974, for the Site 'Livermore'

reasons.

Figure 12 shows the typical operating characteristics of a large WECS. For the DOE/NASA-Lewis 100 kW MOD-0 unit (49), the cut-in speed is 10 mi/h, the rated speed is 18 mi/h, and the furling speed is 40 mi/h. The 2000 kW MOD-1 design (by NASA-LeRC) employs a cut-in speed of 11 mi/h, rated speed of 25 mi/h, and a cut-out speed of 35 mi/h (50).

Between the cut-in and the rated speeds, the relationship between the electrical output and the wind speed is non-linear due to the combined effects of aeroturbine (coefficient of performance versus tip speed ratio) and generator (efficiency versus output) characteristics.

2.3.2 WECS Capacity Outage

Because of constant variations in the wind input, the output of a WECS lies between zero and the rated value for nearly half of the time (or even longer for poor wind regime months). This is analogous to unscheduled outages of conventional generating units and as such can be included in reliability studies in a similar manner.

If over a long period of time, T, the output of a WECS is C_{wk} for a total period of time, T_k, then the availability, A_{wk}, of the capacity, C_{wk}, is given (with mechanical outages neglected) by

$$A_{wk} = \frac{T_k}{T} \qquad (2.6)$$

in which both T_k and T have the same units of time (usually hours) and T does not include any time during which the unit was down for scheduled maintenance. It follows from this that A_{wk} is also the probability of outage of capacity, O_k, where

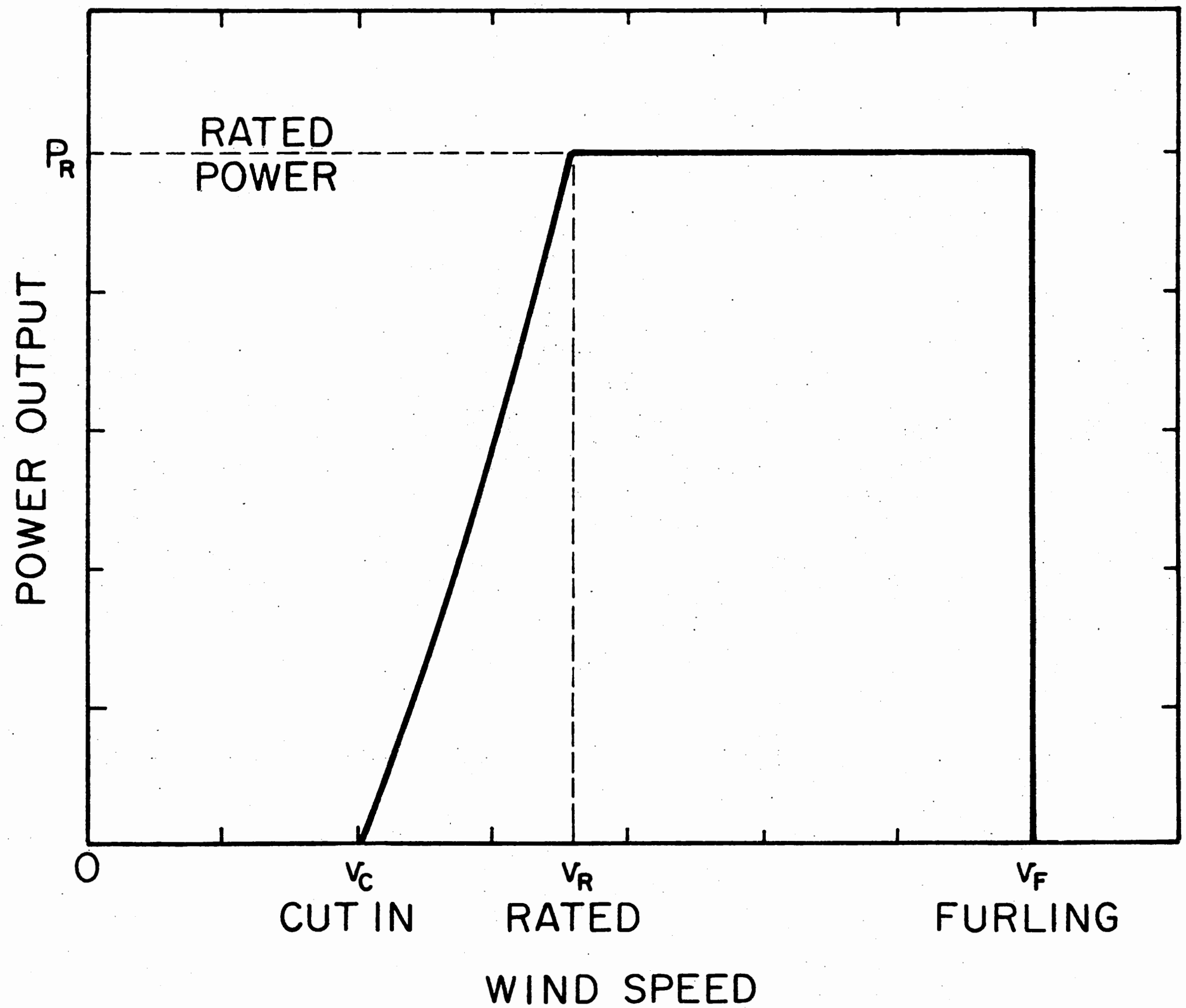


Figure 12. Typical Electrical Output Characteristics of a Large WECS

$$O_k = (C_w - C_{wk}) \tag{2.7}$$

The nature of the WECS output is such that several partial capacity states may be necessary to model its behavior. The number of such states to be considered depends upon the type of wind data available, the nature of the wind regime, characteristics of the electrical components, availability of computational time, and the accuracy desired.

The wind speed data for the Hawaiian site are available to the first decimal place accuracy (see Table I). Use of such data directly for the development of WECS model will require a large number of partial capacity states. To reduce the number of partial capacity states to a reasonable value without unduly compromising the accuracy requires the modification of such wind speed data by rounding off the data to the nearest integer. Table V shows such modified data for the month of March, 1977, for the Hawaiian site. The wind speed data for the California site is already available in the modified form. These data can be handled by employing nine output capacity states in all (on the basis of integer values of wind speeds and the characteristics of the MOD-0 NASA Lewis wind turbine generator) for the WECS. A full capacity state for WECS corresponds to a wind speed greater than or equal to 18 mi/h but less than or equal to 40 mi/h. A zero capacity output state corresponds to wind speeds greater than 40 mi/h or less than or equal to 10 mi/h. A partial capacity output state is assigned to each one mile increment in wind speed above 10 mi/h up to and including 17 mi/h. Once the number of states is selected, the required probabilities can be obtained by combining the WECS output characteristics and the wind speed-duration curve (actual or any one of the mathematical models

TABLE V

TYPICAL MODIFIED WIND SPEED DATA FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

Day	Hour of day																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	28	26	26	27	30	33	31	29	32	30	30	27	28	32	30	28	28	27	27	28	28	26	26	29
2	32	29	27	26	25	27	26	25	26	27	28	32	30	30	30	29	29	30	28	28	28	27	27	27
3	29	27	27	26	26	27	29	27	28	29	30	31	34	31	24	25	24	27	28	29	27	27	27	27
4	27	29	30	27	24	28	29	29	28	29	28	28	28	25	29	28	--	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
6	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
7	--	--	--	--	--	--	--	--	--	--	--	--	--	33	32	32	31	34	33	30	29	27	29	29
8	29	30	30	30	27	27	28	26	28	30	29	34	33	37	37	32	31	30	30	30	30	31	27	27
9	29	28	26	28	31	30	30	25	24	25	24	24	20	23	28	28	27	27	21	20	18	18	17	19
10	20	14	14	19	24	27	25	23	24	26	26	25	24	26	28	29	26	27	26	26	26	25	27	27
11	28	25	24	28	29	31	31	30	28	29	31	29	20	28	32	30	32	26	34	32	26	30	35	33
12	34	35	39	37	38	39	37	34	38	35	33	36	31	30	32	30	28	31	24	23	19	22	22	24
13	28	28	27	26	24	26	26	29	31	29	34	38	37	37	39	39	39	38	39	39	38	37	36	35
14	36	38	36	35	34	34	34	36	35	37	35	35	34	34	32	28	30	30	34	34	34	32	35	31
15	29	30	27	32	29	26	31	30	29	28	33	32	29	29	30	31	30	31	31	33	30	31	35	35
16	34	33	31	37	36	32	33	29	33	32	32	32	28	28	30	31	33	36	37	38	36	37	34	34
17	36	34	33	32	31	27	30	32	36	33	32	37	30	28	31	38	33	34	31	27	26	26	27	33
18	34	31	31	29	28	28	29	28	28	27	28	27	26	26	25	25	26	24	26	26	25	27	28	27
19	27	28	27	26	26	27	29	29	27	29	28	28	26	24	28	29	27	24	25	25	26	25	25	27
20	26	25	26	28	30	33	34	34	30	36	33	30	29	27	27	25	24	25	27	29	30	28	27	27
21	27	26	28	26	28	29	28	26	27	28	29	28	29	28	28	27	30	30	30	30	30	30	32	30
22	31	26	24	25	23	26	30	31	31	29	29	30	28	28	21	27	28	25	26	29	33	34	29	29
23	26	23	26	26	25	26	26	28	31	29	29	29	30	33	30	32	30	31	31	33	29	29	30	29
24	29	25	23	23	22	25	23	23	22	23	25	26	25	24	23	22	24	24	23	27	23	21	23	28
25	30	30	29	33	38	32	32	38	34	30	26	27	25	28	28	24	21	24	25	27	27	26	27	23
26	21	14	11	14	9	4	6	4	8	7	11	14	16	13	12	9	1	1	1	6	14	13	16	22
27	21	19	16	11	13	10	13	16	5	6	17	19	22	21	21	16	14	14	15	12	10	13	12	5
28	14	10	8	10	13	11	10	6	18	18	13	14	9	9	6	9	11	7	6	11	12	5	7	12
29	14	16	14	5	1	4	15	13	11	13	12	6	12	14	19	16	13	10	12	11	12	15	13	13
30	11	14	13	11	12	12	20	20	16	13	7	14	22	14	15	14	3	2	2	1	1	1	1	8
31	10	13	7	6	7	11	12	8	4	1	3	2	3	3	5	2	1	1	1	2	3	6	5	12

discussed earlier) for the site under consideration.

Typical capacity outage probability data for a WECS is shown in Table VI for the Hawaiian site, and Table VII for the California site. The values calculated are based on the characteristics of the DOE/NASA 100 kW MOD-0 system. However, they are valid for other systems also if their characteristics are similar to the MOD-0 unit and if the numbers indicating kW are considered as percentages of rated output.

A comparison of the probabilities of outages of capacities obtained using the mathematical models agree, for the most part, with the values obtained from actual data. The exception is the model with an assumed β of 4 for the months of March and November, 1977, for the Hawaiian site and for the months of January and May, 1974, for the California site. Based on the earlier discussion regarding the selection of the parameter β, the wind regimes of the two months mentioned above for the Hawaiian site qualify for a lower value of β, say 3. The wind regimes during the two months considered for the California site qualify for a still lower value of β, say 2. Tables VIII and IX show the results based on $\beta = 3$ for the Hawaiian site and $\beta = 2$ for the California site along with the values based on actual data for the respective months. It is seen that the agreement in the probability values of states is closer with a properly selected (based on variability) β value.

2.3.3 Combined Systems

The wide variations and the associated uncertainties in WECS outputs are fundamentally contradictory to providing a reliable electric supply to consumers. Obviously, one has to employ some type of storage

TABLE VI

CAPACITY OUTAGE PROBABILITY TABLE FOR WECS FOR THE SITE 'KAHUKU UPPER'

Wind Speed mi/h	Cap. Out kW	Cap. In kW	Probability of States: August, 1976 — Actual	$\beta = 4$	α and β Calculated
≥ 18 ≤ 40	0	100	0.5680119	0.5729079	0.5945981
17	16	84	0.0881913	0.0731208	0.0825419
16	30	70	0.0852017	0.0675933	0.0733633
15	44	56	0.0642750	0.0605413	0.0626239
14	58	42	0.0568012	0.0525704	0.0514387
13	70	30	0.0343797	0.0442572	0.0406937
12	80	20	0.0284006	0.0360986	0.0310011
11	92	8	0.0164424	0.0284816	0.0227074
> 40 ≤ 10	100	0	0.0582960	0.0644287	0.0410318
			March, 1977		
≥ 18 ≤ 40	0	100	0.8029630	0.8623770	0.7947085
17	16	84	0.0029630	0.0279708	0.0321635
16	30	70	0.0118519	0.0238625	0.0291907
15	44	56	0.0059259	0.0200043	0.0261464
14	58	42	0.0251852	0.0164599	0.0230920
13	70	30	0.0222222	0.0132717	0.0200842
12	80	20	0.0192593	0.0104635	0.0171752
11	92	8	0.0162963	0.0080420	0.0144096
> 40 ≤ 10	100	0	0.0933333	0.0175482	0.0430298
			November, 1977		
≥ 18 ≤ 40	0	100	0.0865921	0.0068847	0.0865427
17	16	84	0.0083799	0.0132276	0.0334859
16	30	70	0.0167598	0.0288056	0.0419264
15	44	56	0.0377095	0.0523618	0.0508750
14	58	42	0.0405028	0.0809587	0.0598154
13	70	30	0.0572626	0.1083018	0.0681176
12	80	20	0.0935754	0.1272786	0.0750899
11	92	8	0.0907821	0.1331533	0.0800565
> 40 ≤ 10	100	0	0.5684357	0.4490278	0.5040905

TABLE VII

CAPACITY OUTAGE PROBABILITY TABLE FOR WECS FOR THE SITE 'LIVERMORE'

Wind Speed mi/h	Cap. Out kW	Cap. In kW	Probability of States: May, 1974 — Actual	$\beta = 4$	α and β Calculated
≥ 18 ≤ 20	0	100	0.6209677	0.8706228	0.6434819
16	30	70	0.0362903	0.0267066	0.0309939
15	44	56	0.0134409	0.0224718	0.0297091
14	58	42	0.0645161	0.0185462	0.0282206
13	70	30	0.0053763	0.0149904	0.0265421
12	80	20	0.0470430	0.0118409	0.0246913
11	92	8	0.0053763	0.0091140	0.0226870
> 40 ≤ 10	100	0	0.2069892	0.0257074	0.1936740
			January, 1974		
≥ 18 ≤ 40	0	100	0.3293011	0.2023720	0.2892541
17	16	84	0.0040323	0.0830979	0.0314841
16	30	70	0.0389785	0.0942240	0.0337791
15	44	56	0.0120968	0.0998846	0.0360898
14	58	42	0.0470430	0.0994905	0.0383822
13	70	30	0.0067204	0.0934991	0.0406186
12	80	20	0.0497312	0.0831668	0.0427498
11	92	8	0.0040323	0.0701597	0.0447205
> 40 ≤ 10	100	0	0.5080645	0.1741035	0.4429212

TABLE VIII

COP TABLE USING IMPROVED MODEL FOR THE SITE 'KAHUKU UPPER'

Cap. Out kW	Cap. In kW	Probability of States			
		March, 1977		November, 1977	
		Actual	β = 3	Actual	β = 3
0	100	0.8029630	0.7843006	0.0865921	0.0412848
16	84	0.0029630	0.0325922	0.0083799	0.0288614
30	70	0.0118519	0.0297931	0.0167598	0.0418369
44	56	0.0059259	0.0268933	0.0377095	0.0566461
58	42	0.0251852	0.0239502	0.0405028	0.0718310
70	30	0.0222222	0.0210182	0.0572626	0.0855085
80	20	0.0192593	0.0181475	0.0935754	0.0957496
92	8	0.0162963	0.0153848	0.0907821	0.1010082
100	0	0.0933333	0.0479201	0.5684357	0.4772733

TABLE IX

COP TABLE USING IMPROVED MODEL FOR THE SITE 'LIVERMORE'

Cap. Out kW	Cap. In kW	Probability of State			
		May, 1974		January, 1974	
		Actual	β = 2	Actual	β = 2
0	100	0.6209677	0.5970098	0.3293011	0.2975414
30	70	0.0362903	0.0305780	0.0389785	0.0474661
44	56	0.0134409	0.0297927	0.0120968	0.0503334
58	42	0.0645161	0.0288116	0.0470430	0.0526780
70	30	0.0053763	0.0276348	0.0067204	0.0543731
80	20	0.0470430	0.0262650	0.0497312	0.0552998
92	8	0.0053763	0.0247073	0.0040323	0.0553516
100	0	0.2069892	0.2352008	0.5080645	0.3427522
16	84	-	-	0.0040323	0.0442044

system to supply energy during calm periods or WECS should be operated parallel with existing conventional generators. The latter is the logical choice (from the economic viewpoint) at present and as such, the rest of this study will concentrate on wind-assisted utility systems. For such combined systems, the term "penetration" is defined as the ratio of the WECS capacity to the total installed capacity (WECS and conventional).

When several conventional generators and WECS are operating in parallel, probability models of both can be convolved in a straightforward manner to derive a combined capacity outage probability table. In this study, all conventional generating units are represented by two state (binary) models with availability (q) = 0.98 and unavailability (p) = 0.02 (21).

Tables X and XI show typical combined capacity outage probability data for twenty percent penetration (total capacity = 500 kW; WECS capacity = 100 kW) for the month of August, 1976, for the Hawaiian site and for the month of May, 1974, for the California site. Probability values less than 10^{-6} have been neglected in compiling these tables. It can be seen that the differences in the probability values computed using actual data and using the mathematical models are smaller than the corresponding differences in Tables VII and VIII for WECS alone.

2.4 Calculation of a Reliability Index

2.4.1 Load Model

By combining any one of the generation models developed in the previous section with a suitable load model, an index representing the

TABLE X

COP TABLE FOR COMBINED SYSTEM WITH 20% PENETRATION
FOR AUGUST, 1976, FOR THE SITE 'KAHUKU UPPER'

Cap. In kW	Probability of States		
	Actual	$\beta = 4$	α and β Calculated
500	0.5239161	0.5284320	0.5484384
484	0.0813447	0.0674443	0.0761340
470	0.0785873	0.0623459	0.0676680
456	0.0592852	0.0558414	0.0577623
442	0.0523916	0.0484893	0.0474454
430	0.0317107	0.0408214	0.0375346
420	0.0261958	0.0332962	0.0285944
408	0.0151659	0.0262705	0.0209446
400	0.0965391	0.1025625	0.0826169
384	0.0066404	0.0055057	0.0062150
370	0.0064153	0.0050895	0.0055239
356	0.0048396	0.0045585	0.0047153
342	0.0042769	0.0039583	0.0038731
330	0.0025886	0.0033324	0.0030640
320	0.0021384	0.0027181	0.0023342
308	0.0012380	0.0021445	0.0017098
300	0.0056987	0.0061716	0.0044601
284	0.0002033	0.0001685	0.0001903
270	0.0001964	0.0001558	0.0001691
256	0.0001482	0.0001395	0.0001443
242	0.0001309	0.0001212	0.0001186
230	0.0000792	0.0001020	0.0000938
220	0.0000655	0.0000832	0.0000715
208	0.0000379	0.0000657	0.0000523
200	0.0001522	0.0001665	0.0001132
184	0.0000028	0.0000023	0.0000026
170	0.0000027	0.0000021	0.0000023
156	0.0000020	0.0000019	0.0000020
142	0.0000018	0.0000017	0.0000016
130	0.0000011	0.0000014	0.0000013

TABLE XI

COP TABLE FOR COMBINED SYSTEM WITH 20% PENETRATION FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

Cap. In kW	Probability of States		
	Actual	β = 4	α and β Calculated
500	0.572761	0.593527	0.803035
470	0.033473	0.028588	0.024633
456	0.012347	0.027403	0.020727
442	0.059508	0.026030	0.017106
430	0.004959	0.024482	0.013827
420	0.043391	0.022774	0.010922
408	0.004959	0.020926	0.008406
400	0.237676	0.227090	0.089265
370	0.002732	0.002334	0.002010
356	0.001012	0.002237	0.001692
342	0.004858	0.002125	0.001396
330	0.000405	0.001998	0.001128
320	0.003542	0.001859	0.000891
308	0.000405	0.001708	0.000686
300	0.017017	0.016066	0.003942
270	0.000084	0.000071	0.000061
256	0.000031	0.000068	0.000051
242	0.000149	0.000065	0.000043
230	0.000012	0.000061	0.000035
220	0.000108	0.000057	0.000027
208	0.000012	0.000052	0.000021
200	0.000497	0.000467	0.000086
170	0.000001	0.000001	0.000001
156	0.000001	0.000001	0.000001
142	0.000002	0.000001	0.000001
130	0.000001	0.000001	0.000001
120	0.000001	0.000001	0.000001
108	0.000001	0.000001	0.000001
100	0.000005	0.000005	0.000001

expected risk of loss of load is derived. Figure 13 shows a load model that is traditionally used in such studies. It is a plot of peak load versus the number of time units the load is greater than or equal to the value during the study period. With WECS present and with the availability of hourly wind data, the most appropriate time unit to use is hours, and the final result for the loss of load will then be in terms of hours per study period (hours or months).

Referring back to Figure 13, it is seen that the minimum peak load is taken as 40 percent of the maximum peak load. This is fairly typical for such load models. To study the influence of the load model itself (and indirectly, the amount of reserve capacity), the maximum peak load is varied from 50 percent to 100 percent of the total (WECS plus conventional) installed capacity in six steps. This procedure is repeated for eight different values of penetration to study its effect on the reliability of the combined system. Changes in the penetration values were simulated by maintaining the WECS capacity constant (at 100 kW) and varying the number of conventional units (100 kW each) operating in parallel.

2.4.2 Loss of Load Probability (LOLP) Method

(21, 51)

The purpose of providing reserve capacity is to decrease the probability of occurrence of loss of load. The work described in section (2.3.3) dealt with loss of generation capacity only. The system load, however, undergoes hourly, daily, and seasonal variations. Any capacity outages, therefore, may or may not result in a loss of load depending on whether the remaining capacity is sufficient to supply

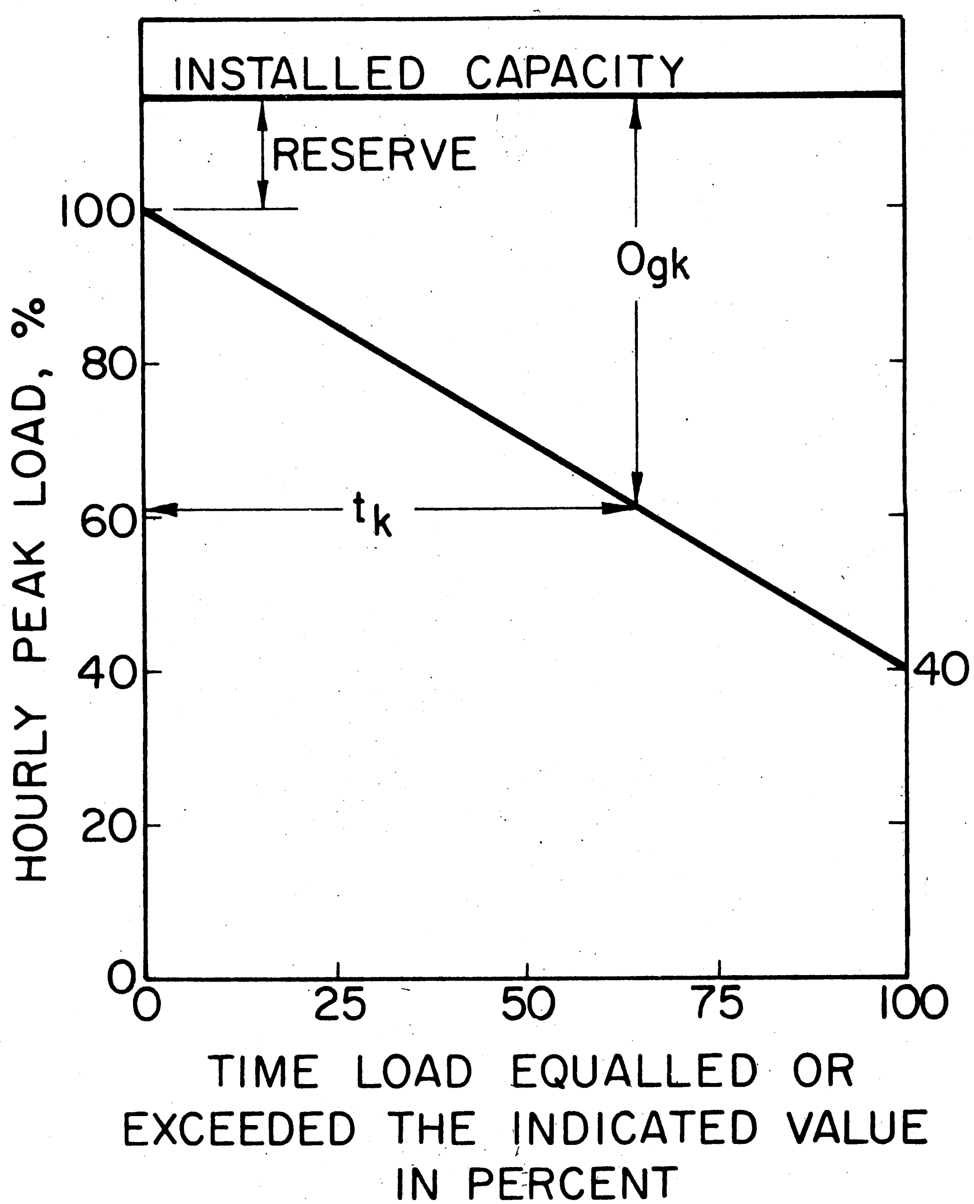


Figure 13. Load Model Used in the Study

the load while the outage exists. To take this factor into account, a load duration curve is needed in addition to generation probabilities of the combined system previously calculated. The above load duration curve can be modified to allow for the possibility of carrying load at a reduced voltage, if necessary.

Let O_{g1}, O_{g2},....., O_{gk}, $O_{g(k+1)}$,....., be the combined system (WECS plus conventional) exact generation capacity outage values obtained for the combination of WECS and a number of conventional generating units. These are shown by vertical lines on the load model (Figure 13). In the long run average duration in the study period the load exceeds the available generating capacity, otherwise known as the loss of load probability (LOLP), may be calculated by noting that with an exact capacity outage of O_{gk}, loss of load is likely to occur during the time t_k when the load exceeds the available capacity. If A_{gk} is the probability of outage of capacity, O_{gk}, then the product, $A_{gk}t_k$, gives a measure of the likelihood of loss of load contributed by the combined system capacity outage, O_{gk}. By summing the contributions from all the combined system exact capacity outage values, O_{g1}, O_{g2} ....., O_{gk}, $O_{g(k\pm1)}$,...., the loss of load proability is obtained as below:

$$\mathrm{LOLP} = \sum_k A_{gk}t_k \qquad (2.8)$$

Figures 14 through 18 show the computed values (sample data for 20 percent penetration for the months of March, 1977, and May, 1974, for Kahuku Upper and Livermore are tabulated in Tables XII and XIII, respectively), of LOLP plotted against the peak load in per-unit for different penetrations for the three sample months (August, 1976, March,

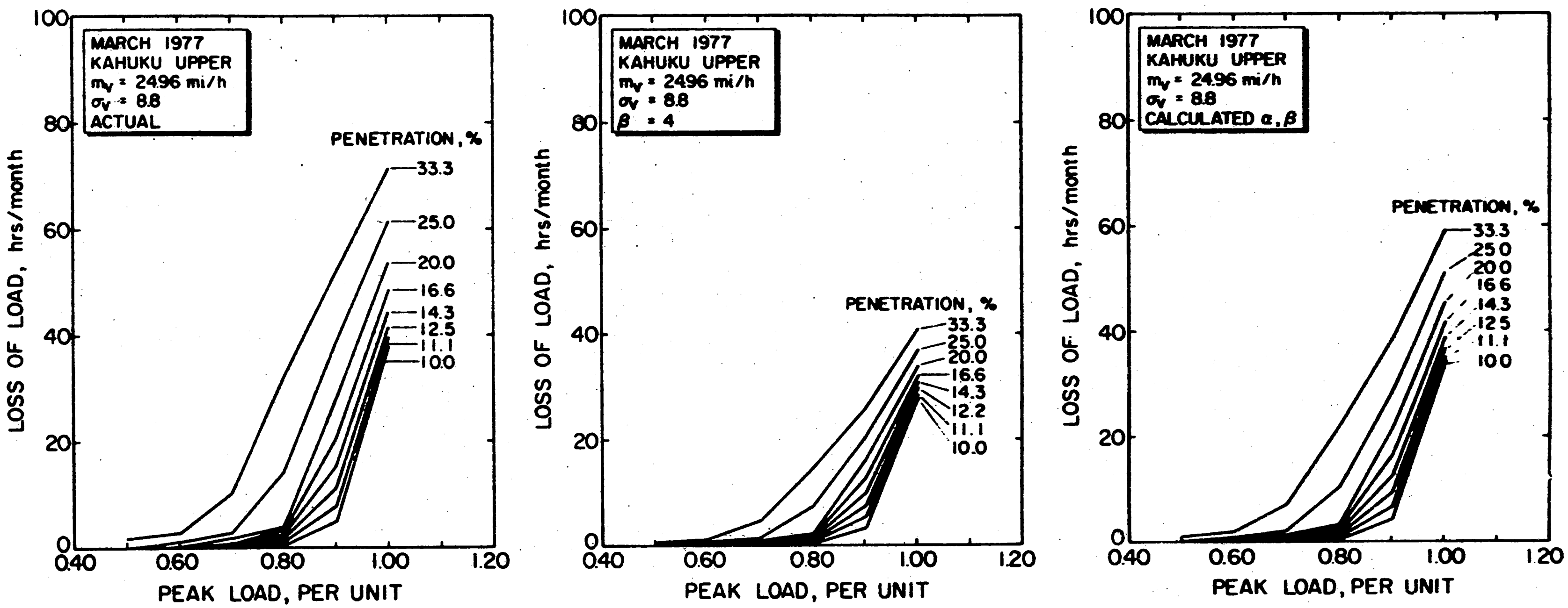


Figure 14. Expected Loss of Load for the Month of March, 1977, for the Site 'Kahuku Upper'

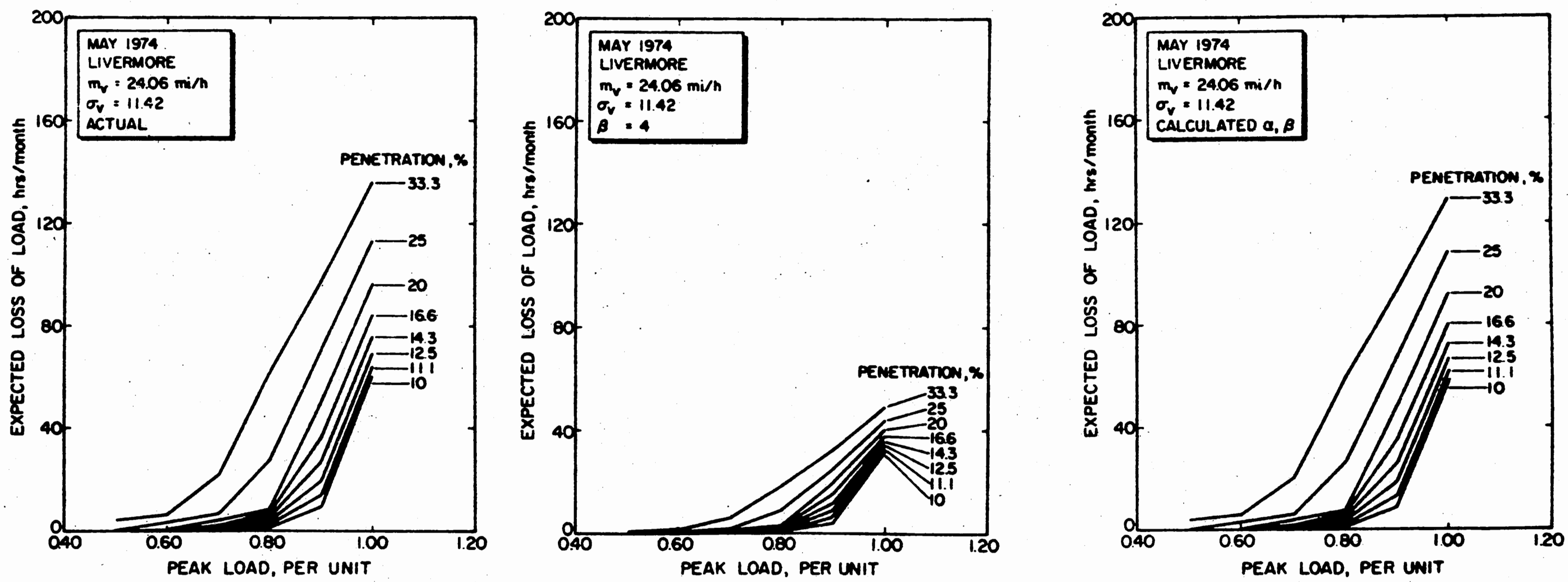


Figure 15. Expected Loss of Load for the Month of May, 1974, for the Site 'Livermore'

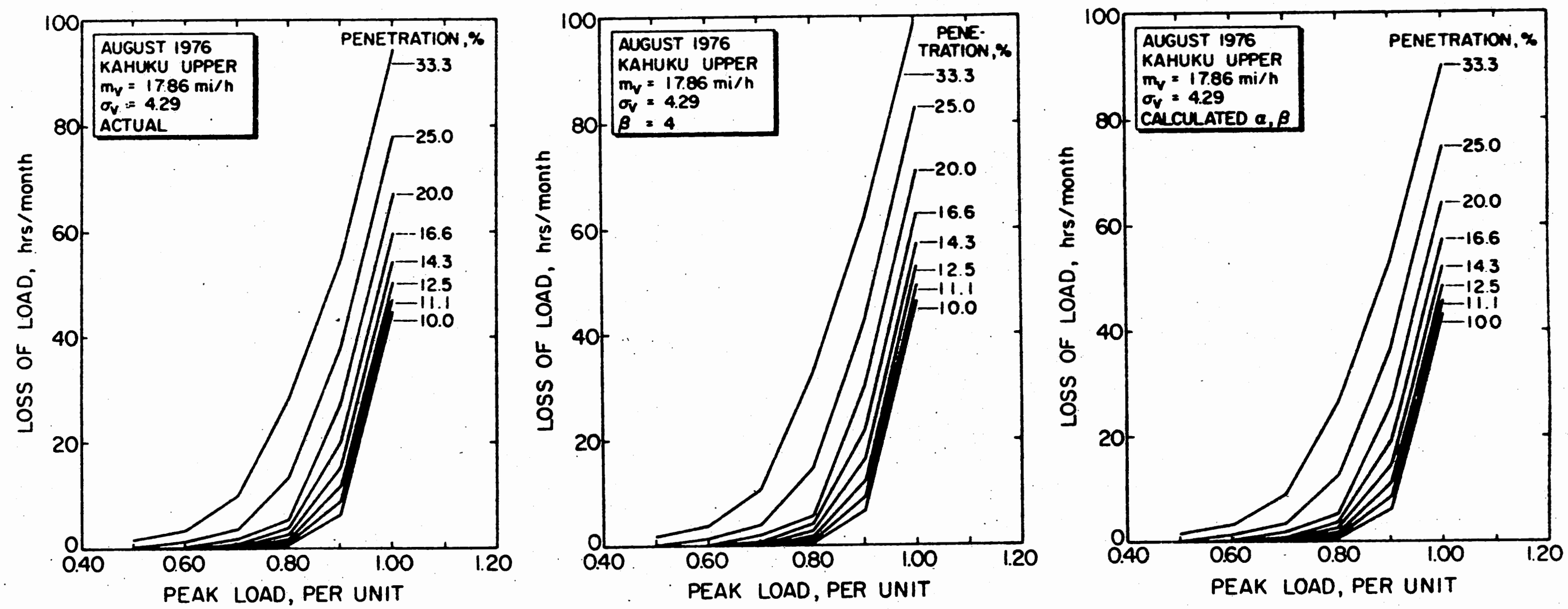


Figure 16. Expected Loss of Load for the Month of August, 1976, for the Site 'Kahuku Upper'

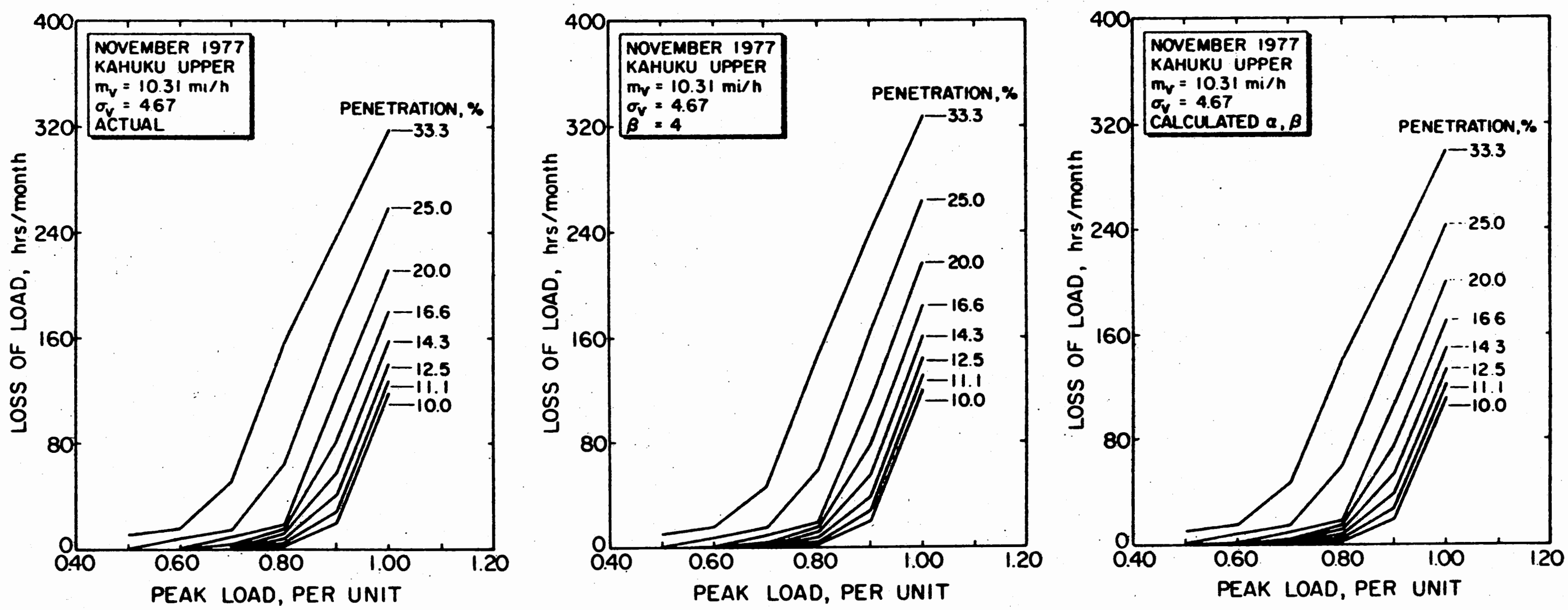


Figure 17. Expected Loss of Load for the Month of November, 1977, for the Site 'Kahuku Upper'

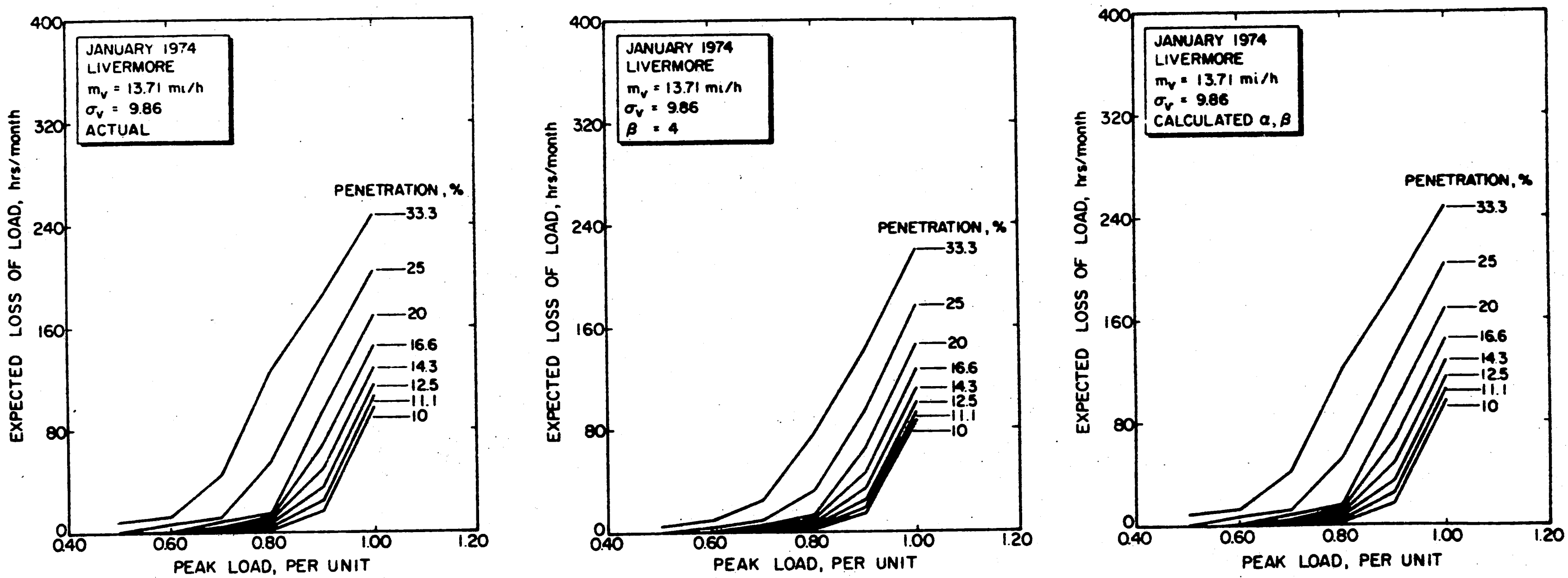


Figure 18. Expected Loss of Load for the Month of January, 1974, for the Site 'Livermore'

TABLE XII

LOSS OF LOAD PROBABILITY DATA FOR 20% PENETRATION FOR MARCH, 1974, FOR THE SITE 'KAHUKU UPPER'

Load % of Installed Capacity	Actual	α and β Calculated	$\beta = 4$
50	0.076690	0.048100	0.027654
60	0.149432	0.117455	0.074294
70	2.093428	1.408845	0.904663
80	4.166291	3.345196	2.248528
90	28.567190	21.573270	16.143400
100	54.114310	45.643960	34.329100

TABLE XIII

LOSS OF LOAD PROBABILITY DATA FOR 20% PENETRATION FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

Load % of Installed Capacity	Actual	α and β Calculated	$\beta = 4$
50	0.154869	0.149284	0.036851
60	0.303609	0.288280	0.091480
70	4.035583	3.895436	1.150754
80	8.125736	7.742704	2.721691
90	49.967020	48.416100	19.395900
100	96.101650	92.149940	40.349220

1977, and November, 1977) for the Hawaiian site, Kahuku Upper, and for the two months (January, 1974, and March, 1974) for the California site, Livermore.

Each figure consists of three parts:

a) expected loss of load with actual (measured hourly wind speed) data,

b) expected loss of load using the model with $\beta = 4$ and α computed from the mean wind speed and Equation (2.3),

c) expected loss of load using the model with both α and β calculated from the mean wind speed and the variance and Equations (2.3) and (2.4).

These results and their implications are discussed in the following section.

2.5 Discussion

In Figures 14 through 18, the plots are made up of straight-line segments to emphasize the fact that the break points are indeed the calculated values and that many more runs may be necessary to locate the intermediate points required to draw smooth curves. An examination of these results reveals that when the peak load is lower than the conventional generation capacity, the influence of WECS on the combined-system expected loss of load is not significant. As the peak load approaches and exceeds the conventional generation capacity, the expected loss of load increases sharply. This indicates a low confidence in wind generation. In addition, the expected loss of load increases with an increase in the penetration and decreases with an increase in the mean wind speed (better wind regime). Although not immediately obvious from the figures, for a given peak load (less than or equal to the conventional generation capacity), removal of WECS increases the system loss of load expectancy. From this statement, one can infer that it is possible to assign a capacity credit to WECS--the amount of conventional capacity that should be added to realize an identical decrease in the expected loss of load (see reference 38).

Referring to Figure 14, it is seen that the general nature of variation of the expected loss of load is the same with all three approaches. In fact, the maximum difference between the figures obtained using actual data and mathematical model is less than six percent. Similar consistency is exhibited in Figure 15 also, with a maximum difference of 15 percent between the LOLP obtained using actual data and from calculated α and β. However, the difference between actual and the model with $\beta = 4$ is large--around 40 percent maximum for the Hawaiian site and very large for the California site. This is due to an inappropriate choice of β. As discussed earlier, for the month of March, 1977, for the Hawaiian site, a realistic value of β is 3 and for the month of May, 1974, for the California site, a realistic value of β is 2 (extremely large variance--over 100). These choices for the β value will once again bring the actual and the model values within 15 percent. The wind regime during November, 1977, for the Hawaiian site and during January, 1974, for the California site are very poor, and these are reflected in the high values of expected loss of load shown in Figures 15 and 17. Even with a β value of 4, the models and the actual figures agree within six percent for the Hawaiian site and within 12 percent for the California site. Better choices for the β value (3 in case of the Hawaiian site and 2 in case of the California site) do not improve significantly the agreement between the actual and the model with an assumed β value.

2.6 Consideration of Scheduled Maintenance and Mechanical Outages of WECS

Watchorn (52) has worked extensively on seasonal and miscellaneous capacity reductions, and scheduled and routine maintenance requirements. A simple maintenance schedule was incorporated in a digital computer program by Kirchmayer et al. (51). In a combined generation system (WECS plus conventional), maintenance reduces the generation capacity and should be considered as such. However, without significant error, it may be considered as an increase in the system load. The increase of load considered depends on the type of generation system and the duration of operation of the unit (52). As an example, thermal generation system scheduled maintenance involves maintenance of boilers, turbines, and electric generators and, moreover, the older the unit, the longer the scheduled maintenance. Inclusion of maintenance by this procedure alters the peak load variation, as shown in Figure 19. Figure 19 is obtained from Figure 13 by raising the resulting maximum effective load level to the minimum possible amount (minimum ordinate on the load duration curve) consistent with the maintenance period. A typical maintenance schedule assumed for all conditions is shown in Table XIV and in Figure 19 for a total generation capacity of 1000 kW (nine conventional generating units of 100 kW each plus one WECS of 100 kW). Figure 19 involves the scheduled maintenance of conventional generating units only. Each of the conventional generating units in the system is assumed to be withdrawn from service for an average

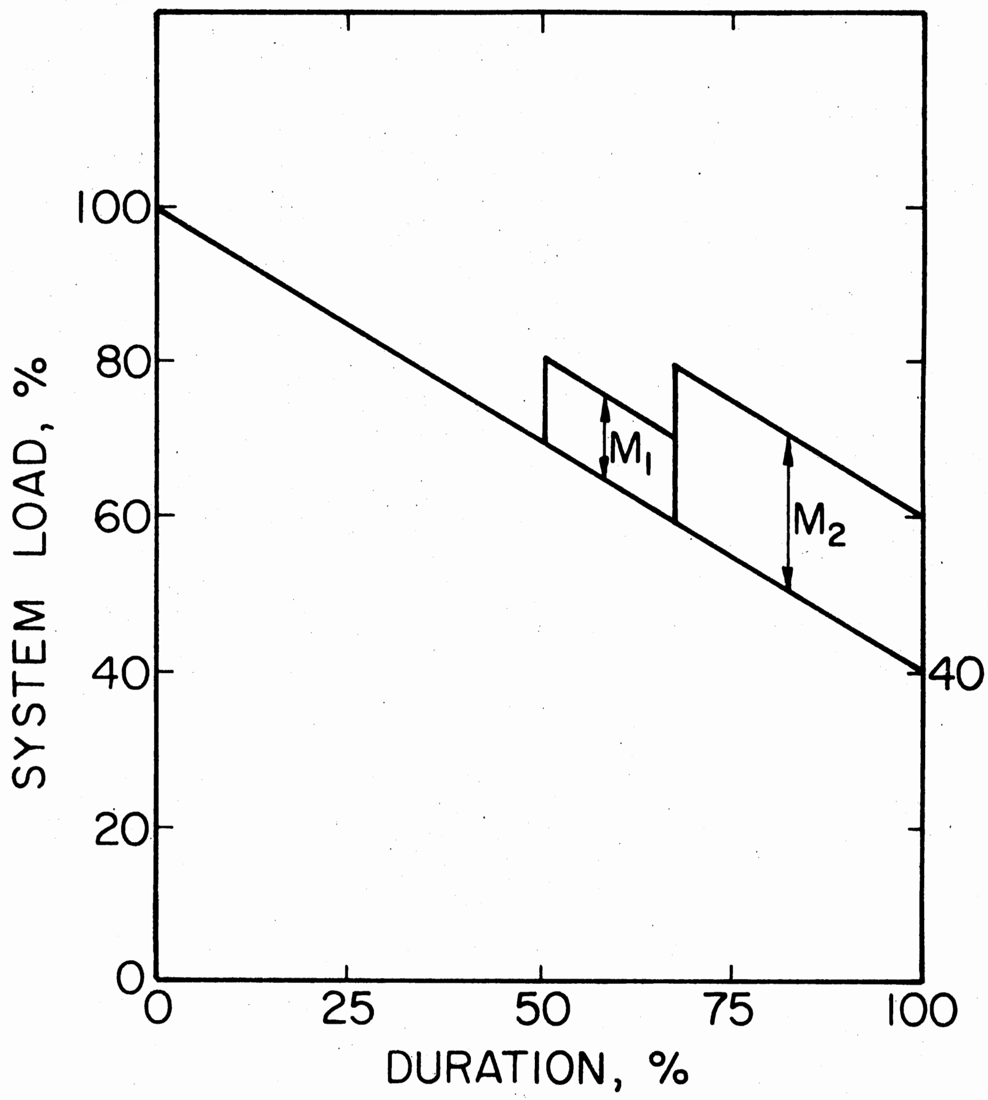


Figure 19. Modified Load Characteristics to Include Maintenance and Mechanical Outages

period of 40 hours a month. In the case of WECS, the maintenance schedule was arranged during the calm (less than cut-in) period within the time under consideration. Such a procedure makes sense from the economic point of view (extract maximum energy during good wind speeds). If such a schedule for WECS is not possible, then maintenance could be arranged during the low output hours and its effect can be incorporated by altering the load model as discussed above for conventional generating units. Such changes can be easily incorporated in the computer program.

TABLE XIV

MAINTENANCE PATTERN

Time, at the End of the Interval (Hours)	Capacity Out of Service During Interval (Hours)
384	M_0 = 0
504	M_1 = 100 kW
744	M_2 = 200 kW

It is reasonable to assume a mechanical outage value of 0.01 for WECS, and its effect can be considered by derating the capacity of WECS by 0.01. Melton (38) suggested that forced outages due to mechanical failure combined with scheduled maintenance averaged to about three percent for an individual WECS. Therefore, derating the WECS capacity by this amount can account for the expected mechanical outage and scheduled maintenance for reliability studies.

2.7 Capacity Credit

Due to wide variations in the output capacity resulting from variations in the wind input, WECS alone cannot be expected to meet unscheduled load demands or assist in a crisis arising due to the failure of a conventional generating unit operating in parallel with WECS. As such, one is likely to conclude that installation of WECS will not displace the installation of any amount of conventional generation capacity. However, using the approach for determining the reliability indices for conventional generation systems, it can be shown that installation and operation of WECS in parallel with utility grids indeed improves the overall system reliability and therefore it is possible to "assign" a capacity credit for WECS. Determination of capacity credit for WECS is a complex problem. It depends upon factors such as machine parameters, generation mix (penetration), load demand, wind regime, and the like. Instead of consideraing all of these factors in detail, a simple approach suggested by Melton (38) will be used. In this method, the WECS in the generation mix is replaced by a highly reliable conventional generation unit whose capacity is varied from a low value to a value equal to the WECS rating and for each value the reliability index is computed for the same load demand. This reliability index is plotted against the capacity of the conventional unit added. The value of the capacity readoff from this plot corresponding to the expected loss of load with the WECS in the combined system is indicative of the capacity credit that can be assigned for WECS.

To estimate the capacity credit for the two sites under consideration, the WECS in the generation mix is replaced by a conventional generating unit with failure and repair rates of 0.01 failures/day and 0.49 repairs/day, respectively. The capacity of the unit replacing the WECS in the generation mix is varied from 10 kW to 100 kW in steps of 10 kW and the reliability index corresponding to each capacity value is determined assuming the load to remain the same. This procedure is repeated for different load demands for the period under consideration. A typical plot of reliability index versus the capacity of the replacing conventional unit for maximum generation capacity of 500 kW (four conventional generating units of 100 kW capacity each plus a conventional generating unit replacing WECS with maximum capacity 100 kW) and for a maximum load (see page 46) of 80 percent of the system generation capacity is shown in Figure 20. Plots are obtained for different installed capacities and for different load demands. It has been observed that the value of capacities readoff from these plots corresponding to the expected loss of load with WECS in the combined system are different for different load demands and for different generation mixes. As such, for a given wind regime and for a certain value of generation mix, it is logical to discuss a capacity credit range, determined from the plots for different load values. The procedure is continued for the same wind regime but with different generation mixes. A mean of these capacity credit ranges is representative of the expected value of the capacity credit that can be assigned to the WECS for the wind regime under consideration. Determination of a more appropriate and realistic range of capacity credit requires the computation of

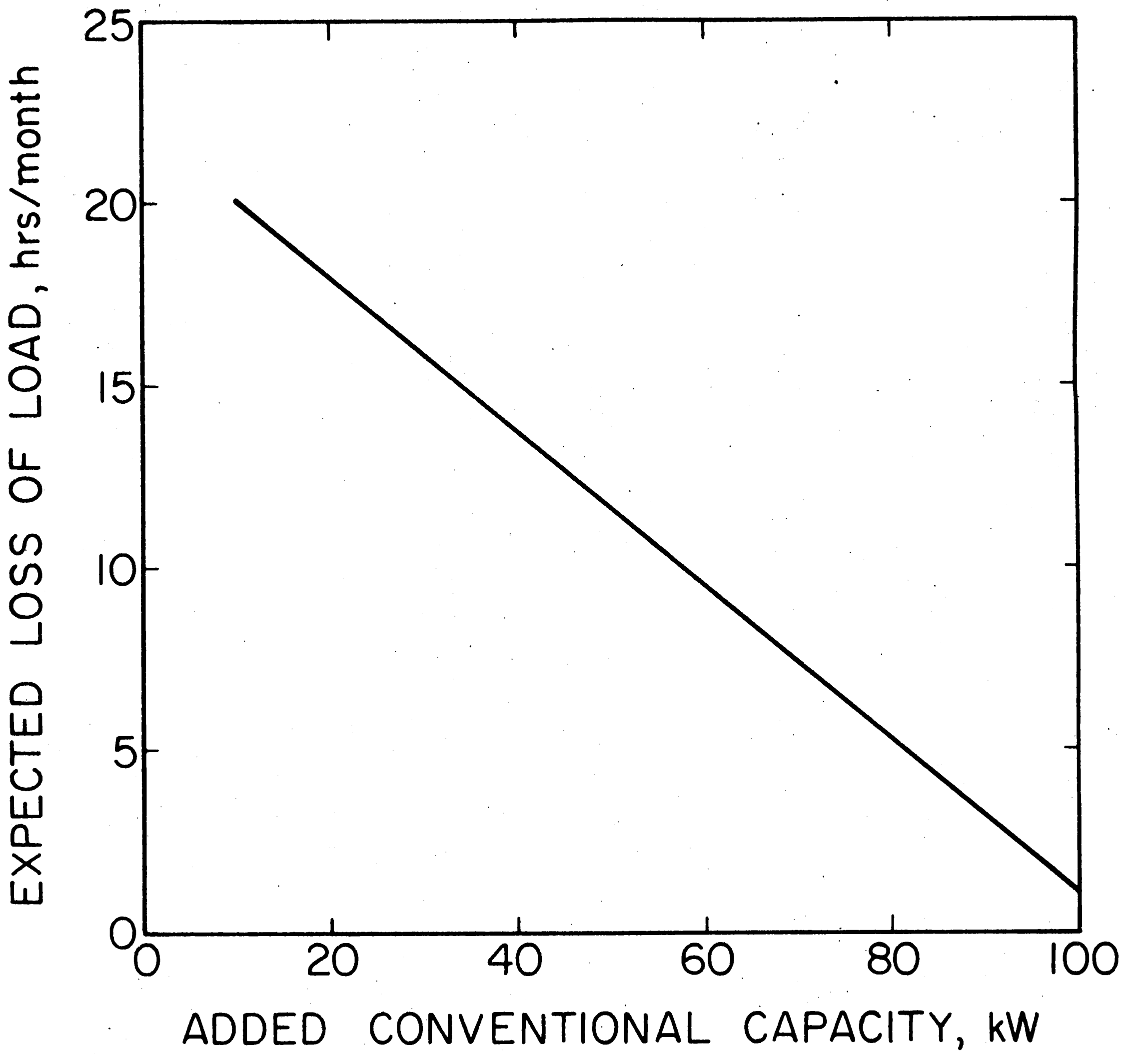


Figure 20. Variation of Expected Loss of Load With Added Conventional Capacity

capacity credit ranges for a similar period over several years (ten to fifteen years) and taking a mean of these ranges. The results with hourly wind speed data for low mean wind speed and high mean wind speed months for the two sites, 'Kahuku Upper' and 'Livermore' are given in Table XV.

TABLE XV

EXPECTED CAPACITY CREDIT RANGE FOR THE SITES 'KAHUKU UPPER' AND 'LIVERMORE'

Site	Month and Year	Mean Speed mi/h m_v	Variance σ_v^2	Capacity Credit kW
Kahuku Upper	March 1977	24.96	77.41	50-60
	November 1977	10.31	21.81	0-10
Livermore	January 1974	13.71	97.21	20-30
	May 1974	24.06	130.34	40-50

2.8 Conclusions

Probability models of wind speed can be used to develop capacity outage probability tables for wind electric conversion systems. These tables have been employed in the reliability evaluation of wind systems operating in parallel with conventional generators.

The primary step in the procedure is the selection of a suitable model for the wind speed distribution. This depends on the nature of the wind data available for the site in question. It has been shown that, in most cases, the mean (hourly) wind speed and a knowledge of its variability are enough to make an appropriate selection (of β and consequently of the model). The range of values for the parameter β **are** discussed by considering two totally different sites. If both mean and variance are known, it is possible to arrive at a fairly accurate model.

The family of expected loss of load curves computed and presented for two typical WECS sites should lead to an understanding of the inter-action of the basic parameters involved and the manner in which they influence the overall system reliability. Procedures to include the effects of scheduled and mechanical outages in the system have also been discussed.

CHAPTER III

MARKOV MODEL FOR WECS AND ITS APPLICATION IN RELIABILITY STUDIES USING THE FREQUENCY AND DURATION APPROACH

3.1 Introduction

Static generating capacity reliability evaluation of conventional generation systems has been under investigation over the last thirty years. Excellent papers have been published on modeling a conventional generation system and on its application in reliability studies. With the expected entry of large WECS and their operation in parallel with the utility grids in the near future, estimation of generation reserve and the load-carrying capability of the overall system assumes importance. An accurate assessment of the reliability of such combined systems requires the development of a more realistic model for WECS than the one employed in the previous chapter.

The Markov process is a particular kind of stochastic process which finds increasing application in power systems reliability studies (34, 53). Interest in the Markov process arises from the fact that it models real life situations fairly accurately and the mathematical formulation is well developed and relatively simple. Appendix A gives a brief summary of the assumptions and the equations involved. Based on this approach, a Markov model is developed for WECS in this chapter.

It is a multi-state model, derived from the measured hourly wind data. The longer the duration over which data is available, the better the model and the representation.

In recent years, increasing attention is being given to the development of reliability measures that are valid for the entire (generation and transmission) power system (32). Since frequency and duration approach is the accepted practice for evaluating transmission system reliability, development of a Markov model for WECS offers the opportunity for the eventual integration of generation and transmission system studies with the ultimate goal of arriving at an overall reliability model and reliability indices.

3.2 Markov Model for WECS

In modeling WECS, the unit is defined by a maximum capability and by the long-run behavior pattern with regard to the occurrence and the cyclic interchange between its different states (full capacity, zero capacity, and a number of partial capacity states). The WECS is characterized by the existence of various amounts of capacities available (or conversely, an outage), the expected availabilities of these capacities and the expected recurrence, or the cycle time of these states.

The WECS is described in terms of a number of capacity states and the rates of departures between the states. Further, the model in terms of exact capacity states can be readily transformed into a cumulative model. These models are used to implement the commonly used generation system reliability computation techniques to generate information concerning the frequency and the duration of the outage states. These measures for the generation system are compatible with the transmission and distribution system reliability measures.

The primary goal of this chapter is to present a logical development of a generation model for WECS based on the Markov model and to compute the system reliability using a suitable load model (Markov chain model) when the WECS is operating in parallel with other conventional generators.

The ability of a WECS to supply power is equal to its instantaneous generation capacity. This is a value changing from time to time and is dependent upon the environment about the plant and the state of the associated auxiliary equipment. The capacity may be at full machine rating for certain periods of time, changing suddenly to a lower (partial capacity) value due to a change in the input wind speed or due to a loss of certain auxiliary equipment, or it may be zero when the wind speed is low or too high. The transitions from one capacity state to another are assumed to take place instantaneously and they may occur at any time. The average amount of time the capacity remains at a certain value before transitioning to some other capacity state is called the residence time for that state.

A partial capacity state is a relatively short term randomly occurring derating of the WECS and is caused by the variation of the input wind speed. As defined in this thesis, the partial capacity states are seasonal and hence are predictable. Mechanical outages, including the loss of a portion of the unit auxiliary equipment and scheduled maintenance of the WECS which may reduce the maximum capability of an array of WECS are excluded from consideration in developing the model.

The Markov model proposed for WECS is shown in Figure 21. The

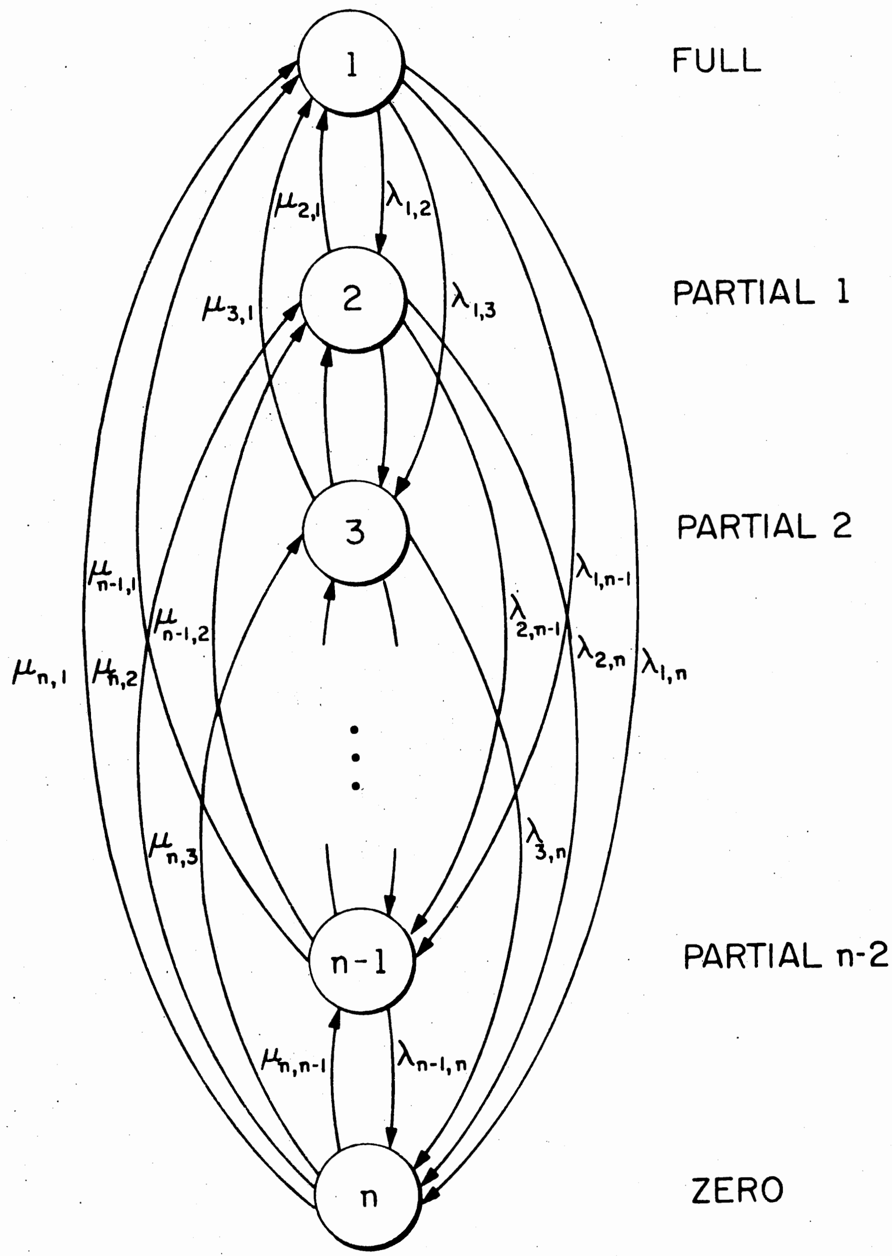


Figure 21. Markov Model of an n-State System

assumptions involved are the same as those given in Appendix A for the homogeneous discrete-state continuous-transition Markov process.

The approach described in Appendix A for computing steady state probabilities cannot be applied directly to the WECS model since the information available is only the hourly wind speed input to WECS over a certain period of time and the rates of departures between the states is not available directly.

Biggerstaff and Jackson (34), Adler (54), and Cook et al. (55) have developed models incorporating a partial capacity state in addition to full capacity and zero capacity states for conventional generating units. In the present work on WECS, the method developed by Biggerstaff and Jackson has been extended to recognize and include a number of partial capacity states in WECS capacity.

Biggerstaff and Jackson have also shown that the number of transitions out from a state in the long run is equal to the number of transitions into the state. Thus, the rates of departure to down and up states are given by:

$$\rho_{jk} = \frac{\text{Number of transitions from the higher (lower) capacity state } j \text{ to the lower (higher) capacity state } k}{\text{Long-run duration of time the output stayed in the capacity state } j} \tag{3.1}$$

and the availability of a state j is given by

$$A_j = \frac{t_j}{T} = \frac{t_j}{t_1 + t_2 + \ldots\ldots + t_n} \tag{3.2}$$

where t_j is the long-run duration of time the output stayed in state j and T is the total time under consideration.

Hall et al. (31) have shown that the frequency of encounter and the cycle time of state j, in the long-run, are given by the following equations:

$$f_j = (\text{availability of state } j) \times \begin{pmatrix} \text{total rate of departure} \\ \text{from state } j \end{pmatrix} \quad (3.3)$$

$$\left.\begin{matrix} \text{cycle time} \\ \text{for state } j \end{matrix}\right\} = \frac{1}{\text{frequency of encounter of state } j} \quad (3.4)$$

3.3 Exact-state Capacity Model for WECS

The exact-state capacity model for WECS for use in the frequency and duration approach is derived from the basic parameters for each of the capacity outage states--namely, the probability and effective rates of departure to lower and higher capacity states.

3.3.1 Wind Data and Aeroturbine-Generator Characteristics

Hourly wind speed data are essential for the approach followed in the present studies. The wind speed data could be average values over one minute, five minutes, or even ten minute durations, every hour on the hour. The data for the two sites, 'Kahuku Upper' of Hawaii and 'Livermore' of California have been considered in the present studies. DOE/NASA-Lewis 100 kW MOD-0 unit has been considered once again for the reliability studies.

3.3.2 Availabilities of Output Capacity States of WECS

On the basis of integer values of wind speeds (modified wind speed data for the Hawaiian site) and the characteristics of the MOD-0 NASA-Lewis wind turbine generator, nine output capacity (full output capacity, zero output capacity and seven partial output capacity) states have been employed (see WECS Capacity Outage, page 33). The magnitude of the output capacity of each partial capacity is computed from the characteristic of the wind turbine generator under consideration (see Figure 12). For each output capacity state, the total number of hours the output remained in that state is extracted from the (modified) input wind speed data. These numbers of hours, when divided by the total number of hours under consideration, yield the availabilities of the various output capacity states of the WECS.

3.3.3 Rates of Departure to Down and Up States

Computation of the rates of departure from each of the WECS output states to all of the other down and up states requires the counting of the number of transitions from each of the WECS states to all other down and up states. This process is made easy by an additional modification of the wind speed data used in the computation of the availabilities. Wind speeds greater than or equal to 18 mi/h but less than or equal to 40 mi/h are replaced by 18 mi/h, and the wind speeds greater than 40 mi/h or less than or equal to 10 mi/h are replaced by 10 mi/h, keeping all other wind speed values unchanged. Such modified wind speed data for the two sites under study are shown in Tables XVI and XVII. The total number of transitions from each of the wind speed values (which corresponds to an output state of WECS) to all other lower and higher speeds (which corresponds to lower and higher capacity states) in the modified wind data array are counted. These

TABLE XVI

MODIFIED WIND SPEED DATA TO COMPUTE THE TRANSITIONS FROM ONE STATE TO ANOTHER FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

Day	Hour of day																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
2	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
3	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
4	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	--	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
6	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
7	--	--	--	--	--	--	--	--	--	--	--	--	--	18	18	18	18	18	18	18	18	18	18	18
8	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
9	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	17	18
10	18	14	14	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
11	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
12	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
13	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
14	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
15	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
16	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
19	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
20	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
21	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
22	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
23	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
24	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
25	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
26	18	14	11	14	10	10	10	10	10	10	11	14	16	13	12	10	10	10	10	10	14	13	16	18
27	18	18	16	11	13	10	13	16	10	10	17	18	18	18	18	16	14	14	15	12	10	13	12	10
28	14	10	10	10	13	11	10	10	18	18	13	14	10	10	10	10	11	10	10	11	12	10	10	12
29	14	16	14	10	10	10	15	13	11	13	12	10	12	14	18	16	13	10	12	11	12	15	13	13
30	11	14	13	11	12	12	18	18	16	13	10	14	18	14	15	14	10	10	10	10	10	10	10	10
31	10	13	10	10	10	11	12	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	12

TABLE XVII

MODIFIED WIND SPEED DATA TO COMPUTE THE TRANSITIONS FROM ONE STATE TO ANOTHER FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

	Hour of day																							
Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	18	18	18	18	18	18	18	18	18	18	10	18	10	10	10	18	18	10	18	10	10	18	18	18
2	18	18	18	18	18	18	18	18	18	15	14	14	14	18	18	18	18	18	18	18	18	18	18	18
3	18	18	18	18	18	16	18	14	10	10	10	10	10	18	10	16	18	18	18	18	18	18	18	18
4	18	18	18	18	18	18	18	14	16	16	12	12	14	12	10	12	18	18	18	18	18	18	18	18
5	18	18	18	18	18	12	12	13	10	11	10	10	14	10	12	12	18	18	18	18	18	18	12	10
6	10	18	18	18	10	15	10	14	10	10	10	12	10	15	12	14	14	18	18	18	18	18	16	18
7	16	18	12	18	10	10	10	10	10	10	10	10	10	10	14	14	16	12	14	18	18	18	18	18
8	18	18	16	11	10	10	10	10	10	10	10	12	10	15	18	18	18	18	18	18	18	10	18	18
9	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	10	10	10	18	10	10	10
10	10	10	18	18	18	18	16	14	18	14	12	18	14	10	16	14	18	18	18	18	18	18	18	18
11	18	18	18	18	18	10	10	10	10	10	16	12	10	16	16	18	18	18	18	18	18	18	18	18
12	18	18	10	18	10	15	18	10	18	10	18	18	18	18	18	18	10	10	10	10	10	10	18	18
13	18	18	18	18	18	18	18	18	18	18	18	18	18	14	18	18	18	18	10	18	18	18	18	18
14	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	10	10	10	10	10	10
15	18	10	10	18	18	18	18	18	18	18	18	18	18	18	18	18	10	10	10	10	10	18	18	18
16	18	10	18	18	10	18	18	18	18	18	18	18	18	14	18	18	18	18	18	18	18	18	18	14
17	18	18	18	18	18	18	10	12	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
18	12	12	15	18	10	15	18	18	18	18	14	10	18	18	18	18	18	18	18	18	18	18	18	18
19	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	10	18	18	18	10	18
20	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
21	18	18	18	18	10	10	12	10	10	10	10	10	10	10	10	14	18	16	18	18	18	18	18	18
22	18	18	18	10	18	18	14	14	18	12	10	12	14	10	10	14	16	18	18	18	18	18	18	18
23	18	18	18	18	18	18	14	12	10	18	18	14	15	14	14	18	18	18	18	18	18	18	18	18
24	18	18	18	18	12	12	10	10	10	10	14	14	10	14	18	18	18	18	18	18	18	18	18	18
25	18	18	18	16	10	10	10	10	10	14	12	14	14	10	10	10	18	16	15	14	13	14	10	12
26	10	11	12	12	10	14	16	18	18	18	18	18	18	18	14	15	13	12	14	18	18	18	14	14
27	16	14	18	16	16	18	18	12	14	18	18	18	18	18	18	18	18	18	18	10	10	10	10	10
28	10	10	10	10	10	18	18	18	18	18	18	18	18	18	18	18	18	10	10	10	10	10	10	10
29	10	10	10	10	18	18	18	18	18	14	10	10	10	16	18	18	18	18	18	18	18	18	18	18
30	18	14	10	10	12	13	10	11	16	18	18	16	16	12	12	10	18	18	18	18	18	18	18	18
31	18	18	18	10	14	18	18	10	12	10	10	16	18	18	16	18	18	18	18	18	18	18	18	18

numbers are given in Tables XVIII and XIX for the Hawaiian and California sites. The number of transitions from an output capacity state to a lower (higher) output capacity state when divided by the total number of hours the output remained in that output capacity state (from which transitions are emanating) yields the corresponding rate of departure to the down (up) state. Tables XX and XXI show the rates of departures to down and up states for 'Kahuku Upper' and 'Livermore.'

Using the results obtained thus far, the frequency of encounter and the cycle time of an exact output capacity state k of WECS in the long run can be calculated as follows:

$$\left.\begin{array}{l}\text{frequency of}\\ \text{encounter of state k}\end{array}\right\} = \begin{bmatrix}\text{availability}\\ \text{of state k}\end{bmatrix} \times \begin{bmatrix}\text{total rate of}\\ \text{departure from}\\ \text{state k}\end{bmatrix} \qquad (3.5)$$

$$\left.\begin{array}{l}\text{the cycle time}\\ \text{of state k}\end{array}\right\} = \frac{1}{\text{frequency of encounter of state k}} \qquad (3.6)$$

Tables XXII and XXIII give (in consolidated form) the exact-state output capacity model for WECS. It lists capacity on outage, capacity in service, availability, total rate of departure from each state to lower and higher states, frequency of encounter, and cycle time of exact capacity states for the month of March, 1977, for 'Kahuku Upper' and for the month of May, 1974, for 'Livermore.'

3.4 Markov Model for Conventional Generating Units

In practice, it is rare to operate the WECS alone (because of wide variations in the input speed). They will be operated in parallel with a number of conventional generating units. Since WECS has been modeled

TABLE XVIII

TOTAL NUMBER OF TRANSITIONS FROM ONE STATE TO ANOTHER FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

From State	To State 1	2	3	4	5	6	7	8	9
					Down State				
1	-	1	4	0	3	1	0	0	0
2	-	-	0	0	0	0	0	0	0
3	-	-	-	0	2	3	0	1	1
4	-	-	-	-	1	2	1	0	0
5	-	-	-	-	-	2	0	1	5
6	-	-	-	-	-	-	3	4	4
7	-	-	-	-	-	-	-	1	6
8	-	-	-	-	-	-	-	-	2
9	-	-	-	-	-	-	-	-	-
					Up State				
1	-	-	-	-	-	-	-	-	-
2	2	-	-	-	-	-	-	-	-
3	1	0	-	-	-	-	-	-	-
4	0	0	0	-	-	-	-	-	-
5	3	0	2	2	-	-	-	-	-
6	0	0	2	0	1	-	-	-	-
7	1	0	0	1	2	0	-	-	-
8	0	0	0	0	3	2	4	-	-
9	1	1	0	1	3	4	4	4	-

TABLE XIX

TOTAL NUMBER OF TRANSITIONS FROM ONE STATE TO ANOTHER FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

From State	To State 1	2	3	4	5	6	7	8	9
					Down State				
1	-	0	11	1	15	0	7	0	32
2	-	-	0	0	0	0	0	0	0
3	-	-	-	1	3	0	4	1	1
4	-	-	-	-	3	1	1	0	1
5	-	-	-	-	-	1	4	0	11
6	-	-	-	-	-	-	1	0	2
7	-	-	-	-	-	-	-	0	13
8	-	-	-	-	-	-	-	-	2
9	-	-	-	-	-	-	-	-	-
					Up State				
1	-	-	-	-	-	-	-	-	-
2	0	-	-	-	-	-	-	-	-
3	13	0	-	-	-	-	-	-	-
4	4	0	0	-	-	-	-	-	-
5	16	0	5	2	-	-	-	-	-
6	0	0	0	0	1	-	-	-	-
7	5	0	0	1	7	2	-	-	-
8	0	0	1	0	0	0	1	-	-
9	28	0	6	5	10	0	10	3	-

TABLE XX

RATE OF DEPARTURE FROM ONE STATE TO ANOTHER FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

From State	To State 1	2	3	4	5	6	7	8	9
					Down State				
1	-	0.0018450	0.0073801	0.0000000	0.005535	0.0018450	0.0000000	0.0000000	0.0000000
2	-	-	0.0000000	0.0000000	0.000000	0.0000000	0.0000000	0.0000000	0.0000000
3	-	-	-	0.0000000	0.250000	0.3750000	0.0000000	0.1250000	0.1250000
4	-	-	-	-	0.250000	0.5000000	0.2500000	0.0000000	0.0000000
5	-	-	-	-	-	0.1176471	0.0000000	0.0588235	0.2941176
6	-	-	-	-	-	-	0.2000000	0.2666667	0.2666667
7	-	-	-	-	-	-	-	0.0769231	0.4615384
8	-	-	-	-	-	-	-	-	0.1818181
9	-	-	-	-	-	-	-	-	-
					Up State				
1	-	-	-	-	-	-	-	-	-
2	1.0000000	-	-	-	-	-	-	-	-
3	0.1250000	0.0000000	-	-	-	-	-	-	-
4	0.0000000	0.0000000	0.0000000	-	-	-	-	-	-
5	0.1764706	0.0000000	0.1176471	-	-	-	-	-	-
6	0.0000000	0.0000000	0.1333333	0.0000000	0.6666667	-	-	-	-
7	0.0769231	0.0000000	0.0000000	0.0769231	0.1538461	0.0000000	-	-	-
8	0.0000000	0.0000000	0.0000000	0.0000000	0.2727273	0.1818181	0.3636363	-	-
9	0.0158730	0.0.58730	0.0000000	0.158730	0.0476190	0.0634921	0.0634921	0.0634921	-

TABLE XXI

RATE OF DEPARTURE TO DOWN AND UP STATES FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

From State	To State 1	2	3	4	5	6	7	8	9
					Down State				
1	-	0.0000000	0.0238095	0.0021645	0.0324675	0.0000000	0.0151515	0.0000000	0.0692641
2	-	-	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
3	-	-	-	0.0370370	0.1111111	0.0000000	0.1481481	0.0370370	0.0370370
4	-	-	-	-	0.3000000	0.1000000	0.1000000	0.0000000	0.1000000
5	-	-	-	-	-	0.0208333	0.0833333	0.0000000	0.2291666
6	-	-	-	-	-	-	0.2500000	0.0000000	0.5000000
7	-	-	-	-	-	-	-	0.0000000	0.3714285
8	-	-	-	-	-	-	-	-	0.5000000
					Up State				
1	-	-	-	-	-	-	-	-	-
2	0.0000000	-	-	-	-	-	-	-	-
3	0.4814814	0.0000000	-	-	-	-	-	-	-
4	0.4000000	0.0000000	0.0000000	-	-	-	-	-	-
5	0.3333333	0.0000000	0.1041666	0.0416667	-	-	-	-	-
6	0.0000000	0.0000000	0.0000000	0.0000000	0.2500000	-	-	-	-
7	0.1428571	0.0000000	0.0000000	0.0285714	0.2000000	0.0571429	-	-	-
8	0.0000000	0.0000000	0.2500000	0.0000000	0.0000000	0.0000000	0.0571429	-	-
9	0.1818181	0.0000000	0.0389610	0.0324675	0.0649350	0.0000000	0.0649350	0.0194805	-

TABLE XXII

EXACT COP TABLE FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

Cap. Out kW	Cap. In kW	Availability	Rate of Departure Down States	Rate of Departure Up States	Frequency of Encounter / hr.	Cycle Time in hrs.
0	100.0	0.8029630	0.0166052	0.0000000	0.0133333	75.00002
16	84.0	0.0029630	0.0000000	1.0000000	0.0029630	337.50000
30	70.0	0.0118519	0.8750000	0.1250000	0.0118519	84.37500
44	56.0	0.0059259	1.0000000	0.0000000	0.0059259	168.75000
58	42.0	0.0251852	0.4705882	0.4117647	0.0222222	45.00000
70	30.0	0.0222222	0.7333333	0.2000000	0.0207407	48.21429
80	20.0	0.0192593	0.5384615	0.3076923	0.0162963	61.36363
92	8.0	0.0162963	0.1818181	0.8181817	0.0162963	61.36365
100	0.0	0.0933333	0.0000000	0.2857143	0.0266667	37.50000

TABLE XXIII

EXACT COP TABLE FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

Cap. Out kW	Cap. In kW	Availability	Rate of Departure Down States	Rate of Departure Up States	Frequency of Encounter / hr.	Cycle Time in hrs.
0	100.0	0.6209677	0.1428571	0.0000000	0.0887096	11.273
30	70.0	0.0362903	0.3703703	0.4814814	0.0309140	32.348
44	56.0	0.0134409	0.5999998	0.4000000	0.0134409	74.400
58	42.0	0.0645161	0.3333333	0.4791666	0.0524193	19.077
70	30.0	0.0053763	0.7500000	0.2500000	0.0053763	186.000
80	20.0	0.0470430	0.3714285	0.4285714	0.0376344	26.571
92	8.0	0.0053763	0.5000000	0.5000000	0.0053763	186.000
100	0.0	0.2069892	0.0000000	0.4025971	0.0833333	12.000

as a Markov process, it is necessary to employ a Markov model for conventional generating units also.

3.4.1 Binary Model for Conventional Generating Units

A simple two-state model for a conventional generating unit is shown in Figure 22a. The unit is a reversible device which is either in the available (up) or in the repair (failed) state. It is assumed that the mean time to failure 'm' and the mean repair time 'r' are finite and constant. The assumption of a constant failure rate and a constant repair rate brings the conventional generating unit model into the most restrictive class of the Markov process. Since both m and r are finite and constant over a long period of time, the conventional generating unit availability is a fraction greater than zero.

Expressions for the time-dependent probabilities for the two states can be derived in a strightforward manner.

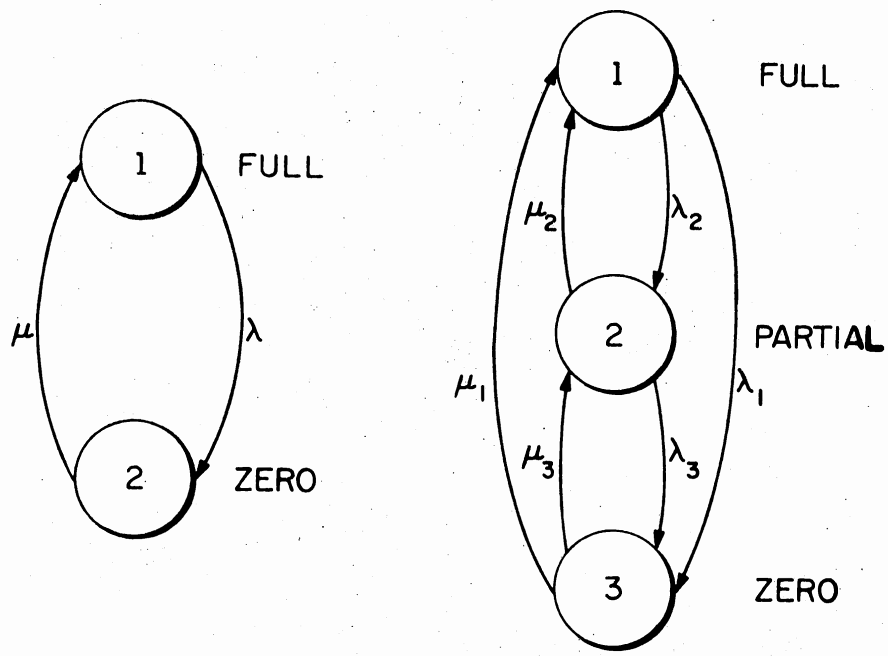
$$q_c(t) = \frac{\mu_c}{(\lambda_c+\mu_c)} + \frac{\lambda_c e^{-(\lambda_c+\mu_c)t}}{(\lambda_c+\mu_c)} \qquad (3.7)$$

$$1-q_c(t) = \frac{\lambda_c}{(\lambda_c+\mu_c)} - \frac{\lambda_c e^{-(\lambda_c+\mu_c)t}}{(\lambda_c+\mu_c)} \qquad (3.8)$$

The availability of the unit is:

$$A_c = \lim_{t\to\infty} q_c(t) \qquad (3.9)$$

$$= \frac{\mu_c}{(\lambda_c+\mu_c)} \qquad (3.10)$$



(a) (b)

Figure 22. Markov Models for Conventional Generating Units a) Binary Model, b) Ternary Model

$$\text{Unavailability} = \bar{A}_c = 1\text{-}A_c = \frac{\lambda_c}{\lambda_c+\mu_c} \qquad (3.11)$$

and

$$f_c = A_c\lambda_c = \bar{A}_c\mu_c \qquad (3.12)$$

3.4.2 Ternary Model for a Conventional Generating Unit

In the operation of a conventional generating unit, a partial capacity state may arise. This state is a relatively short-term randomly-occurring derated capacity of a generating unit and may be caused by the loss of a portion of the unit auxiliary equipment. Not included in the partial capacity state are seasonal, hence predictable, effects which may reduce the conventional generating unit maximum capability. With one partial capacity (or derated) state introduced in between the full capacity state and the zero capacity state (55), the transition diagram is shown in Figure 22b.

Substituting the appropriate parameters in the third order matrix derived from equation (A.6), and solving it gives the steady-state probabilities of the up state (A_{c1}), the derated state (A_{c2}) and the failed state (A_{c3}) as follows:

$$A_{c1} = (\mu_{c3}\mu_{c2} + \mu_{c1}\mu_{c2} + \mu_{c1}\lambda_{c3})/\text{Den} \qquad (3.13)$$

$$A_{c2} = (\mu_{c1}\lambda_{c2} + \mu_{c2}\lambda_{c1} + \mu_{c3}\lambda_{c2})/\text{Den} \qquad (3.14)$$

$$A_{c3} = (\mu_{c2}\lambda_{c1} + \lambda_{c3}\lambda_{c1} + \lambda_{c3}\lambda_{c2})/\text{Den} \qquad (3.15)$$

in which

$$Den = \mu_{c1}\mu_{c2} + \mu_{c2}\mu_{c3} + \mu_{c1}\lambda_{c2} + \mu_{c1}\lambda_{c3} + \mu_{c1}\lambda_{c1}$$

$$+ \mu_{c3}\lambda_{c2} + \lambda_{c1}\lambda_{c2} + \lambda_{c2}\lambda_{c3}$$

Cook et al. (55) have shown that there is a consistent but small difference between the ternary and the equivalent binary state representation of a conventional unit. These small differences do not strongly recommend the use of the more complex ternary representation for conventional generating units. Therefore, in this thesis, studies on combined systems (WECS and conventional generating units) are conducted by representing conventional generating units in equivalent binary states with the availability of the up state as 0.98 and with a failure and repair rates of (0.01/24) failures/hour and (0.49/24) repairs/hour, respectively (21).

3.5 Markov Model for a Combined (WECS and Conventional Generating Units) System

When a WECS is operated in parallel with two or more conventional generating units, from the point of view of modeling, it is convenient to start with the WECS and add one conventional generating unit at a time until all of them are included. Employing a binary model for each of the conventional generating units, the total number of output capacity states (N_T) for the combined system (one WECS plus N conventional generating units) is given by:

$$N_T = \begin{bmatrix}\text{total number of}\\ \text{output capacity}\\ \text{states for the WECS}\end{bmatrix} \times \begin{bmatrix}2^N\end{bmatrix} \qquad (3.16)$$

where N is the total number of conventional generating units operating in parallel with the WECS. All other parameters of the combined system are computed in a straightforward manner.

3.5.1 Identical Capacity States

In the construction of the exact-capacity availability or outage tables for a combined system, identical capacity states may be generated by different combinations of WECS and conventional generating unit capacities. In the transition diagram for such a system, if drawn, it will be seen that there is no possibility for direct transfer between any two identical capacity states. Therefore, such capacity states may be merged as discussed below.

Since transfer cannot occur directly between identical capacity states, their availabilities add directly. Let i and j be two identical capacity states and let k designate the merged state. Then the capacity and the availability for the merged state are given as follows (31):

Capacity

$$C_{gk} = C_{gi} = C_{gj} \tag{3.17}$$

Availability

$$A_{gk} = A_{gi} + A_{gj} \tag{3.18}$$

The total rates of departure from the merged state to lower and higher capacity states may be found, respectively, from

$$A_{gk}\,\lambda_{gk} = A_{gi}\,\lambda_{gi} + A_{gj}\lambda_{gj} \tag{3.19}$$

and

$$A_{gk}\mu_{gk} = A_{gi}\mu_{gi} + A_{gj}\mu_{gj} \tag{3.20}$$

By incorporating these relations, the exact capacity availability or outage table can be completed.

3.5.2 Frequency and Duration of Exact-capacity States of the Combined System

Once the availabilities and the rates of departure to down and up states have been determined, the frequency of encounter (f_{gk}) of a state and the duration of existence (D_{gk}) of that state are given by (56):

$$f_{gk} = (A_{gk})(\text{total rate of departure from state k}) \tag{3.21}$$

$$D_{gk} = \frac{A_{gk}}{f_{gk}} \tag{3.22}$$

In addition, the cycle time of exact state k of the combined system is:

$$\tau_{gk} = 1/f_{gk} \tag{3.23}$$

For a combined system with 33.3 percent penetration, Tables XXIV and XXV give the capacity on outage, capacity in service, availability, rates of departure to down and up states, frequency and cycle time for all the exact states.

TABLE XXIV

COP TABLE FOR A COMBINED SYSTEM WITH 33.3% PENETRATION FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

Cap. Out kW	Cap. In kW	Availability	Rate of Departure Down States	Rate of Departure Up State	Frequency (per hour)	Cycle Time (hours)
0	300.0	0.7711656	0.0174385	0.0000000	0.0134480	74.36
16	284.0	0.0028456	0.0008333	1.0000000	0.0028480	351.12
30	270.0	0.0113825	0.8758333	0.1250000	0.0113920	87.78
44	256.0	0.0056913	1.0008310	0.0000000	0.0056960	175.56
58	242.0	0.0241878	0.4714215	0.4117647	0.0213624	46.81
70	230.0	0.0213422	0.7341666	0.2000000	0.0199372	50.15
80	220.0	0.0184966	0.5392948	0.3076923	0.0156664	63.83
92	208.0	0.0156510	0.1826514	0.8181817	0.0156640	63.84
100	200.0	0.1211134	0.0050406	0.2167661	0.0268637	37.22
116	184.0	0.0001161	0.0004167	1.0204150	0.0001186	8434.00
130	170.0	0.0004646	0.8754165	0.1454166	0.0004743	2108.49
144	156.0	0.0002323	1.0004140	0.0204167	0.0002371	4217.00
158	142.0	0.0009873	0.4710047	0.4321812	0.0008917	1121.48
170	130.0	0.0008711	0.7337499	0.2204165	0.0008312	1203.10
180	120.0	0.0007550	0.5388780	0.3281086	0.0006545	1527.78
192	108.0	0.0006388	0.1822347	0.8385982	0.0006521	1533.45
200	100.0	0.0039798	0.0017231	0.2847207	0.0011400	877.19
216	84.0	0.0000012	0.0000000	1.0408320	0.0000012	833333.33
230	70.0	0.0000047	0.8750000	0.1658332	0.0000049	204081.63
244	56.0	0.0000024	1.0000000	0.0408333	0.0000025	400000.00
258	42.0	0.0000101	0.4705882	0.4525979	0.0000093	107526.88
270	30.0	0.0000089	0.7333333	0.2408332	0.0000087	114942.53
280	20.0	0.0000077	0.5384615	0.3485255	0.0000068	147058.82
292	8.0	0.0000065	0.1818181	0.8590149	0.0000068	147058.82
300	0.0	0.0000373	0.0000000	0.3265475	0.0000122	81967.21

TABLE XXV

COP TABLE FOR A COMBINED SYSTEM WITH 33.3% PENETRATION FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

Cap. Out kW	Cap. In kW	Availability	Rate of Departure Down States	Rate of Departure Up States	Frequency (per hour)	Cycle Time (hours)
0	300.0	0.5963774	0.1432911	0.0000000	0.085455	11.70
30	270.0	0.0348532	0.3708043	0.4814814	0.0297049	33.66
44	256.0	0.0129086	0.6004338	0.4000000	0.0129142	77.43
58	242.0	0.0619613	0.3337672	0.4791666	0.0503704	19.85
70	230.0	0.0051634	0.7504340	0.2500000	0.0051657	193.58
80	220.0	0.0451801	0.3718625	0.4285714	0.0361637	27.65
92	208.0	0.0051634	0.5004340	0.5000000	0.0051657	193.58
100	200.0	0.2231342	0.0159947	0.3598371	0.0838609	11.92
130	170.0	0.0014226	0.3705871	0.4921148	0.0012273	814.82
144	156.0	0.0005269	0.6002165	0.4106336	0.0005326	1877.59
158	142.0	0.0025290	0.3335502	0.4898000	0.0020823	480.24
170	130.0	0.0002108	0.7502169	0.2606335	0.0002130	4693.97
180	120.0	0.0018441	0.3716453	0.4392048	0.0014953	668.77
192	108.0	0.0002108	0.5002169	0.5106335	0.0002130	4693.97
200	100.0	0.0083623	0.0044538	0.4015882	0.0033955	294.51
230	70.0	0.0000145	0.3703703	0.5027487	0.0000127	78740.16
244	56.0	0.0000054	0.5999998	0.4212673	0.0000055	181818.18
258	42.0	0.0000258	0.3333333	0.5004339	0.0000215	46511.63
270	30.0	0.0000022	0.7500000	0.2712673	0.0000022	454545.45
280	20.0	0.0000188	0.3714285	0.4498387	0.0000155	64516.13
292	8.0	0.0000022	0.5000000	0.5212673	0.0000022	454545.45
300	0.0	0.0000828	0.0000000	0.4238644	0.0000351	28490.03

3.6 Calculation of a Reliability Index

The event in which ultimate interest rests is the "failure to carry the load" by the generation system. The term "failure to carry the load" includes any situation wherein it is impossible to perform maintenance as scheduled, absence of capacity available for spinning reserve or, still worse, a condition of inadequate capacity requiring system frequency and/or voltage reduction, actual shedding of various amounts of load, or a combination of such emergency measures. Such conditions occur when the available capacity is equal to or less than the load demand.

The generation capacity model described in the last section is in itself a measure of the reliability of the generation system. Generally, the system load undergoes hourly, daily, and seasonal variations. Generation capacity outages may not result in the system loss of load, depending on when the outage occurs. Thus, it appears that the computation of a more adequate measure of the overall system reliability entails the consideration of the expected load pattern. This will require the convolution of the exact state generation model developed earlier for the combined system (WECS plus conventional) with a suitable load model.

3.6.1 Load Model

Since the generation model is based on the Markov process, its combination with the load model to obtain the margin states requires the load model to be a Markov model also.

Appendix B describes the mathematical aspects of the load model that has been utilized in the present studies on frequency and duration approach to reliability evaluation (32). The load is modeled in terms of four hourly peak-load levels (assumed to exist throughout the hour) over a period of 24 hours. Further, it is assumed that the load demand pattern repeats itself on a daily basis during the entire period under consideration. Details of the load demand along with the peak load levels are given below (32):

Week Days (Monday through Friday)

Load Level	No. of Occurrences
peak load	8
80 percent of peak load	5
50 percent of peak load	3
30 percent of peak load	8
	24

Weekends (Saturday and Sunday)

Load Level	No. of Occurrences
peak load	4
80 percent of peak load	2
50 percent of peak load	2
30 percent of peak load	16
	24

Combining the above two load demand patterns (week days and weekends) gives an average load demand for the entire week as follows:

Average Load Demand Over a Week

Load Level	No. of Occurrences
peak load	7
80 percent of peak load	4
50 percent of peak load	3
30 percent of peak load	10
	24

The combined peak load levels and their durations, though not exact, are reasonably accurate for the development of a Markov load model for reliability studies.

Table XXVI shows a typical load model data arrived on the basis of the load demand discussed above. The peak load demand in this table is taken as equal to the installed capacity with a 33.3 percent penetration by WECS. To consider the influence of the load itself, the peak load in the model is varied from 50 percent to 100 percent of the total installed capacity in 10-percent steps.

TABLE XXVI

TYPICAL LOAD MODEL DATA

Load in kW	Availability	Rate of Departure	
		Down State	Up State
300	0.2916667	0.7391304	0.0000000
240	0.1666667	0.5652174	0.3043478
150	0.1250000	0.4347826	0.4782609
90	0.4166667	0.0000000	0.6086957

3.6.2 Reserve Margin - State Model

The exact capacity model developed in the section on identical capacity states and the load model described in the last section can be combined to yield such measures of reliability as the probability of occurrence, the frequency and the duration of the loss of load. As a first step, the models are combined to yield the probability and duration of margin states. Reserve or margin is defined as the available capacity minus the load demand (32). A margin state, m_k, is the result of the combination of the generation capacity, C_{gi}, and the load state, L_j, as given below:

$$m_k = C_{gi} - L_j \tag{3.24}$$

The computation of the complete margin (reserve) state array requires the computation of the rates of departure to smaller and larger margin states. The rates of departure to down (smaller) and up (larger) margin states are given as:

$$\lambda_{mk} = \lambda_{gi} + \mu_{Lj} \tag{3.25}$$

$$\mu_{mk} = \mu_{gi} + \lambda_{Lj} \tag{3.26}$$

In other words, assuming independent generation capacity states and load states, the rate of transfer from a given margin state to a lower (higher) margin state is equal to the rate of transfer down (up) in capacity plus the rate of transfer up (down) in load.

The availability of the margin state is given by

$$A_{mk} = A_{gi}A_{Lj} \tag{3.27}$$

Table XXVII illustrates a typical margin-state array for the exact margin states. This table involves a two-machine system (one WECS and

TABLE XXVII

MARGIN STATE ARRAY FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

		L_i	160.0	128.0	80.0	48.0
Load →		A_{Li}	0.2916667	0.1666667	0.1250000	0.4166667
Generation		λ_{Li}	0.7391304	0.5652174	0.4347826	0.0000000
↓		μ_{Li}	0.0000000	0.3043478	0.4782608	0.6086956
C_1 =	200.0	m	40.0	72.0	120.0	152.0
A_{g1} =	0.7869037	A_m	0.2295136	0.1311505	0.0983629	0.3278764
λ_{g1} =	0.0170218	λ_m	0.0170218	0.3213696	0.4952826	0.6257174
μ_{g1} =	0.0000000	μ_m	0.7391304	0.5652174	0.4347826	0.0000000
	184.0		24.0	56.0	104.0	136.0
	0.0029037		0.0008469	0.0004840	0.0003630	0.0012099
	0.0004167		0.0004167	0.3047644	0.4786775	0.6091123
	1.0000000		1.7391300	1.5652170	1.4347820	1.0000000
	170.0		10.0	42.0	90.0	122.0
	0.0116148		0.0033877	0.0019358	0.0014519	0.0048395
	0.8754166		0.8754166	1.1797630	1.3536760	1.4841110
	0.1250000		0.8641304	0.6902174	0.5597826	0.1250000
	156.0		-4.0	28.0	76.0	108.0
	0.0058074		0.0016938	0.0009679	0.0007259	0.0024198
	1.0004150		1.0004150	1.3047620	1.4786750	1.6091100
	0.0000000		0.7391304	0.5652174	0.4347826	0.0000000
	142.0		-18.0	14.0	62.0	94.0
	0.0246815		0.0071988	0.0041136	0.0030852	0.0102830
	0.4710048		0.4710048	0.7753527	0.9492657	1.0797000
	0.4117647		1.1508940	0.9769821	0.8465472	0.4117647
	130.0		-30.0	2.0	50.0	82.0
	0.0217778		0.0063518	0.0036296	0.0027222	0.0090741
	0.7337499		0.7337499	1.0380970	1.2120100	1.3424450
	0.2000000		0.9391304	0.7652174	0.6347820	0.2000000
	120.0		-40.0	-8.0	40.0	72.0
	0.0188741		0.0055049	0.0031457	0.0023593	0.0078642
	0.5388781		0.5388781	0.8432260	1.0171380	1.1475730
	0.3076923		1.0468220	0.8729097	0.7424749	0.3076923
	108.0		-52.0	-20.0	28.0	60.0
	0.0159704		0.0046580	0.0026617	0.0019963	0.0066543
	0.1822348		0.1822348	0.4865826	0.6604956	0.7909304
	1.1818187		1.5573120	1.3833990	1.2529640	0.8181817
	100.0		-60.0	-28.0	20.0	52.0
	0.1075258		0.0313617	0.0179210	0.0134407	0.0448024
	0.0028345		0.0028345	0.3071823	0.4810953	0.6115301
	0.2460914		0.9852218	0.8113088	0.6808740	0.2460914

TABLE XXVII (Continued)

L_i	160.0	128.0	80.0	48.0
Load → A_{Li}	0.2916667	0.1666667	0.1250000	0.4166667
Generation λ_{Li}	0.7391304	0.5652174	0.4347826	0.0000000
↓ μ_{Li}	0.0000000	0.3043478	0.4782608	0.6086955
84.0	-76.0	-44.0	4.0	36.0
0.0000593	0.0000173	0.0000099	0.0000074	0.0000247
0.0000000	0.0000000	0.3043478	0.4782608	0.6086956
1.0204160	1.7595460	1.5856330	1.4551980	1.0204160
70.0	-90.0	-58.0	-10.0	22.0
0.0002370	0.0000691	0.0000395	0.0000296	0.0000988
0.8750000	0.8750000	1.1793470	1.3532600	1.4836950
0.1454166	0.8845470	0.7106340	0.5801992	0.1454166
56.0	-104.0	-72.0	-24.0	8.0
0.0001185	0.0000346	0.0000198	0.0000148	0.0000494
1.0000000	1.0000000	1.3043470	1.4782600	1.6086950
0.0204167	0.7595470	0.5856340	0.4551992	0.0204167
42.0	-118.0	-86.0	-38.0	-6.0
0.0005037	0.0001469	0.0000840	0.0000630	0.0002099
0.4705882	0.4705882	0.7749360	0.9488490	0.0792830
0.4321813	1.1713110	0.9973987	0.8669639	0.4321813
30.0	-130.0	-98.0	-50.0	-18.0
0.0004444	0.0001296	0.0000741	0.0000556	0.0001852
0.7333333	0.7333333	1.0376800	1.2115930	1.3420280
0.2204166	0.9595470	0.7856340	0.6551992	0.2204166
20.0	-140.0	-108.0	-60.0	-28.0
0.0003852	0.0001123	0.0000642	0.0000481	0.0001605
0.5384615	0.5384615	0.8428093	1.0167210	1.1471560
0.3281089	1.0672380	0.8933263	0.7628915	0.3281089
8.0	-152.0	-120.0	-72.0	-40.0
0.0003259	0.0000951	0.0000543	0.0000407	0.0001358
0.1818181	0.1818181	0.4861659	0.6600789	0.7905138
0.8385983	1.5777280	1.4038150	1.2733800	0.8385983
0.0	-160.0	-128.0	-80.0	-48.0
0.0018667	0.0005444	0.0003111	0.0002333	0.0007778
0.0000000	0.0000000	0.3043478	0.4782608	0.6086956
0.3061309	1.0452600	0.8713483	0.7409135	0.3061309

one conventional generating unit, i.e., 50 percent penetration by WECS) and the load model has four states (Figure 23). The entries in this table for exact margin states represent all possible combinations of generation states and load states.

The frequency of encounter of an exact margin state is given by

$$f_{mk} = (A_{mk})(\lambda_{mk} + \mu_{mk}) \tag{3.28}$$

and the cycle time is given by the reciprocal of the frequency.

In the construction of the exact margin state array for a large generation system with a multi-state load model, identical margin states may be generated. Following the reasoning discussed earlier, these identical margin states can be merged as follows:

$$m_k = m_1 = m_2 = \ldots\ldots m_{N1} \tag{3.29}$$

$$A_{mk} = \sum_{\ell=1}^{N1} A_{m\ell} \tag{3.30}$$

$$f_{mk} = \sum_{\ell=1}^{N1} f_{m\ell} \tag{3.31}$$

and

$$\lambda_{mk} = \sum_{\ell=1}^{N1} A_{m\ell}\lambda_{m\ell}/A_{mk} \tag{3.32}$$

$$\mu_{mk} = \sum_{\ell=1}^{N1} A_{m\ell}\mu_{m\ell}/A_{mk} \tag{3.33}$$

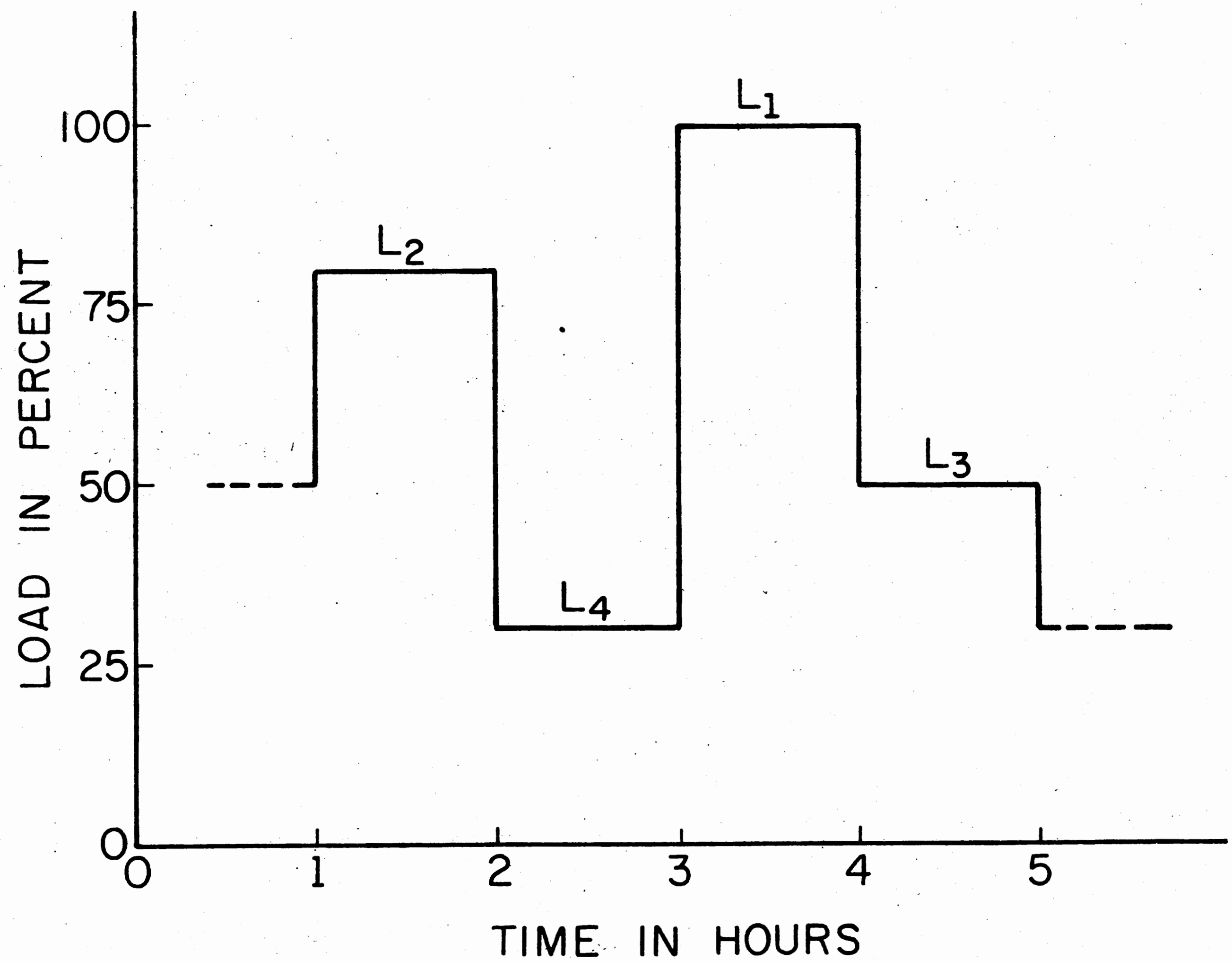


Figure 23. Typical Load Model Based on Markov Chain With Hourly Peak Loads

Equations (3.30) to (3.33) assume that no transfer can take place between any two identical margin states without passing through an intermediate state of differing margin.

3.6.3 Cumulative Margin State

In the case of loss of load probability method, sometimes it is more informative to know the probability of finding an outage of a certain capacity or greater. Similar reasoning holds good in the case of the frequency and duration method for generation model as well as for the reserve margin state model. The availabilities of the cumulative reserve margin states are obtained by first arranging the reserve margin states along with their availabilities in the ascending order starting with the most negative margin state up to the largest margin. Next, the availabilities are summed in a cumulative fashion. The reserve margin states along with their cumulative availabilities are then rearranged in the descending order starting with the largest margin down to the most negative margin. Such cumulative reserve margin data are shown in Tables XXVIII and XXIX for the examples discussed earlier.

3.6.4 Reliability Index

The reserve margin has been defined as the available generation capacity minus the load and a cumulative margin state contains all states with margins less than or equal to the specified margin. Based on this description, a negative margin state constitutes a loss of load due to a deficiency in the system generation capacity of magnitude equal to the margin and a cumulative negative margin state corresponds to a loss of load due to a generation deficiency greater than or equal

TABLE XXVIII

MARGIN STATE PROBABILITIES FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

Margin State in kW	Cumulative Probability	Margin State in kW	Cumulative Probability
255.0	0.9999985	45.0	0.0043410
239.0	0.6786795	39.0	0.0042466
225.0	0.6774939	36.0	0.0042462
211.0	0.5763555	34.0	0.0042074
209.0	0.5739842	33.0	0.0041736
197.0	0.5736285	25.0	0.0040937
195.0	0.5635503	22.0	0.0035943
185.0	0.5621275	20.0	0.0034297
181.0	0.5532350	11.0	0.0032942
180.0	0.5525236	10.0	0.0032932
175.0	0.4239961	9.0	0.0031480
167.0	0.4162892	6.0	0.0031479
164.0	0.4132658	0.0	0.0030801
163.0	0.4127916	-3.0	0.0029543
155.0	0.4062703	-5.0	0.0029501
150.0	0.3531387	-8.0	0.0029495
145.0	0.1263184	-12.0	0.0026616
139.0	0.1240063	-15.0	0.0025551
136.0	0.1239580	-19.0	0.0025514
134.0	0.1230095	-20.0	0.0025511
133.0	0.1221796	-25.0	0.0016337
125.0	0.1202232	-30.0	0.0016305
122.0	0.1048905	-33.0	0.0014103
120.0	0.1008592	-36.0	0.0014091
111.0	0.0975394	-37.0	0.0014089
110.0	0.0974426	-42.0	0.0014061
109.0	0.0938856	-45.0	0.0012198
106.0	0.0938711	-50.0	0.0012032
100.0	0.0922112	-55.0	0.0000416
97.0	0.0891284	-64.0	0.0000406
95.0	0.0887171	-66.0	0.0000402
92.0	0.0886590	-67.0	0.0000399
88.0	0.0816043	-75.0	0.0000391
85.0	0.0789958	-78.0	0.0000344
81.0	0.0786329	-80.0	0.0000327
80.0	0.0786039	-90.0	0.0000313
75.0	0.0521935	-94.0	0.0000299
70.0	0.0518790	-100.0	0.0000292
67.0	0.0464841	-108.0	0.0000279
64.0	0.0463607	-112.0	0.0000249
63.0	0.0463414	-120.0	0.0000239
58.0	0.0460752	-130.0	0.0000150
55.0	0.0415103	-142.0	0.0000128
50.0	0.0397432	-150.0	0.0000109

TABLE XXIX

MARGIN STATE PROBABILITIES FOR MAY, 1974, FOR THE SITE 'LIVERMORE'

Margin State in kW	Cumulative Probability	Margin State in kW	Cumulative Probability
255.0	0.9999985	36.0	0.0079099
225.0	0.7515080	33.0	0.0078221
211.0	0.6624387	25.0	0.0077957
197.0	0.6570601	22.0	0.0067444
195.0	0.6312430	20.0	0.0063229
185.0	0.6268864	11.0	0.0059080
181.0	0.6247349	10.0	0.0059057
180.0	0.6231214	6.0	0.0058706
175.0	0.5237252	0.0	0.0057169
167.0	0.5049002	-3.0	0.0054096
163.0	0.4971551	-5.0	0.0053989
155.0	0.4950036	-8.0	0.0053970
150.0	0.4013857	-12.0	0.0046594
145.0	0.2216335	-15.0	0.0046243
136.0	0.2159860	-19.0	0.0046234
133.0	0.2138346	-20.0	0.0046227
125.0	0.2131892	-25.0	0.0031675
122.0	0.1847047	-30.0	0.0031597
120.0	0.1743779	-33.0	0.0026218
111.0	0.1642123	-37.0	0.0026186
110.0	0.1639928	-42.0	0.0026177
106.0	0.1631323	-45.0	0.0025562
100.0	0.1593673	-50.0	0.0025215
97.0	0.1518373	-55.0	0.0000800
95.0	0.1507835	-64.0	0.0000777
92.0	0.1506057	-67.0	0.0000768
88.0	0.1325337	-75.0	0.0000765
85.0	0.1316732	-78.0	0.0000662
81.0	0.1315854	-80.0	0.0000619
80.0	0.1315196	-90.0	0.0000576
75.0	0.0928246	-94.0	0.0000573
70.0	0.0920562	-100.0	0.0000557
67.0	0.0788787	-108.0	0.0000526
63.0	0.0785626	-112.0	0.0000450
58.0	0.0784748	-120.0	0.0000447
55.0	0.0769688	-130.0	0.0000303
50.0	0.0734582	-142.0	0.0000248
45.0	0.0081404	-150.0	0.0000241

to the specified reserve margin. The availability of the first negative cumulative reserve margin state may be converted to a number representing the loss of load for the period under consideration as follows (57):

$$\left.\begin{array}{l}\text{loss of load}\\ \text{expectancy index}\\ \text{(for the period}\\ \text{under study)}\end{array}\right\} = \left[\begin{array}{l}\text{cumulative probability}\\ \text{of the first negative}\\ \text{margin state}\end{array}\right] \times \left[\begin{array}{l}\text{total number}\\ \text{of hours}\\ \text{under study}\end{array}\right] \quad (3.34)$$

Tables XXX and XXXI show the loss of load expectancy or reliability index for the two sites, 'Kahuku Upper' and 'Livermore' for the same load with different penetrations of WECS.

3.7 Discussion of Results

Though the results for the expected loss of load for WECS assisted generation systems are available for a two-year period for the site, 'Kahuku Upper,' because of the consistent nature of the results, it is sufficient to consider the months with high and low mean wind speeds. The expected loss of load for wind assisted systems depends on three major parameters: wind regime, penetration and load demand, as shown in tables for 'Kahuku Upper' and 'Livermore.' An examination of these tables reveals that, for a given wind regime and with a certain value of penetration by WECS, an increase in the system load demand causes a slight increase in the expected loss of load for the system as long as the load demand is less than or equal to the total conventional generation. When the load demand exceeds the conventional generation capacity, there is a steep rise in the expected loss of load, indicating the low load-carrying capability of WECS. The extent of the occurrence of the expected loss of load depends mainly on the wind regime.

TABLE XXX

LOSS OF LOAD EXPECTANCY TABLE FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'*

Peak Load % of Installed Capacity	Penetration							
	33.3%	25%	20%	16.66%	14.3%	12.5%	11.1%	10%
50	1.99	0.07	0.09	0.00	0.00	0.00	0.00	0.00
60	2.43	1.99	0.14	0.15	0.15	0.00	0.00	0.00
70	29.74	3.42	3.13	2.82	0.24	0.32	0.32	0.01
80	37.70	33.19	4.57	4.37	5.13	5.35	5.03	0.59
90	59.11	46.81	49.13	47.81	46.73	44.89	47.99	8.71
100	66.47	66.37	53.03	56.42	59.70	62.62	65.24	65.39

*(hours)

TABLE XXXI

LOSS OF LOAD EXPECTANCY TABLE FOR MAY, 1974, FOR THE SITE 'LIVERMORE'*

Peak Load % of Installed Capacity	Penetration							
	33.3%	25%	20%	16.66%	14.3%	12.5%	11.1%	10%
50	4.02	0.15	0.17	0.01	0.00	0.00	0.00	0.00
60	5.02	3.65	0.28	0.29	0.28	0.01	0.01	0.00
70	55.40	7.03	6.00	5.21	0.49	0.61	0.63	0.02
80	66.53	58.67	8.97	8.60	9.54	9.04	8.63	1.14
90	111.27	85.74	86.31	76.29	78.12	68.99	72.02	15.80
100	125.31	122.37	96.61	100.00	102.94	105.05	107.27	105.27

*(hours)

A better wind regime gives a lower value for the loss of load, and vice versa. The influence of penetration on the expected loss of load is complicated by the fact that the load model is not linear but stepped (Markov model with discrete load levels). In general, a decrease in the penetration causes a decrease in the loss of load.

3.8 Conclusions

A Markov model for WECS has been developed on the basis of available hourly wind speed data. The parameters for the model are evaluated by extracting information from the hourly wind speed data over a certain period of time. The model is then used to compute the reliability of a combined system by the frequency and duration approach.

The main step in the approach is the modeling of WECS by a certain number of output capacity states. This number depends both on the type of hourly wind speed data available and on the characteristics of the WECS under consideration. Once the number of states to be employed in the model is decided, computation of parameters of the model is straightforward, as described in this chapter. The WECS model thus developed is combined with the model for conventional generating units to obtain a model for the combined system. An integration of this model with a load model (based on the Markov chain) yields a set of reserve margin states which could be further utilized to compute a reliability index--a technique which is well developed and described in the literature.

The Markov model developed for WECS allows the inclusion of other components of the power system such as transmission and distribution lines to evaluate the overall reliability of the complete system. This topic is discussed in the next chapter.

Tables of expected loss of load given in this chapter are for two typical sites--totally different in terrain and geography. They provide an insight into the reliability aspects of WECS in power systems.

CHAPTER IV

INFLUENCE OF TRANSMISSION SYSTEM ON THE RELIABILITY OF WECS ASSISTED UTILITY SYSTEMS

4.1 Introduction

Over the last few decades, power system planning engineers have been posed with the problem of obtaining a meaningful quantitative relationship between power system reliability and the cost of the system. This involves a study and evaluation of all three major branches--generation, transmission, and distribution. Modes and events leading to a failure of the system, development of mathematical models and a determination of the parameters involved and their applications to actual situations leading to the reliability evaluation process for the three branches mentioned above are fairly well developed. In the reliability evaluation process, the generation system has been rated high (meaning most developed) among the three branches, since investigations in this area have been initiated early and extensively carried over the last several decades. Next in the rating is the distribution branch. The transmission sector of the power system has been rated low in the reliability evaluation process. It does not mean that the transmission system is the most unreliable sector of the power system; in fact, of the total failures in a power system, transmission system failures account for only ten percent. Though the failures in the transmission system are fewer in number, they could become a major cause of collapse of the power system, as happened in the big northeast blackout in the United States in November, 1965, and again in New York City in July, 1977. The major reason for such disastrous failures is the complex nature of the transmission sector compared to the simple parallel configuration of the generation system and the series structure in distribution systems (58).

The transmission system would be an integral part of future WECS installations because their most likely locations would be far from load centers and they should be interconnected with utility grids to avoid the large loss of load (see Chapters II and III). In this chapter, influence of the transmission system has been considered in its simplest form. The cases discussed are 1) a WECS connected to a load bus by a transmission line; 2) a WECS operating in parallel with a number of conventional generating units supplying a load center through a transmission line, and 3) a WECS in series with a transmission line is connected to a load bus; at the load bus, a number of conventional generating units are operating in parallel.

This chapter also considers the parallel operation of two WECS (located in totally different wind regimes) interconnected by a transmission line and develops a capacity outage probability table for such a system configuration.

4.2 Transmission System Outages

Reliability studies on transmission systems were initiated in the fifties. Earlier papers (59 to 61) on primary feeders and distributors discuss the basic reliability concepts, modeling and estimation of parameters and their application in reliability analyses. The studies in this area took an important turn with the publication of two papers (62, 63) in 1964 by Todd, and Gaver et al., wherein environmental severity variations were considered in an analysis based on the Markov theory.

Transmission system outages may be "scheduled" or forced. In either case, the outage occurs when the circuit breaker at the source bus is tripped. Under proper network operation, this should result in automatic tripping of all of the network protective circuit breakers located in the low voltage side of the network transformers supplied by the primary feeders. Thus, the primary feeder is totally isolated from the source as well as the distribution network.

When the feeder is ready for service, it is re-energized by closing the circuit breaker at the source bus. Under proper voltage conditions, the system delivers power from the source to the distribution network. If a number of feeders emanate from a bulk power source, an outage of one primary feeder reduces the total feeder and transformer capacity. In most power systems, the outage of a single feeder can be tolerated for a considerable length of time. However, consecutive losses of additional feeders would bring the remaining feeders as well as network-unit capacity below that required to meet the load demand.

Scheduled outages of transmission systems are initiated for the purpose of testing, maintenance, or network extension. Since such outages are scheduled, the time of their occurrence is known and their duration of existence can be estimated. But studies on forced outages require a probabilistic approach. Such outages may arise due to network transformer faults, cable failure, junction failures, and the like.

In recent studies on composite (generation plus transmission) systems, the evaluation of the risk of loss of load included contingencies such as unacceptable voltages and circuit overloads (64). But, as the first step in the studies pursued in this chapter, only the transmission system outages are considered. The transformers and other protective devices are assumed to be ideal with 100 percent availabilities. Further, it has been assumed that the transmission system is operating in normal weather environment all of the time (one state condition of environment) and contingencies such as unacceptable voltages and circuit overloads are not possible.

4.3 Markov Model for a Transmission Line

Under the assumptions stipulated in the last section, all transmission systems reduce to a single transmission line for the examples considered in this chapter. A transmission line has two possible states--an operable state or state No. 1 (full capacity output state or Up state), and a failed state or state No. 2 (zero capacity output state or Down state). A third state or partial capacity state is not possible. The up-times and the down-times are assumed to be exponentially distributed. Transitions from one state to the other are allowed at any instant of time. This brings the transmission line model into the homogeneous discrete-state continuous-time Markov process discussed previously. Figure 22a shows the state space diagram for this binary model. Since up-times and down-times are exponentially distributed, transition rates λ_T and μ_T in the model are constant. With a transition from up-state to down-state of λ_T, the expected value of up-time or the residence time in state No. 1 is $(1/\lambda_T)$ and, similarly, with the transition rate from down-state to up-state being μ_T, the expected value of down time or the residence time in state No. 2 is $(1/\mu_T)$.

For this binary model, the availability and the unavailability can be computed, as discussed previously. The results are:

$$A_T = \frac{\mu_T}{\lambda_T + \mu_T} \tag{4.1}$$

$$\bar{A}_T = 1 - A_T = \frac{\lambda_T}{\lambda_T + \mu_T} \tag{4.2}$$

The transmission line considered for studies in this chapter is assumed to have failure and repair rates of 0.002/24 failures/hour and 1.998/24 repairs/hour. This gives the availability (steady state probability of the Up state) for the line as 0.999 (32).

4.4 Generation Models

Evaluation of the reliability at the load bus due to the combined effects of generation and transmission facilities requires models for both generation and transmission systems. A model for the transmission line based on the Markov process has been discussed in the last section. The generation system consists of WECS as well as conventional units. An individual model for each of the two types of generation and a model for the combined system are necessary for the reliability studies in this chapter. Markov models for WECS, conventional generation units and for the combined system have already been discussed in Chapter III. These models are employed in the evaluation of the reliability of composite systems at the load bus, as discussed in the next section.

4.5 Case Studies

Three typical cases are examined to study the effect of including the transmission system in the reliability calculations. These cases, though simple, represent the basic configurations expected to be encountered as WECS make their entry into the power systems of the future. The following assumptions are implicit in the analysis that follows:

a) The model for the transmission line is based on a two-state Markov process.

b) The model for the WECS and conventional generation system are also based on the Markov process.

c) The behavior of the transmission line, WECS and conventional generation units are statistically independent of each other.

The three examples considered for analysis are based on simple configurations of the composite system wherein one WECS and a single transmission line are present along with a number of conventional generating units. The point of interest is the load bus. The three examples studied are given below.

I. One WECS connected to a load bus by a transmission line (Figure 24a).

II. One WECS, operating in parallel with a number of conventional generating units supplying a load center through a transmission line (Figure 24b).

III. A WECS in series with a single transmission line is connected to a load bus; at the load bus a number of conventional generating units are operating in parallel (Figure 24c).

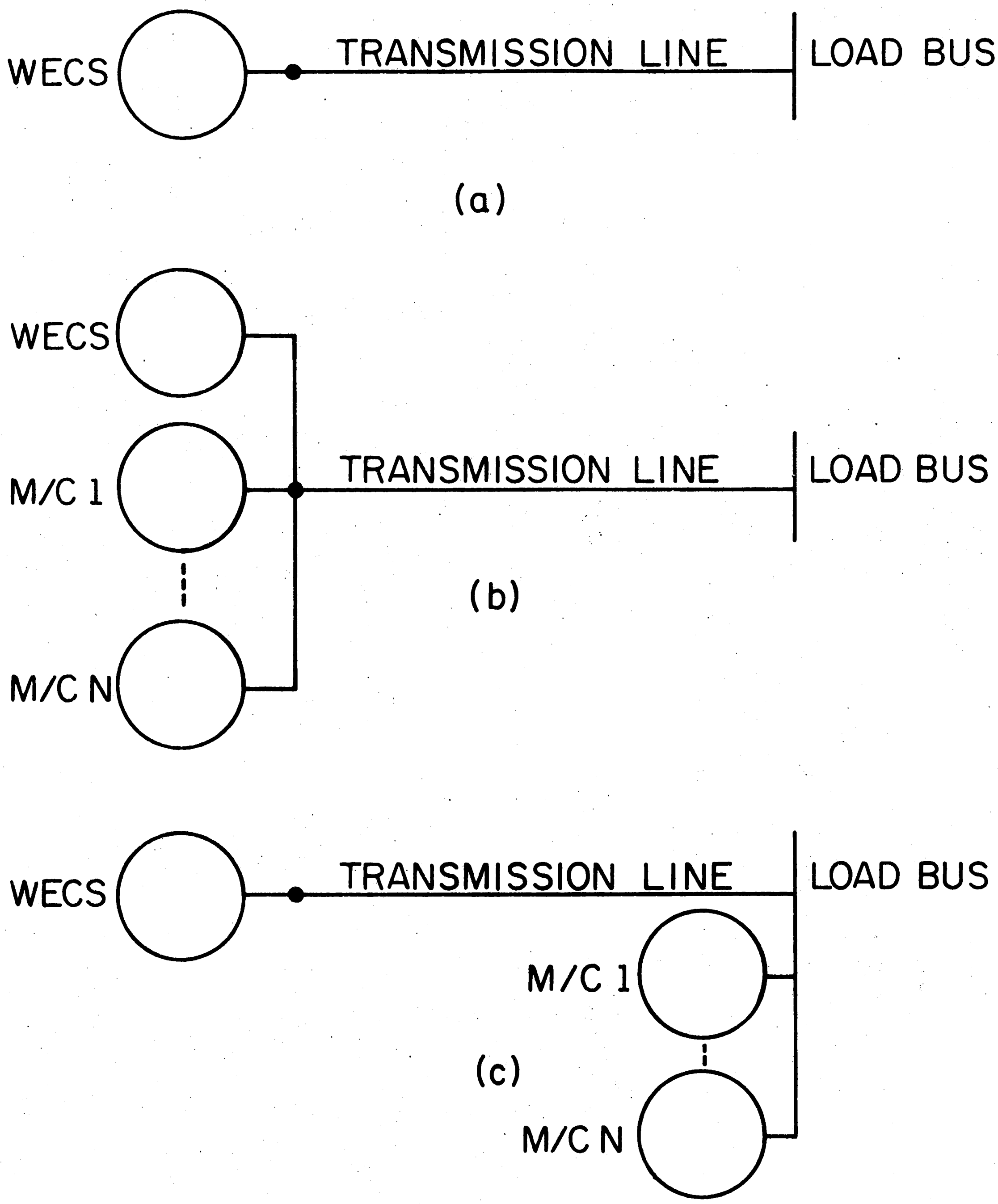


Figure 24. Composite Systems Under Study

Examples I and II are similar in nature; example III is a simple extension of example I. As such, example I is discussed in detail.

Example I

The two-state model for transmission line discussed in the section on the Markov model for a transmission line, with capacity C_T and failure and repair rates of λ_T and μ_T is considered in the analysis. The model used for WECS is a multi-state model discussed in the section on the Markov model for WECS. The ultimate objective of the analysis is to obtain a list of capacities available, availabilities of various capacities and the frequency of their occurrence, all at the load bus. This information is obtained by analyzing the system in two steps (32).

Step (i) - Transmission line is up.

When the transmission line is up, the output capacity at the load bus is the generation capacity as long as it does not exceed the capacity of the transmission line. Therefore, the capacity available is

$$C_{wkT} = \min\ (C_{wk},\ C_T) \tag{4.3}$$

and the availability of the capacity C_{wkT} is

$$A_{wkT} = A_{wk} \cdot A_T \tag{4.4}$$

Since the behaviors of the generation system and the transmission line are assumed to be statistically independent, and since these two are in series, the total rate of departure to lower capacity state is computed from the fact that either the capacity of WECS can go down or the capacity of the transmission line can go down. Thus,

$$\lambda_{wkT} = \lambda_{wk} + \lambda_T \tag{4.5}$$

Since the transmission line is in the Up state and as it does not have a higher capacity state, the rate of departure to the higher capacity state is equal to the total rate of departure (to a higher capacity state) of the generation system alone. Thus,

$$\mu_{wkT} = \mu_{wk} \tag{4.6}$$

Step (ii) - Transmission line is down.

When the transmission line is down, the output capacity at the load bus being equal to the generation capacity not exceeding the capacity of the transmission line which is zero, we get

$$C_{wkT} = \min (C_{wk}, C_T) \tag{4.7}$$

$$= 0$$

and the availability of the capacity C_{wkT} is

$$A_{wkT} = A_{wk} \cdot \bar{A}_T \tag{4.8}$$

With the transmission line down, the total rate of departure to Down state obviously is

$$\lambda_{wkT} = 0 \tag{4.9}$$

Unless the transmission line goes up, the output of the system cannot go up. Therefore, the total rate of departure to Up state is

$$\mu_{wkT} = \mu_T \tag{4.10}$$

When the results of step (i) and step (ii) are arranged in the descending order of capacities, one may encounter identical capacity states. These identical capacity states can be merged as before into a single equivalent merged state using equations (3.17) through (3.20) (see pages 84-85). The results for a 100 kW WECS in series with a transmission line of 100 kW capacity is given in Table XXXII. It is logical to have a transmission line capacity of 100 kW to utilize the full output of the WECS whenever it is available.

Example II

Since the generation due to WECS is statistically independent of the generation capacity of conventional generation units, the procedure discussed in the section on the Markov model for a combined system can be used to construct a combined system model. Once a model for the combined system is available, steps (i) and (ii) of Example I can be followed to derive the capacities available, availabilities of various capacities and the total rate of departure to lower and higher capacities at the load bus. The results for a 20 percent penetration of WECS and a transmission line of 500 kW capacity are given in Table XXXIII.

Example III

The procedure outlined for Example I gives the capacities available, availabilities of various capacity states, and the total rates of departure to lower and higher capacities at the load bus due to a WECS and a transmission line. Since at the load bus a number of conventional generating units are operating in parallel, because of the statistically independent behavior of WECS, transmission line and conventional generation units, the conventional generation unit model can be combined with the model of a WECS in series with a transmission line (Example I) in a straightforward manner. The results shown in

TABLE XXXII

COP TABLE FOR WECS IN SERIES WITH A TRANSMISSION LINE

Cap. Out kW	Cap. In kW	Availability	Rate of Departure Down States	Rate of Departure Up States	Frequency of Encounter / hr.	Cycle Time in hrs.
0	100	0.8021600	0.0166885	0.0000000	0.0133868	74.70
16	84	0.0029600	0.0000833	1.0000000	0.0029602	337.81
30	70	0.0018400	0.8750833	0.1250000	0.0118410	84.45
44	56	0.0059200	1.0000820	0.0000000	0.0059205	168.91
58	42	0.0251600	0.4706715	0.4117647	0.0222021	45.05
70	30	0.0222000	0.7334166	0.2000000	0.0207218	48.26
80	20	0.0192400	0.5385448	0.3076923	0.0162816	61.42
92	8	0.0162800	0.1819015	0.8181817	0.0162814	61.42
100	0	0.0941464	0.0000000	0.2837632	0.0267153	37.43

TABLE XXXIII

COP TABLE FOR COMBINED WIND ELECTRIC AND CONVENTIONAL UNITS IN SERIES WITH A TRANSMISSION LINE FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

Cap. Out kW	Cap. In kW	Availability	Rate of Departure Down States	Rate of Departure Up State	Frequency of Encounter / hrs.	Cycle Time in hrs.
0	500.0	0.7406275	0.0166233	0.0000000	0.0123117	81.22
16	484.0	0.0027329	0.0000181	1.0000000	0.0027330	365.90
30	470.0	0.0109318	0.8750181	0.1250000	0.0109319	91.48
44	456.0	0.0054659	1.0000170	0.0000000	0.0054660	182.95
58	442.0	0.0232300	0.4706063	0.4117647	0.0204975	48.79
70	430.0	0.0204971	0.7333513	0.2000000	0.0191310	52.27
80	420.0	0.0177641	0.5384796	0.3076923	0.0150315	66.53
92	408.0	0.0150312	0.1818362	0.8181817	0.0150314	66.53
100	400.0	0.1465467	0.0068669	0.1679318	0.0256162	39.04
116	384.0	0.0002231	0.0000136	1.0002200	0.0002231	4481.30
130	370.0	0.0008924	0.8750133	0.1252218	0.0008926	1120.33
144	356.0	0.0004462	1.0000120	0.0002219	0.0004463	2240.66
158	342.0	0.0018963	0.4706015	0.4119862	0.0016737	597.49
170	330.0	0.0016732	0.7333463	0.2002214	0.0015621	640.18
180	320.0	0.0014501	0.5384747	0.3079139	0.0012274	814.75
192	308.0	0.0012270	0.1818316	0.8184031	0.0012273	814.78
200	300.0	0.0088783	0.0024742	0.2264221	0.0020411	489.93
216	284.0	0.0000068	0.0000091	1.0004410	0.0000068	146357.80
230	270.0	0.0000273	0.8750088	0.1254438	0.0000273	36589.42
244	256.0	0.0000137	1.0000060	0.0004438	0.0000137	73178.94
258	242.0	0.0000581	0.4705969	0.4122082	0.0000512	19513.18
270	230.0	0.0000512	0.7333416	0.2004436	0.0000478	20907.57
280	220.0	0.0000444	0.5384701	0.3081358	0.0000376	26608.30
292	208.0	0.0000376	0.1818270	0.8186246	0.0000376	26610.52
300	200.0	0.0002403	0.0017486	0.2562426	0.0000620	16129.62
316	184.0	0.0000001	0.0000045	1.0006630	0.0000001	
330	170.0	0.0000004	0.8750043	0.1256656	0.0000004	2688738.00
344	156.0	0.0000002	1.0000020	0.0006658	0.0000002	5377485.00
358	142.0	0.0000008	0.4705926	0.4124302	0.0000007	1433866.00
370	130.0	0.0000007	0.7333373	0.2006655	0.0000007	1536349.00
380	120.0	0.0000006	0.5384659	0.3083577	0.0000005	1955207.00
392	108.0	0.0000005	0.1818224	0.8188470	0.0000005	1955448.00
400	100.0	0.0000031	0.0007026	0.2743754	0.0000008	1189808.00

Table XXXIV are for a 100 kW WECS in series with a transmission line of 100 kW capacity with four conventional units (of 100 kW capacity each) operating in parallel at the load bus.

4.6 Reliability Study

The behavior of WECS is different from that of a conventional generating unit. Economic considerations dictate that they should generate as much energy as possible, limited only by the wind input. Since input wind speed to WECS is generally varying, the output from WECS in general consists of a sequence of ups and downs and in some cases the output is likely to remain at zero for several days. Therefore, it is highly unlikely to operate a large capacity WECS alone as the generation in a power system to supply a certain load. Hence, WECS is operated in parallel with utility grids, directly or through a transmission line, depending upon the location of the WECS. Therefore, Example I discussed in the last section is purely academic and has not been considered further. The calculations of probability of outages and the results given in Tables XXXIII and XXXIV for Examples II and III, however, provide a measure of the reliability of the generation system. Understanding the load carrying capability of these systems requires incorporation of the variability of the system load. A suitable load model for use in Examples II and III would obviously be a load model based on the Markov chain. The theory and the mathematical aspects of such load models have been discussed in detail in Appendix B. The technique required to arrive at the risk of the expected loss of load using a generation model based on the Markov process and a load model based on the Markov chain is the well known "frequency and duration" approach (32). This approach

TABLE XXXIV

COP TABLE FOR WECS IN SERIES WITH A TRANSMISSION LINE AND AT THE LOAD BUS A NUMBER OF CONVENTIONAL MACHINES OPERATING IN PARALLEL

Cap. Out kW	Cap. In kW	Availability	Rate of Departure Down States	Rate of Departure Up State	Frequency of Encounter / hr.	Cycle Time in hrs.
0	500.0	0.7398868	0.0167066	0.0000000	0.0123610	80.90
16	484.0	0.0027302	0.0001014	1.0000000	0.0027305	366.24
30	470.0	0.0109208	0.8751014	0.1250000	0.0109219	91.56
44	456.0	0.0054604	1.0001000	0.0000000	0.0054610	183.12
58	442.0	0.0232068	0.4706896	0.4117647	0.0204789	48.83
70	430.0	0.0204766	0.7334347	0.2000000	0.0191135	52.32
80	420.0	0.0177464	0.5385629	0.3076923	0.0150179	66.59
92	408.0	0.0150161	0.1819195	0.8181817	0.0150177	66.59
100	400.0	0.1464002	0.0069502	0.1679318	0.0256027	39.06
116	384.0	0.0002229	0.0000969	1.0002200	0.0002229	4485.42
130	370.0	0.0008915	0.8750966	0.1252218	0.0008918	1121.35
144	356.0	0.0004457	1.0000950	0.0002219	0.0004459	2242.71
158	342.0	0.0018944	0.4706848	0.4119862	0.0016722	598.03
170	330.0	0.0016716	0.7334297	0.2002214	0.0015606	640.76
180	320.0	0.0014487	0.5385580	0.3079139	0.0012263	815.48
192	308.0	0.0012258	0.1819149	0.8184031	0.0012262	815.53
200	300.0	0.0088695	0.0035575	0.2264221	0.0020398	490.25
216	284.0	0.0000068	0.0000924	1.0004410	0.0000068	146492.10
230	270.0	0.0000273	0.8750921	0.1254438	0.0000273	36623.02
244	256.0	0.0000136	1.0000890	0.0004438	0.0000137	73246.13
258	242.0	0.0000580	0.4706802	0.4122082	0.0000512	19530.87
270	230.0	0.0000512	0.7334249	0.2004436	0.0000478	20926.62
280	220.0	0.0000443	0.5385534	0.3081358	0.0000375	26632.32
292	208.0	0.0000375	0.1819103	0.8186246	0.0000375	26634.95
300	200.0	0.0002401	0.0018319	0.2562426	0.0000620	16140.55
316	184.0	0.0000001	0.0000879	1.0006630	0.0000001	
330	170.0	0.0000004	0.8750876	0.1256656	0.0000004	2691207.00
344	156.0	0.0000002	1.0000850	0.0006658	0.0000002	5382423.00
358	142.0	0.0000008	0.4706759	0.4124302	0.0000007	1435166.00
370	130.0	0.0000007	0.7334207	0.2006655	0.0000007	1537749.00
380	120.0	0.0000006	0.5385492	0.3083577	0.0000005	1956972.00
392	108.0	0.0000005	0.1819057	0.8188470	0.0000005	1957242.00
400	100.0	0.0000031	0.0007859	0.2743754	0.0000008	1190638.00

has been discussed in detail in Chapter III (see pages 64 to 98). To understand the influence of different parameters-wind regime, generation mix (penetration) and load demand, these parameters are varied in a systematic way in the simulation studies. For a given wind regime and with a certain generation mix (penetration), the peak load demand is varied from 50 percent to 100 percent of the total system generation (assuming the transmission line capability is equal to maximum generation available at its input end) in steps of 10 percent. The procedure is continued for different generation mixes and different wind regimes. The results for Examples II and III are given in Tables XXXV and XXXVI, and discussed in the following section.

4.7 Discussions

Results of the expected loss of load for examples II and III are computed for high and low mean wind speed months for both sites--'Kahuku Upper' and 'Livermore.' These results appear consistent in their nature, as such results given in Tables XXXV and XXXVI are for the high mean wind speed month (March, 1977) for the site 'Kahuku Upper' only. When these results are compared with the results of Chapter III (see Table XXIX), we find that the introduction of a single transmission line in a generation system (WECS and/or conventional) causes an increase in the risk value of the loss of load. Though there is a definite increase in the risk value, the increase is not significant because of the high reliability of the transmission line. Comparison of Tables XXXV and XXXVI gives a reading of the reliability of the systems considered as Examples II and III. An examination of these tables reveals that under the conditions of identical machine capabilities, load

TABLE XXXV

LOLP TABLE FOR COMPOSITE SYSTEM OF EXAMPLE II FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

Peak Load % of Installed Capacity	33.3%	25%	20%	16.6%	14.3%	12.5%	11.1%	10%
50	2.667124	0.7476575	0.7621801	0.0045254	0.0056825	0.0001653	0.0	0.0
60	3.097981	2.659359	0.8136821	0.151999	0.1521866	0.0108841	0.0139808	0.0005657
70	30.38157	4.091211	3.800469	2.817931	0.2481104	0.3295364	0.3383005	0.02681
80	38.33744	33.82884	5.244245	4.368268	5.132797	5.354084	5.03761	0.6170425
90	59.72149	47.43466	49.75868	47.76074	46.68635	44.85003	47.93826	8.736546
100	67.08065	66.97918	53.65611	56.3708	59.64376	62.56779	65.1934	65.3534

TABLE XXXVI

LOLP TABLE FOR COMPOSITE SYSTEM OF EXAMPLE III FOR MARCH, 1977, FOR THE SITE 'KAHUKU UPPER'

Peak Load % of Installed Capacity	33.3%	25%	20%	16.6%	14.3%	12.5%	11.1%	10%
50	2.003402	0.0730066	0.0876182	0.0045471	0.0057098	0.0001661	0.0	0.0
60	2.434269	1.995085	0.1393561	0.1526926	0.1532169	0.010931	0.0140545	0.0005681
70	29.89224	3.432816	3.139592	2.835472	0.2491407	0.3309647	0.3401859	0.0269199
80	37.84809	33.3384	4.591048	4.38581	5.153748	5.378415	5.064282	0.619444
90	59.3301	46.9445	49.27024	47.949	46.8764	45.02928	48.11778	8.767554
100	66.68922	66.585	53.16767	56.55905	59.83386	62.75965	65.38716	65.53317

demand, wind regime, and assuming the transmission line capability as equal to the total system generation at its input, the system given by Example II has a higher risk of losing the load compared to the system given by Example III. This is indicative of the low confidence (wide variability in the output of WECS) in the operation of WECS alone and transmitting its output to a load center (bus). But operating WECS in parallel with a number of conventional generating units smoothes out the variations in the output of WECS and transmitting the combined output to a load center is preferable from the overall reliability viewpoint. This can be seen from the results of Table XXXVI for Example III.

4.8 Interconnection of Two WECS

The advantages of interconnecting two power systems through a tie line are well known. The major benefits are 1) the possibility of interchange of energy between systems, and 2) the improvement in the reliability of both systems. The interconnection offers an opportunity for the two systems to share each other's capacity reserves by taking advantage of load diversities (hourly, daily, or seasonal) in the two systems, diversity of forced outages and the opportunity for a planned maintenance on the basis of an integrated system. Interconnection benefits mainly depend on the operating reserve in the individual systems, limitations of the tie line, and the agreement between the two systems regarding emergency power assistance. Interconnection also affords the opportunity to take advantage of large unit sizes available at present (65, 66, 21).

WECS normally operate for a considerable period of time at much lower capacities than their rated value. Therefore, they cannot derive all of the interconnection benefits enunciated above. Still, interconnection of two WECS located in different wind regimes should improve the overall system reliability. The other benefits are not of much significance with interconnected WECS (67).

In the studies pursued on interconnection of WECS, it has been assumed that the behavior of the two WECS and the transmission line are statistically independent. Figure 25 shows a schematic of the system--WECS No. 1 connected to WECS No. 2 through a transmission line. An examination of this figure indicates that this system is an extension of Example I considered earlier (see page 110). Thus, the model developed for Example I can be integrated with the model of WECS II to develop a model for the integrated system. The technique is straightforward and is discussed in Chapter III (see page 83). For the example studied, WECS I is assumed to be in a location whose wind regime is similar to 'Kahuku Upper' and WECS II is assumed to be located at a site with a wind regime similar to the 'Livermore.' Both units are assumed to be identical (DOE/NASA 100 kW MOD-0 unit). The transmission line interconnecting the two WECS is assumed to have a capacity of 100 kW with an availability of 0.999, failure rate of 0.002/24 failures/hour and 1.998/24 repairs/hour. Wind regimes for the month of May, 1977, is used in the simulation study. Since the wind speed data for this month are not available for the 'Livermore' site, the wind speed data for May, 1974, are assumed to be repeated during the month of May, 1977. Table XXXVII shows the capacities on outage, capacities available, the availabilities of the various capacities, and the frequency of encounter of each state in the interconnected system at the location of WECS

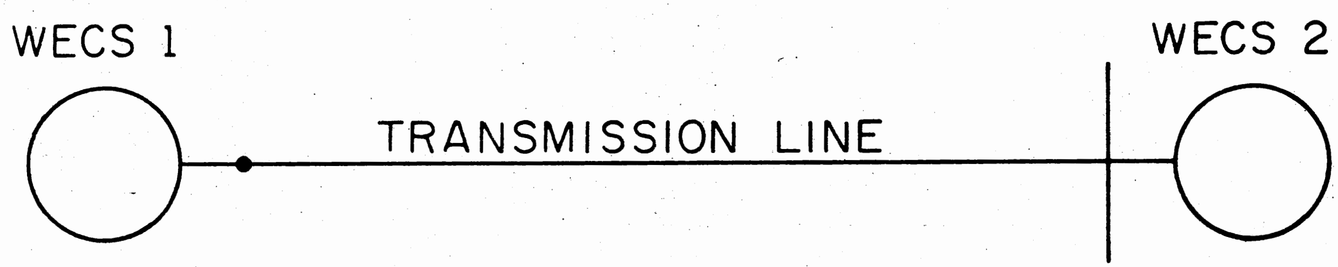


Figure 25. Interconnected Two WECS System

TABLE XXXVII

COP TABLE FOR TWO WECS INTERCONNECTED SYSTEM

Cap. Out kW	Cap. In kW	Availability	Rate of Departure Down States	Rate of Departure Up State	Frequency of Encounter / hr.	Cycle Time in hrs.
0	200.0	0.3702068	0.2825798	0.0000000	0.1046129	9.56
16	184.0	0.0817123	0.4082465	0.3979592	0.0658769	15.18
30	170.0	0.0916744	0.4296838	0.4410582	0.0798247	12.53
44	156.0	0.0597086	0.4045686	0.4446861	0.0507078	19.72
46	154.0	0.0047754	0.6357597	0.8794406	0.0072357	138.20
58	142.0	0.0643108	0.3792713	0.4810572	0.0553284	18.07
60	140.0	0.0058619	0.7026691	0.8762311	0.0092553	108.05
70	130.0	0.0140446	0.4914732	0.4132611	0.0127067	78.70
74	126.0	0.0130268	0.6250477	0.8844545	0.0196639	50.85
80	120.0	0.0363840	0.4496863	0.4678569	0.0333239	29.95
86	114.0	0.0007075	1.0153880	0.6479592	0.0011768	849.79
88	112.0	0.0099063	0.6000093	0.9101830	0.0149604	66.84
92	108.0	0.0048729	0.4697127	0.6711111	0.0055591	179.89
96	104.0	0.0061903	0.6368179	0.8265306	0.0090586	110.39
100	100.0	0.1252629	0.1462947	0.4050828	0.0690671	14.48
102	98.0	0.0059304	0.5575996	0.9263527	0.0088005	113.63
108	92.0	0.0007075	0.7653894	0.8979592	0.0011768	849.79
110	90.0	0.0057933	0.6197091	0.8750115	0.0086651	115.41
114	86.0	0.0006822	0.9154266	0.7566134	0.0011407	876.68
116	84.0	0.0299229	0.2801797	0.8151383	0.0327751	30.51
122	78.0	0.0007039	0.7077749	1.0051260	0.0012056	829.44
124	76.0	0.0040968	0.5864264	0.8854617	0.0060300	165.84
128	72.0	0.0013500	0.6110454	0.9064169	0.0020485	488.16
130	70.0	0.0233826	0.2621560	0.8307548	0.0255551	39.13
136	64.0	0.0004837	0.7015754	0.9850739	0.0008158	1225.81
138	62.0	0.0028244	0.4575911	0.9635780	0.0040140	249.13
140	60.0	0.0000938	0.9808525	0.7115384	0.0001588	6296.17
144	56.0	0.0172453	0.2100648	0.8539206	0.0183487	54.50
150	50.0	0.0012904	0.5791036	0.9832160	0.0020160	496.03
158	42.0	0.0086804	0.0986149	0.8840592	0.0085300	117.23
160	40.0	0.0006317	0.4715118	1.0285710	0.0009476	1055.35
162	38.0	0.0001083	0.7334164	0.9999997	0.0001877	5327.54
170	30.0	0.0036185	0.2316238	0.8633467	0.0039622	252.39
172	28.0	0.0001985	0.4546286	1.3090890	0.0003501	2856.00
180	20.0	0.0028264	0.1045995	0.9944283	0.0031063	321.93
184	16.0	0.0000144	0.5000833	1.5000000	0.0000289	34629.20
192	8.0	0.0005612	0.0048721	1.3947460	0.0007855	1273.03
200	0.0	0.0002070	0.0000000	0.4858466	0.0001006	9943.95

II. Table XXXVIII lists the cumulative probabilities for this example.

4.9 Conclusions

The Markov model developed for WECS in Chapter III along with the models available for conventional generating units and transmission lines have been used in this chapter to evaluate the reliability at a load bus for a composite system. The composite systems used in the studies constitute the basic configurations that can be expected when WECS, conventional generating units, and a transmission line are present.

The basic approach in the method followed is the well known "frequency and duration" technique. A model for WECS and/or a model for conventional generation units are combined with a two (Up and Down) state model for the transmission line to derive a model for the composite system, depending on the specific configuration studied. To evaluate the reliability of this composite system, a suitable load model is used and the variability of the load at the load bus is also considered.

The studies presented in this chapter are versatile in the sense that the risk levels due to the transmission line alone can be evaluated by treating the generation system as fully (100 percent) available. In turn, the risk levels due to generation capacity alone can be obtained (results of Chapter III) by treating the transmission system as fully (100 percent) available. The case of an interconnected two-WECS system has also been studied. For a single 100 kW WECS located in 'Kahuku Upper' and in 'Livermore,' it was found earlier that the availabilities of the rated output capacity state for the month of May, 1977, were 59.7 percent and 62.1 percent, respectively. From

Table XXXVIII it can be seen that the availability of 100 kW or more for the interconnected two WECS system is 88.8 percent--a significant improvement. This improvement is a direct consequence of interconnecting two WECS located in two different wind regimes. Further conclusions on this aspect will have to come from future work in this area.

TABLE XXXVIII

CUMULATIVE PROBABILITY OF INTERCONNECTED TWO WECS SYSTEM

Cap. in kW	Cumulative Probability
200.0	0.9999986
184.0	0.6297917
170.0	0.5480794
156.0	0.4564050
154.0	0.3966964
142.0	0.3919210
140.0	0.3276103
130.0	0.3217484
126.0	0.3077039
120.0	0.2946771
114.0	0.2582932
112.0	0.2575858
108.0	0.2476795
104.0	0.2428067
100.0	0.2366164
98.0	0.1113535
92.0	0.1054230
90.0	0.1047156
86.0	0.0989223
84.0	0.0982401
78.0	0.0683172
76.0	0.0676134
72.0	0.0635167
70.0	0.0621667
64.0	0.0387841
62.0	0.0383004
60.0	0.0354760
56.0	0.0353821
50.0	0.0181369
42.0	0.0168465
40.0	0.0081660
38.0	0.0075344
30.0	0.0074261
28.0	0.0038076
20.0	0.0036090
16.0	0.0007827
8.0	0.0007682
0.0	0.0002070

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary and Concluding Remarks

Techniques for evaluating the reliability of power systems involving conventional generation units are well developed and have been in use for at least two decades. These studies are firmly established in the power industry and the necessary standards are fairly well laid out for all three major sectors (generation, transmission, and distribution) of the power system. The entry of WECS is one in a series of new types of generators added to the family of power system components over the decades. During the last five years, research and development around the world has laid the groundwork necessary for the design, development, and fabrication of large WECS for the generation of electricity. The wide variability in the output of a WECS due to the vagaries of the wind input suggests operation of WECS in parallel with existing utility grids. Such a scenario brings into focus various reliability questions --the reliability of WECS-assisted generation systems, composite systems, interconnected systems, etc. It is also necessary to study the influence of factors such as wind regime, generation mix (penetration), load demand (and, indirectly, the amount of reserve) and the like, on the overall system reliability. Solution to these problems requires a systematic development of WECS models and their use from the point of view of reliability. In this thesis, basic reliability models are developed for WECS and they are used to study the influence of major parameters that are likely to affect a wind-assisted utility system.

The practice, at present for the selection of sites for WECS is based on hourly wind speed and direction data collected over several years. Such information, though extremely useful, may not be available for many potential wind sites.

Chapter II discusses the development of probability models for WECS based on commonly available parameters such as mean and/or variance of wind speed. A Weibull model with parameters α and β is used to fit the actual wind speed distribution. The parameters are determined from the mean and variance of wind speed. The distribution function is utilized to obtain the wind speed duration curve. The combination of this duration curve with the characteristic of the wind turbine generator (WTG) leads to a probability model for WECS, in terms of capacities available and the availabilities of various capacities. This model is combined with an appropriate model for conventional generation units to evolve a model for the combined system. The combined system model is convolved with a suitable load model to evaluate the reliability of the system. The results of the expected loss of load are within a range of 5-15 percent of the results obtained with actual data for the two sites studied--'Kahuku Upper' in Hawaii and 'Livermore' in California. If the variance is not available, a knowledge of the variability of the wind speed can be utilized to estimate the parameter β. For low mean wind speed (less than about 13 mi/h) months with low variability or high mean wind speed with high variability, a β value in the range of 1.5 to 3.0 may be chosen. High mean wind speed (above 13 mi/h) and low variability requires a β value of 3 to 5. Such a model, with a properly estimated β value, gives good results depending upon how close the estimated β value is to the calculated β. The farther the estimated β is from the calculated β value, the larger the difference in the results of the expected loss of load. In the absence of any knowledge on the variability, mean wind speed alone can be utilized with an assumed β value between 3 and 4. In this case, the final results on most occasions are within 40 percent of the results computed with actual data. The expected loss of load value itself depends upon factors such as load demand, generation mix (penetration) and wind regime. For a given wind regime and generation mix, an increase of system load (up to the conventional capacity in the system) causes a slight increase in the expected loss of load. When the system load is greater than the conventional generation capacity, a sharp rise in the expected loss of load occurs, indicating a low confidence in the WECS generation. Further, the expected loss of load increases with increase in penetration, and decreases with an increase in the mean wind speed (better wind regime).

The method suggested by Melton (38) has been utilized to estimate the capacity credit of a WECS. The influence of parameters such as wind regime, generation mix and load demand has been considered in detail in arriving at a range of values for the expected capacity credit. The percentage values for the better wind regime (high mean speed) months for the two sites, 'Kahuku Upper' and 'Livermore' are 50 to 60 and 40 to 50, and for the poor wind regime (low mean speed) months are 0 to 10 and 20 to 30, respectively.

Chapter III discusses a Markov model for WECS. The model is developed from the mean hourly wind speed data and the characteristics of the WTG. It is a multi-state model, the number of states depending on the accuracy required and the output characteristics of the WECS. The model thus evolved is convolved with Markov models for conventional generation units to derive a model for the combined system. For studying a WECS-assisted utility system, a load model based on the Markov chain with hourly peak load values is the logical choice. Computations of the results for the expected loss of load (i.e., the reliability indices for the system) have considered a range of values for the major parameters such as wind regime, generation mix and load demand. It has been observed that, for a given wind regime, and with a certain value of penetration by WECS, an increase in the system load demand causes only a slight increase in the expected loss of load as long as the load demand is less than or equal to the total conventional generation capacity. When the load demand exceeds the conventional generation capacity, there is a steep rise in the expected loss of load, indicating the low load-carrying capability of WECS. A better wind regime gives lower values of loss of load, and vice versa. The influence of penetration on the expected loss of load is complicated since the load model is not linear but stepped (Markov model with discrete load levels). In general, an increase in the generation mix causes an increase in the expected loss of load.

Since large arrays of WECS are expected to be located in remote areas, it is obvious that transmission line is an integral part of a WECS assisted utility system. The line could be simply transporting the power generated by a (or an array of) WECS or it could be paralleling two groups of WECS. Two basic configurations involving WECS, conventional generation units and a transmission line are studied.

One of the examples considers a situation wherein a transmission line is used to transmit the power generated by a WECS operating in parallel with a number of conventional units to a load bus. The example of a WECS in series with a transmission line connected to a load bus at which a number of conventional generating units are operating in parallel has also been studied. The analysis of these two examples showed that the introduction of a transmission line in the generation system causes only a slight increase in the expected loss of load.

Though not all of the traditional benefits of interconnection of two conventional power systems are fully available in the case of the interconnection of two WECS, in the absence of integration of a WECS with a conventional utility grid, interconnection with another WECS located in a totally different wind regime can help to improve the reliability of both systems. An improved performance could be expected if a diversity in the load demands also exists at the two WECS sites.

The studies pursued in this thesis have practical importance. The methodology developed is general and is applicable to any site and for any type of wind turbine generator. The results presented and discussed have laid the groundwork for better understanding of the reliability aspects of wind-assisted utility systems supplying a common load. It should also be helpful for further studies in this area.

5.2 Scope for Future Work

Future work on the reliability of wind-assisted utility systems appears necessary in three areas: 1) improvement of WECS models that have been developed; 2) analysis of other sites and the inclusion of their diversities in the wind regimes for the purpose of making some generalizations, and 3) incorporation of more components in the study to simulate actual power system operating conditions. These are discussed further in the following paragraphs.

Though the WECS models developed in Chapter II are reasonably accurate, refinements are possible to include seasonal, diurnal, and short-term variations.

Capacity credit assigned to a WECS located at a site depends upon parameters such as wind regime, WTG characteristic, generation mix, load demand, and the like. An improvement of the technique used in this thesis is desired to incorporate additional parameters to obtain a representative figure for the capacity credit.

The Markov model developed in Chapter III can be refined. The model employs seven partial capacity states--a result of using integer hourly wind speed data and the characteristic of DOE/NASA 100 kW MOD-0 generator. Doubling or tripling the number of partial capacity states using the hourly wind speed data to the first decimal place accuracy and studying the differences in the results obtained may prove fruitful. The problem, though straightforward, is expensive in terms of computer time. A recursive technique needs to be developed to compute the frequency and duration of residence of cumulative reserve margin states. A method may be devised to compute the expected loss of load using the cumulative load model. When a WECS is operated in parallel with older (or large modern) conventional machines, a multistate (3 or more) model of conventional machine should be utilized in the analysis. The load model based on the Markov chain and hourly peak loads utilized in this thesis is a theoretical load model. A load model developed on the basis of actual hourly load data of a particular system under study will be more informative and representative of actual operating conditions.

Composite system reliability studies (including WECS) need special attention. The studies undertaken in this thesis assumed that the transmission line is operating in normal weather (one environment) state all of the time and is free from contingencies such as unacceptable voltages and circuit overloads and only simple configurations of WECS, conventional generation system and transmission line are considered. A realistic study in this area should include stormy weather conditions (two state environment) and contingencies such as unacceptable voltages, line overloads and the like for the transmission lines. Maintenance outages of different system components also need to be incorporated in further studies.

Future studies on interconnected WECS should take into account tie line limitations, if any, instantaneous diversities in the wind regimes, and the load sharing characteristics of the two WECS.

The studies documented in this thesis are based on hourly wind speed data for two sites located in totally different wind regimes ('Kahuku Upper' in Hawaii, and 'Livermore' in California). Any generalization of the findings of this thesis will require the study and evaluation of many more sites for longer periods of time (ten to fifteen years).

The reliability studies of WECS-assisted power systems considered in this thesis involves simple combinations of power system components --WECS, conventional machines and transmission line. More and more power system components need to be included in the system studies to make the reliability studies more representative of conditions in actual power systems.

The wind turbine generators considered for the reliability analysis have all been of the constant- or nearly constant-speed constant-frequency type which are popular at present. Similar studies need to be undertaken on wind turbine generators with variable-speed constant frequency WTG which are quite likely to emerge in the power system of the future.

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APPENDIX A

MARKOV PROCESS

Before discussing the Markov process, the general idea of a stochastic process is introduced (53). A stochastic process is a process which develops in time according to certain probabilistic laws. A common example of a stochastic process is the sequence of "up" and "down" states occupied by a transmission system or a conventional generating unit (binary model) or any other power system or electronic component which exists in two states only. Such equipment or component, as it fails, is repaired in a certain amount of time and put back in operation. The transitions are shown in Figure 22a to be possible from state 1 to state 2, and vice versa. The time spent in state 1 during a particular occupancy of that state is designated as the residence time of state 1. Such times are random variables which obey probabilistic laws which govern the stochastic process.

There are four general types of Markov processes, depending on whether the states of the process are discrete or continuous, and whether transitions from one state to another are permitted at any time (continuous time) or are permitted only at discrete time intervals (discrete transitions). Only the discrete state continuous transition Markov process (or chain) will be discussed here, as this class of the Markov process is finding considerable application in the power system work. Since the transition rates are constant and not functions of time, discussions are limited to homogeneous discrete state continuous transition Markov process (or chain).

The properties of a homogeneous discrete-state continuous-transition Markov process (or chain) are given below.

1) The system considered can be characterized as being in one of a set of mutually exclusive, collectively exhaustive discrete states,

$S_1, S_2, \ldots\ldots, S_n$.

2) Changes of states are possible at any instant of time.

3) The probability of departure from a state depends only on the current state--meaning the probability of departure from a state is independent of the past history such as states previously occupied and the time spent in the current state. Further, the probability of departure is independent of the independent variable time. These conditions imply that the state residence times are exponentially distributed--often a fair assumption in power system reliability analysis.

4) The probability of more than one change of state during an appropriately chosen small interval of time is negligible.

These conditions are reasonably satisfied by WECS. It has been further assumed that outages due to scheduled maintenance and mechanical outages are neglected.

Patton (68) has derived the mathematical expressions for a multi-state Markov model. Following his approach, let

$q_i(t)$ = probability that the system is in state i at time t

ρ_{ij} = rate of departure from state i to state j, assumed to be constant

Then, for an n-state system, probability of finding the system in state i at time $t + \Delta t$, is given by

$$q_i(t + \Delta t) = q_i(t) \left[1 - \sum_{\substack{j=1 \\ j\neq i}}^{n} \rho_{ij}\Delta t \right] + \sum_{\substack{j=1 \\ j\neq i}}^{n} q_j(t)\rho_{ji}\Delta t \qquad \text{(A.1)}$$

Probability of being in state i at time t and not leaving that state during the interval Δt	Probability of being in any other state j at time t and transitioning to state i during the interval Δt

This equation can be re-written as follows:

$$\frac{q_i(t+\Delta t)-q_i(t)}{\Delta t} = - q_i(t) \sum_{\substack{i=1 \\ j\neq i}}^{n} \rho_{ij} + \sum_{\substack{j=1 \\ j\neq i}}^{n} q_j(t)\, \rho_{ji} \qquad \text{(A.2)}$$

Taking the limit of this set (for different i's) of equations as $\Delta t \to 0$, we get n first-order differential equations as given below:

$$\frac{dq_i(t)}{dt} = \dot{q}_i(t) = -q_i(t) \sum_{\substack{j=1 \\ j\neq i}}^{n} \rho_{ij} + \sum_{\substack{j=1 \\ j\neq i}}^{n} q_j(t)\rho_{ji} \qquad \text{(A.3)}$$

This set of n differential equations can be put in a matrix form as:

$$\begin{bmatrix} \dot{q}_1(t) \\ \dot{q}_2(t) \\ - \\ - \\ \dot{q}_n(t) \end{bmatrix} = \begin{bmatrix} -\sum_{j=2}^{n} \rho_{1,j} & \rho_{2,1} & \rho_{n,1} \\ \rho_{1,2} & -\sum_{\substack{j=1 \\ j\neq 2}}^{n} \rho_{2,j} & \rho_{n,2} \\ - & - & - \\ - & - & - \\ \rho_{1,n} & \rho_{2,n} & -\sum_{j=1}^{n-1} \rho_{n,j} \end{bmatrix} \begin{bmatrix} q_1(t) \\ q_2(t) \\ - \\ - \\ q_n(t) \end{bmatrix} \qquad \text{(A.4)}$$

For known initial conditions, it is quite difficult to obtain a general time-dependent expression for the probability of existence in any state i of the system if the number of states is large. These time-dependent (transient state) probabilities are finding application in near-term future reliability of systems such as in spinning reserve reliability evaluations (34).

In static generation reliability and system planning studies, the interest lies in the steady state solutions for the state probabilities. These are obtained by taking the limit as t tends to ∞ in the expressions for the time-dependent probabilities. Since time-dependent expressions for the state probabilities are difficult to obtain, and if only steady-state probabilities are of interest, a much easier method to compute the steady state probabilities (availabilities) is available and it is described next.

One equation in the set for determining steady state probabilities of states is the statement that the sum of all of the availabilities must be unity.

$$\sum_{i=1}^{n} A_i = 1 \qquad \text{(A.5)}$$

The remaining (n-1) equations are obtained from the matrix equation (A.4) by replacing the time-dependent state probabilities by their steady state values A_1, A_2,.....,A_n and their derivatives $\dot{A}_1$, $\dot{A}_2$,.....,$\dot{A}_n$, by zero (since A_1, A_2,.....,A_{n-1} are constants). Thus, matrix equation (A.4) using equation (A.5) is rewritten as follows:

$$
\begin{bmatrix} 0 \\ 0 \\ - \\ - \\ 0 \\ \\ 1 \end{bmatrix} =
\begin{bmatrix}
-\sum_{j=2}^{n} \rho_{1,j} & \rho_{2,1} & \rho_{n-1,1} & \rho_{n,1} \\
\rho_{1,2} & -\sum_{\substack{j=1 \\ j\neq 2}}^{n} \rho_{2,j} & \rho_{n-1,2} & \rho_{n,2} \\
- & - & - & - \\
- & - & - & - \\
\rho_{1,n-1} & \rho_{2,n-1} & -\sum_{\substack{j=1 \\ j\neq n-1}}^{n} \rho_{n-1,j} & \rho_{n,n-1} \\
 & & & \\
1 & 1 & 1 & 1
\end{bmatrix}
\begin{bmatrix} A_1 \\ A_2 \\ - \\ - \\ A_{n-1} \\ \\ A_n \end{bmatrix} \qquad (A.6)
$$

This set of algebraic equations can be easily solved using a digital computer to determine the steady state probabilities (availabilities) when the numerical values of the transition rates are known.

APPENDIX B

LOAD MODEL

There are two basic types of Markov-chain load models, the exact state model and the cumulative state model (32, 56). The most widely used load model is the exact state model. These models realize the actual load cycle by approximating a sequence of load levels which is assumed to be a stationary random process (53). The commonly used load model represents the load cycle by an alternating sequence of peak and off-peak loads on a daily basis. A special case of such a model allows the load to transit from one peak load to the next peak load directly. The discrete load levels of the exact state model is assumed to be a recurring process with the parameters consisting of state probabilities and transitions to higher and lower loads. The exact-state load model can be combined with the exact generation capacity model to yield the frequency and duration of the expected loss of load (or, more generally reserve margin states).

The development of the exact state load model is based on the following assumptions:

1) Hourly loads during the study period are represented by a set of N load levels or load states.

2) The sequence of hourly peak loads is a random sequence of the N load states.

3) The load model is statistically stationary.

4) The distribution of residence times in each load state is exponential.

5) At each transfer to a new load state, the probability of transfer to a particular state is directly proportional to the long term average probability of existence of the new states, A_{Li}.

6) Load state transitions occur independent of generation state transitions.

7) The mean duration of peak load is one hour.

A typical load model is shown in Figure 23. It is realistic to allow the peak loads to transfer to the next peak load directly. The constancy of the load during the entire hour of residence is justified since no significant changes in the load are expected within an hour.

A Markov chain analysis is employed in the development of the load model (32). The development of the model is based on considering the load to have N distinct states, all of which are equally likely to occur. Further, the transfer to all states is allowed directly. The matrix differential equation for such a system (on the basis of Appendix A) is

$$\begin{bmatrix} \dot{q}_1(t) \\ \dot{q}_2(t) \\ - \\ - \\ - \\ \dot{q}_n(t) \end{bmatrix} = \begin{bmatrix} -\lambda & \lambda/(N-1) & - & - & \lambda/(N-1) \\ \lambda/(N-1) & -\lambda & - & - & \lambda/(N-1) \\ - & - & - & - & - \\ - & - & - & - & - \\ - & - & - & - & - \\ \lambda/(N-1) & - & - & - & -\lambda \end{bmatrix} \begin{bmatrix} q_1(t) \\ q_2(t) \\ - \\ - \\ - \\ q_n(t) \end{bmatrix} \quad \text{(B.1)}$$

Since the residence time of each load state is one hour, the total rate of departure from a state is one per hour. Under steady-state conditions, the above matrix differential equation reduces to

$$\dot{q}_i(t) = 0 \quad \text{(B.2)}$$

The solution for the steady-state probabilities is

$$q_i = \frac{1}{N} \text{ where } i = 1,2,\ldots\ldots,N \tag{B.3}$$

Several of these equally likely-occurring states can be merged into an equivalent state. To achieve this, the states are arranged in the descending order of the load demand starting with the maximum load state. If all of the load states between the lower load state K and the higher load state J are merged to form an equivalent state L, then the availability and the rates of departure to lower and higher load states from the merged state L are given by

$$A_{LL} = \sum_{i=j}^{K} A_i \tag{B.4}$$

$$= \frac{K + 1 - J}{N} \tag{B.5}$$

$$\lambda_{LL} = \frac{(N - K)}{(N - 1)} \tag{B.6}$$

and

$$\mu_{LL} = \frac{(J - 1)}{(N - 1)} \tag{B.7}$$

The total rate of departure to lower and higher states can be re-written as

$$\lambda_{LL} = \frac{(N - K)/N}{(1 - 1/N)} \tag{B.8}$$

$$= \sum_{i=j+1}^{N} A_i/(1 - 1/N) \tag{B.9}$$

and

$$\mu_{LL} = \frac{(J - 1)/N}{(1 - 1/N)} \tag{B.10}$$

$$= \sum_{i=1}^{J-1} A_i/(1 - 1/N) \tag{B.11}$$

Therefore, the total rate of departure from load state L, adding equations B.8 and B.10

$$\lambda_{LL} + \mu_{LL} = \frac{1 - (K + 1 - J)/N}{(1 - 1/N)} \tag{B.12}$$

$$= \frac{1 - A_{LL}}{(1 - 1/N)} \tag{B.13}$$

and the frequency of encounter of load state L is

$$f_{LL} = A_{LL}(1 - A_{LL}) /(1 - 1/N) \tag{B.14}$$

The hourly load data (averaged to consider the differences in the load demand during weekdays and weekends) given in the section on Load Model is for a period of 24 hours. It is assumed that the load cycle repeats on a daily basis over the study period under consideration. This load demand has 24 basic number of load states which are equally likely to occur. Since the load states are arranged in the descending order, merging the first seven states gives the peak load state (refer to load demand of section on Load Model), and using the equations derived above, the availability and the rates of departure to lower and higher load states are

$$A_{L1} = \frac{(7 + 1 - 1)}{24} = 0.2911667$$

$$\lambda_{L1} = \frac{(24 - 7)}{23} = 0.7391304$$

$$\mu_{L1} = \frac{(1 - 1)}{23} = 0.0$$

The frequency of encounter of the load state 1 is given by

$$f_{L1} = (0.2911667)(0.7391304)$$

$$= 0.2155797$$

A similar procedure is used to find the parameters of all of the other load states. The results of the load model are given in Table XXVI and a time-plot is shown in Figure 23.

VITA[2]

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