RELIABILITY EVALUATION OF ELECTRIC POWER GENERATION SYSTEMS WITH SOLAR POWER

A Thesis

by

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ABSTRACT

Conventional power generators are fueled by natural gas, steam, or water flow. These generators can respond to fluctuating load by varying the fuel input that is done by a valve control. Renewable power generators such as wind or solar, however, are not controllable since their fuel sources are intermittent in nature. This creates difficulties for designing generation systems having renewable sources. Therefore, a mechanism is needed to predict their power outputs and evaluate the generation system reliability. This information is used to calculate the reliability indices such as Loss of Load Expectation (LOLE), frequency of capacity deficiency, and Expected Unserved Energy (EUE). These indices help to estimate to what extent renewable power plants with intermittent sources can substitute for other power generations in the system while maintaining the same reliability standards. This study is used in generation planning of power systems with intermittent sources.

The primary objective of this thesis is to study reliability evaluation of generation systems including Photovoltaic (PV) and Concentrated Solar Power (CSP) plants. Unit models of PV and CSP are developed first, and then generation system model is constructed to evaluate the reliability of generation systems.

In addition to reliability indices calculations, a methodology is developed to evaluate the capacity credit of PV and CSP plants. This is accomplished by calculating the Effective Load Carrying Capability (ELCC) of these plants. ELCC is the extra load that can be served after addition of the solar power plant to the conventional system. The capacity credit information, in addition to its use in generation system planning, can also be used for cost comparison between conventional power plants and solar power plants.

The methodology developed in this thesis is applied to IEEE Reliability Test System (IEEE-RTS) to study the system reliability for different penetration levels of solar power and evaluate their capacity credits. It is found that generation system reliability drops as solar power penetration level increases. Also, solar plant capacity credit drops as its penetration level increases in generation system.

DEDICATION

To my parents and grandparents for their love and support

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NOMENCLATURE

LOLE	Loss of Load Expectation
EUE	Expected Unserved Energy
PV	Photovoltaic
CSP	Concentrated Solar Power
ELCC	Effective Load Carrying Capability
NREL	National Renewable Energy Laboratory
SRRL	Solar Radiation Research Laboratory
BMS	Base Measurement System

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1 Background

Sources of renewable energy have become increasingly popular in recent years due to environmental concerns resulting from fossil fuel consumption in conventional power plants. The conventional power generators are mainly gas turbines and steam turbines. This generation mix is changing with the rapid growth in the number of renewable power plants such as solar and wind. As of today, the percentage of renewable power generation is small in the generation mix, but all indications are that it is increasing rapidly. However, the increase in penetration level of renewable power introduces its own challenges. The key challenge is the intermittency of renewable power and difficulty in its predictability [1]. Renewable power plants generate power when the fuel source is available. Therefore, they are not dispatchable like the traditional power plants [2]. These difficulties contribute to operational challenges of power systems with high integration of renewable sources. There are issues in power system planning, scheduling, frequency regulations, and stability [1]. These challenges have led to view renewable power plants as energy sources, rather than power sources [2]. But, since in power system operation, power availability is more critical than energy availability in meeting the load, it is important to evaluate the power capacity value, also known as capacity credit, of these plants. All of these issues are subjects of ongoing research. These studies are trying to improve the existing methodology or come up with new solutions to tackle these issues.

This thesis develops a methodology for quantitative reliability study of generation systems with solar power and to evaluate the capacity credit of solar power plants. This methodology assists power system planners in designing generation systems with renewable power, in particular solar power, which meets the required reliability standards.

1.2 Literature Review

Extensive research has been done to deal with operational challenges of renewable power. Since wind technology is more mature than solar, most of available literature focuses on wind power. However, one can expect similar challenges and solutions in solar power.

There are many papers that deal with unpredictability of renewable sources. These studies use historical weather and load data to predict the power generation and load on hourly basis. The correlation between generation and load needs to be considered. Ref. [3] addresses a probabilistic study of wind electric conversion systems from the point of view of reliability and capacity credit. It models wind generators as multistate units. This paper does not consider the correlation between generation and load. It also does not take into account the failure characteristic of wind generators. Ref. [4] develops a methodology for photovoltaic system reliability and economic analysis. This methodology is based on load reduction approach. This paper also does not take into account the failure characteristics of photovoltaic system. Ref. [5] studies reliability modeling of generation systems including unconventional energy sources. It considers two unconventional sources: wind and photovoltaic power plants. This paper calculates the loss of load expectation (LOLE) and frequency of capacity deficiency on hourly basis for the generation system. It does not, however, calculate the expected unserved energy (EUE). Ref. [6] develops an efficient technique for reliability analysis of power systems including time dependent sources. It uses the clustering technique to calculate the LOLE and EUE. This paper does not address frequency calculations. Ref. [7] develops a method for calculating expected unserved energy in generating system reliability analysis. It introduces the concept of expected value or mean value of capacity outage. This is used to calculate the LOLE and EUE on hourly basis, but in a more efficient way than ref. [5]. It does not, however, calculate the frequency of capacity deficiency. Ref. [8] studies reliability evaluation of grid-connected photovoltaic power systems. It analyses component failures in utility scale PV power system, but it does not address the reliability impact of PV on the overall generation system.

There are a number of papers that study capacity credit of wind power plants. Ref. [9] evaluates current methods to calculate capacity credit of wind power. A chronological reliability method and a probabilistic reliability method to calculate the capacity credit is explained. Ref. [10] calculates capacity value of wind power using the LOLE and effective load carrying capability (ELCC) indices, iteratively. These approaches can also be used to evaluate capacity credit of solar power plants.

1.3 Organization of Thesis

Chapter II introduces basic concepts of generation system reliability. Reliability modeling of generation units is formulated in Chapter III. The configuration of large scale PV and CSP plants is studied. This configuration is important factor in reliability studies. Generation system model for each subsystem is developed in Chapter IV. Chapter V formulates methodologies for calculating the reliability indices such as LOLE, Frequency of capacity deficiency, and EUE of the composite generation system. In addition, this chapter introduces methods to evaluate capacity credit of solar power plants. Chapter VI provides a case study for reliability evaluation of generation systems with solar power. The IEEE Reliability Test System is used for this case study. Finally, Chapter VII draws a conclusion about the methodologies developed and the case study results.

CHAPTER II

BASIC RELIABILITY CONCEPTS

2.1 Basics

System reliability is defined as the probability that the system will perform its intended function for a given period of time under stated environmental conditions [11]. Electric power system reliability can be defined as the probability that electricity is being delivered to customers with the required amount and quality. The objective of electric power systems is to supply electrical energy to consumers at low cost while simultaneously providing acceptable, or economically justifiable, service quality [11]. An electric power system is very complex and consists of many components. Therefore, its reliability studies are performed for different subsystems. Three major areas of power system reliability analysis are:

- Generation system reliability
- Transmission system reliability
- Distribution system reliability.

The focus of this thesis is on generation system reliability. Generation system reliability deals with the relative ability of the system to supply system load considering that generation units may be out of service when needed due to planned or unplanned outages or that the basic energy sources may be inadequate [11]. Generation system reliability, also known as generation system adequacy, is to be contrasted with security which deals with the relative ability of the system to survive sudden shocks or upsets such as faults or equipment failures without cascading failures or loss of stability [11]. Generation system reliability is usually measured through the use of some reliability indices which quantify system reliability performance and it is enforced through a criterion based on an acceptable value of this reliability index [11]. Some utilities rely on adequacy criteria whose values have been chosen based on engineering judgment to yield a reasonable balance between system cost and reliability performance and which have been validated by historical experience. However, if adequacy criteria are based on probabilistic indices which bear reasonable relationships to the actual reliability performance of the system, more pragmatic methods may be employed to determine proper values of the criteria [11].

2.2 Reliability Indices

Reliability indices of generation system can be broadly divided into two categories [11]:

1. Deterministic indices: These indices reflect postulated conditions. They are not directly indicative of electrical system reliability and are not responsive to most parameters which influence system reliability performance. Therefore, these indices are of limited value for choosing between planning alternatives. Their calculation is however, simple and requires little data.
2. Probabilistic indices: These indices directly reflect the uncertainty which is inherent in the power system reliability problem and have the capability

of reflecting the various parameters which can impact system reliability. Therefore, probabilistic indices permit the quantitative evaluation of system alternatives through direct consideration of parameters which influence reliability. This capability accounts for the increasing popularity and use of probabilistic indices.

There are normally two deterministic indices that are used for generation system reliability [11]:

1. Percent reserve margin: defined as excess of installed generating capacity over annual peak load expressed in percent of annual peak load. It provides a reasonable relative estimate of reliability performance if parameters other than margin remain essentially constant. It, however, does not directly reflect system parameters such as unit size, outage rate, and the load shape.
2. Reserve margin in terms of largest unit: this index recognizes the importance of unit capacities in relationship to reserve margin.

There are a number of probabilistic indices that are used for generation system reliability evaluation. Each index gives information about the expected behavior of the system.

Let us consider Fig. 1. In this figure, the y-axis is power and the x-axis is time. The straight line represents the load (assumed to be constant for simplicity), and the other line represents the available generation capacity. The generation capacity can change due to failures and repairs of the generating units.

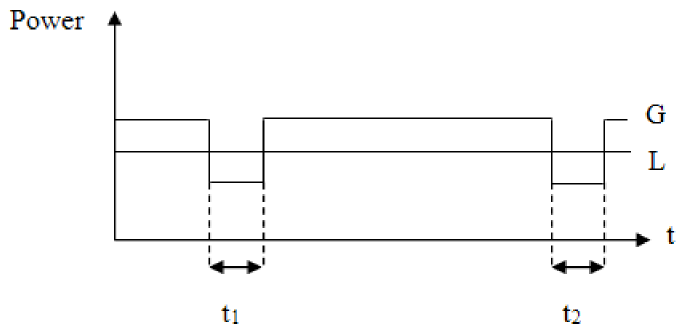

Figure 1 - Generation-load model example for LOLE

In order to evaluate the reliability of the generation-load system, one desirable index is the probability of generation capacity deficiency or loss of load probability. This can be estimated as $(t1+t2)/t$.

In this example the sample size is only two and it is understood that this is not sufficient for purposes of estimation but this simple example can be used to illustrate the basic concepts. Alternatively, we can introduce loss of load expectation that gives us information about the time duration that is used. The estimate is given by $((t1+t2)/t\,)t$.

Now, let us consider the two graphs in Fig. 2. The LOLE of both graphs are the same. However, these two graphs do not represent the same scenario. In order to differentiate these two scenarios of generation capacity deficiency, it is required to introduce another reliability index called frequency of capacity deficiency. The frequency in the first graph is 1 while the frequency in the second graph is 2. In addition to frequency, the duration of each frequency can also be considered. This is referred to as frequency & duration index.

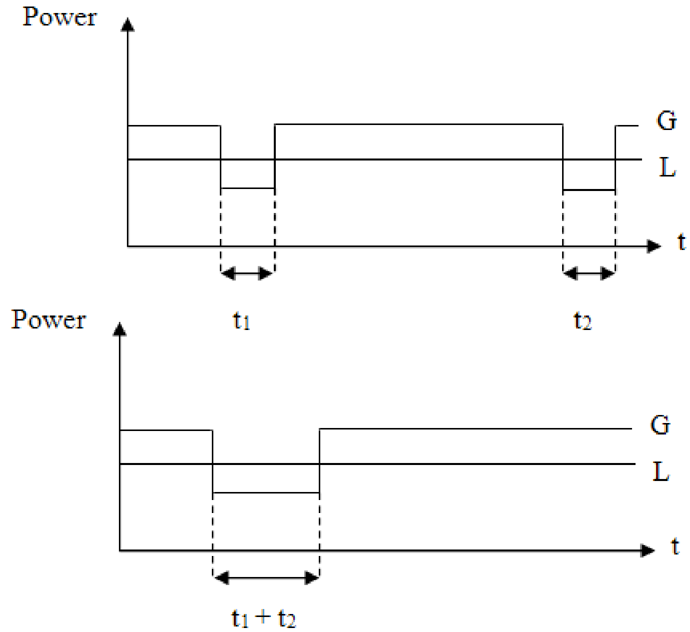

Figure 2 - Generation-load model example for Freq & Duration

Next, let us consider the two graphs in Fig. 3:

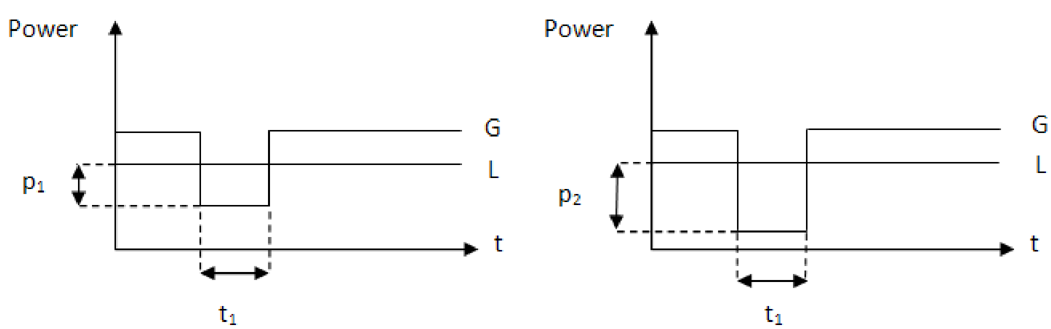

Figure 3 - Generation-load model example for EUE

They both have same LOLE and Freq & Duration. However, they are different scenarios of generation capacity deficiency. Therefore, another reliability index needs to be introduced to differentiate these scenarios. This index is called Expected Unserved Energy (EUE). EUE calculated the total energy that was not supplied due to the generation capacity deficiency.

These three indices, which are the main probabilistic indices for generation system reliability evaluation, are defined below [11]:

1. Loss of Load Expectation (LOLE):
    a. DLOLE is the expected number of days per year on which insufficient generating capacity is available to serve the daily peak load
    b. HLOLE is the expected number of hours per year when insufficient generating capacity is available to serve the load
2. Frequency and Duration of capacity shortage events (F&D):
    a. Frequency of generating capacity shortage events is defined to be the expected (average) number of such events per year
    b. Duration is the expected length of capacity shortage periods when they occur
3. Expected Unserved Energy (EUE): This index measures the expected amount of energy which will fail to be supplied per year due to generative capacity differences and/or shortages in basic energy supplies.

CHAPTER III

GENERATION UNIT MODELING

In order to evaluate reliability of generation systems, each generator must be represented by a model. These models reflect the performance of generators in various states. The individual generator model is referred to as unit model. Unit models indicate various states with transition rates between them. From these transition rates, probability of each state, and frequency of transition from one state to another state is obtained for generating units. Unit models are combined together to obtain the generation system model. The unit modeling of conventional and solar generators is described next.

3.1 Conventional Unit Modeling

The conventional generator can be modeled as a *2*-state or a *3*-state unit. If modeled as a *2*-state unit, they have up-state where the unit is fully available and down-state where the unit is on forced outage. On the other hand, if modeled as a *3*-state unit, there is a third state in which the unit is said to be derated. In this case, the unit is operating below the rated capacity because of partial failure. In this thesis, the conventional generator is modeled as a *2*-state unit, which is shown in Fig. 4.

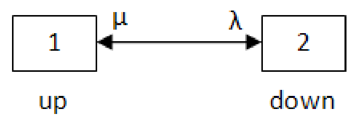

Figure 4 - *2*-state unit model of a conventional generator

The transition rate from up-state to down-state is called failure rate and is represented by λ, and the transition rate from down-state to up-state is called repair rate and is represented by μ. Frequency of encountering state *j* from state *i* is the expected number of transition from state *i* to state *j* per unit time. The frequency of transition from one state to another state is calculated based on frequency balance approach. The frequency balance concept states that in steady state, frequency of encountering a state equals the frequency of exiting from that state [11]. The state probabilities and the transition frequency in a *2*-state unit are calculated as:

$$p_{up} = p_1 = \frac{\mu}{\lambda + \mu}$$

$$p_{down} = p_2 = \frac{\lambda}{\lambda + \mu}$$

$$f_{12} = f_{21} = \frac{\lambda\mu}{\lambda + \mu}$$

where

- λ is the failure rate of the generator
- μ is the repair rate of the generator
- f_{ij} is the frequency of transition from state *i* to state *j*.

In a *2*-state unit with rated capacity of *C*, when the unit is in up-state, the available capacity is *C* and the capacity outage level is *0*. On the other hand, when the unit is in down state, the available capacity is *0* and the capacity outage level is *C*.

3.2 Solar Unit Overview

There are two types of solar generators considered in this thesis. These are photovoltaic (PV) generators and concentrated solar power (CSP) generators. A brief introduction about PV and CSP units and their principle of power generation is given before modeling these units.

3.2.1 PV Units

PV plants generate power by converting the solar radiations into electricity. The solar radiation conversion into electricity is accomplished in photovoltaic cells. In order to increase the generated voltage and current, these cells are connected in series-parallel combinations. A number of PV cells connected in series form a PV panel or a PV module. These modules are building blocks of a PV system. PV systems are used either as a stand-alone system in which case it consists of few modules or as a grid-connected unit in which case it consists of several thousands of modules. These grid-connected PV units are called utility scale PV plants and are typically greater than 1 MW in size. In a utility scale PV plant, modules are interconnected in certain configurations. A number of PV modules connected in series form a string and a number of strings in parallel form an array. Therefore, an array is a series-parallel combination of PV modules to achieve a desired voltage and current level. These arrays are connected to a central inverter. In a utility scale PV plant there are a number of central inverters depending on the number of arrays and plant rating. In this thesis, since large scale solar power plant is intended, utility scale PV plant is considered for reliability evaluation. There are various configurations for large scale PV units. Fig. 5 shows a typical configuration of a utility scale PV unit [8].

Some PV plants have tracking system to follow the solar radiation and increase the plant energy output. This, however, increases the plant investment cost. For utility scale PV plant, this increased cost is usually more than the gained output, and so most of the utility scale PV plants do not have tracking system. The PV panels are tilted in a certain angle to maximize radiation absorption. The tilt angle is proportional to latitude of the plant location.

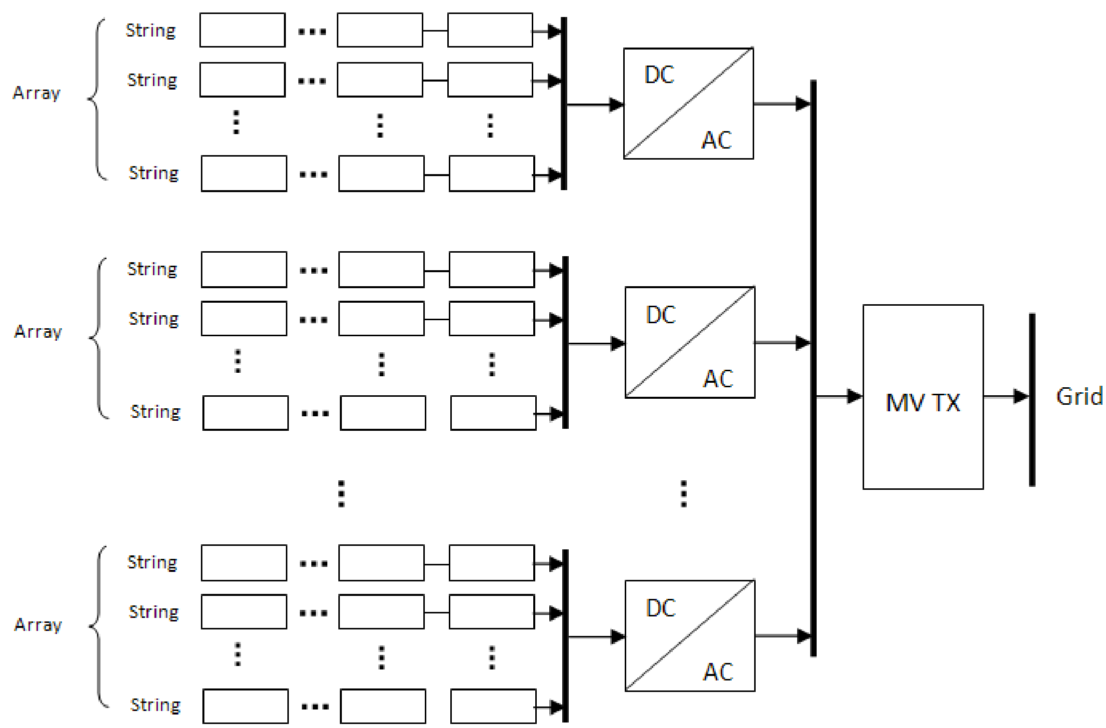

Figure 5 - Utility scale PV unit configuration

3.2.2 CSP Units

CSP plants generate power by concentrating sunlight to generate heat and convert that heat into electrical power in thermal plants. The solar heat is concentrated into a point using reflecting mirrors to produce high temperature. This temperature is used to absorb heat by a working fluid. Typically, molten salt is used for this purpose due to its heat transfer and thermal storage capabilities. This fluid is moved to a high temperature tank from where it is taken to boiler for steam production. After producing steam, the fluid is moved to a low temperature tank and then goes back to the solar field. The steam is used to produce electricity in the conventional steam turbines. These processes are shown in Fig. 6.

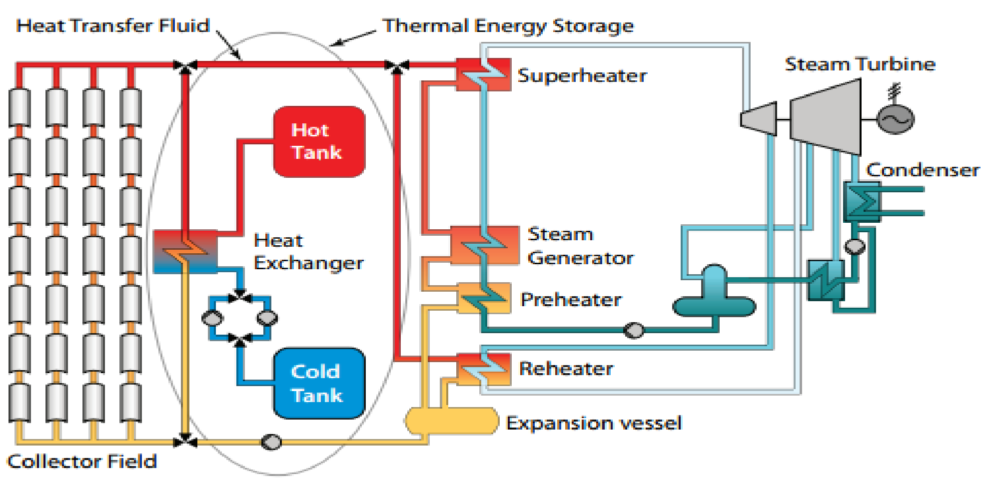

Figure 6 - CSP plant configuration [12]

With significant drop in PV modules manufacturing cost in recent years, CSP plants are less attractive economically; however, they have an advantage over PV plants from system operation point of view. A desirable feature in CSP plant is the ability to store the thermal energy. This is done in the high temperature tank. The duration of this storage depends on the working fluid and the tank, which can be from several hours up to few days [13][14]. This makes CSP plants to be dispatchable as long as thermal storage is available. Consequently, the CSP plants are called partially dispatchable generators. Even in the absence of storage, unlike PV plants, the CSP plant output does not drop immediately due to thermal inertia [13][14].

Since CSP plants concentrate the solar radiation to generate heat, they must have a sun tracking system. Otherwise, the plant efficiency drops significantly. There are different types of CSP technologies. These technologies differ in means to concentrate the sunlight:

- Parabolic trough: this technology uses linear parabolic trough as a reflector to concentrate the sunlight. A receiver consisting of a tube positioned along the focal line of the reflectors. The working fluid flows through this tube to absorb the heat. The reflectors have a single-axis tracking system to reflect the sun to the focal line during daylight. The parabolic trough technology is more dominant for large CSP plants due to its lower cost [15].
- Dish engine: this technology uses parabolic dish of mirrors as a reflector to concentrate the sunlight. This sunlight is focused into the power conversion unit located at the focal point of the dish. The reflector has a two-axis tracking system to reflect the sun to the focal point during daylight. The power conversion unit consists of the thermal receiver and

the engine or generator. The receiver absorbs the heat and transfers it to the engine that produces electricity. The most common type of engine used is the Stirling engine. The dish engine system produces relative small amounts of electricity compared to other CSP technologies (3-25 kW) [15].

- Concentrating linear Frensel reflector: this technology uses linear flat or slightly curved mirrors as a reflector to concentrate the sunlight. The receiver tubes are fixed in space above the mirrors. The reflector mirrors are mounted on trackers on the ground [15].
- Solar power tower: this technology uses large flat mirrors as a reflector to concentrate the sunlight. The receiver is located at the top of a tall tower. The reflector mirrors are mounted on a two-axis tracking system [15].

3.3 Solar Unit Modeling

After understanding the basic principle of operation of solar units, it is needed to model each unit to be used for reliability studies. This model is developed for PV and CSP units in subsequent sections.

3.3.1 PV Units

A typical grid-connected utility scale PV unit consists of PV modules, inverters, and transformers as it was shown in Fig. 5.

There are a number of ways in which a PV plant can fail:

- Failure in PV modules or cells
- Failure in inverters
- Failure in the transformer.

There are other components, such as DC links and AC buses, in a PV plant that can also fail, but due to low probability of failure and redundancy, their failures are not considered. In case of failure in modules or cells, the array is still producing power, but less than its rated value. Since number of failed cells or panels is small compared to available ones, its impact on overall PV plant availability is minor. Consequently, the module or cell failure is not considered in PV unit modeling.

Therefore, a PV unit failure is mainly due to failure in inverters or the transformer. Consequently, for the PV unit model the number of states depends on the number of inverters, where number of inverters depends on the plant size. For a PV unit with n inverters each rated m MW, the unit rating is $n \times m$ MW. The number of states in this case is $n+1$.

The same *2*-state model that was used for a conventional generator is also used for inverters with λ_I and μ_I being inverter's failure and repair rate. The probability of up- and down-states of the inverter is p_{Iup} and p_{Idown}, respectively. Since the inverters are independent of each other, i.e. there is no common mode failure, the transition can only occur from one state to another adjacent state. The state transition diagram for an *n*-inverter system is shown in Fig. 7.

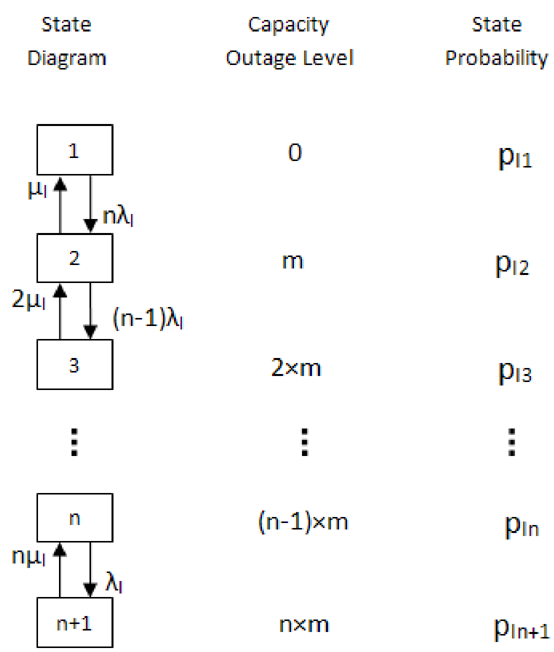

Figure 7 - State transition diagram for an *n*-inverter system

The probability of each state depends on the number of inverters. In order to explain the state probability calculations, let's assume that there are 10 inverters (*n*=10) and each inverter is rated at 1 MW (*m*=1). In this case, there are 11 states and probability of each state needs to be calculated. Each state probability depends on the number of scenarios in which that state can occur. For example, the first state (all inverters up) has only one scenario. The second state (only one inverter down) has 10 scenarios namely inverter 1 down, inverter 2 down, …, inverter 10 down. The number of scenarios and state probabilities for *10*-inverter case is shown in Table 1.

The frequency of transition from one state to another state is calculated based on frequency balance approach. The frequency calculations are given in Table 2.

Table 1 - State probabilities for *10*-inverter system

i	Capacity Outage Levels (MW)	No. of Scenarios	State Probability (p_{Ii})
1	0	1	$(p_{Iup})^{10}$
2	1	10	$10\times(p_{Iup})^{9}\ (p_{Idown})$
3	2	45	$45\times(p_{Iup})^{8}\ (p_{Idown})^{2}$
4	3	120	$120\times(p_{Iup})^{7}\ (p_{Idown})^{3}$
5	4	210	$210\times(p_{Iup})^{6}\ (p_{Idown})^{4}$
6	5	252	$252\times(p_{Iup})^{5}\ (p_{Idown})^{5}$
7	6	210	$210\times(p_{Iup})^{4}\ (p_{Idown})^{6}$
8	7	120	$120\times(p_{Iup})^{3}\ (p_{Idown})^{7}$
9	8	45	$45\times(p_{Iup})^{2}\ (p_{Idown})^{8}$
10	9	10	$10\times(p_{Iup})\ (p_{Idown})^{9}$
11	10	1	$(p_{Idown})^{10}$

Table 2 - Frequency calculations for *10*-inverter system

Transition Frequency
$f_{12} = f_{21} = p_{I2} \times \mu_I$
$f_{23} = f_{32} = p_{I3} \times 2\mu_I$
$f_{34} = f_{43} = p_{I4} \times 3\mu_I$
$f_{45} = f_{54} = p_{I5} \times 4\mu_I$
$f_{56} = f_{65} = p_{I6} \times 5\mu_I$
$f_{67} = f_{76} = p_{I7} \times 6\mu_I$
$f_{78} = f_{87} = p_{I8} \times 7\mu_I$
$f_{89} = f_{98} = p_{I9} \times 8\mu_I$
$f_{9,10} = f_{10,9} = p_{I10} \times 9\mu_I$
$f_{10,11} = f_{11,10} = p_{I11} \times 10\mu_I$

Next, we must include the effect of transformer on the inverter state transition diagram. The same *2*-state model that was used for a conventional generator is also used for a transformer with λ_T and μ_T being transformer's failure and repair rates. The probability of up- and down-states of the transformer is p_{Tup} and p_{Tdown}, respectively. The state transition diagram for *10*-inverter with transformer PV unit and the state probability calculations are shown in Fig. 8.

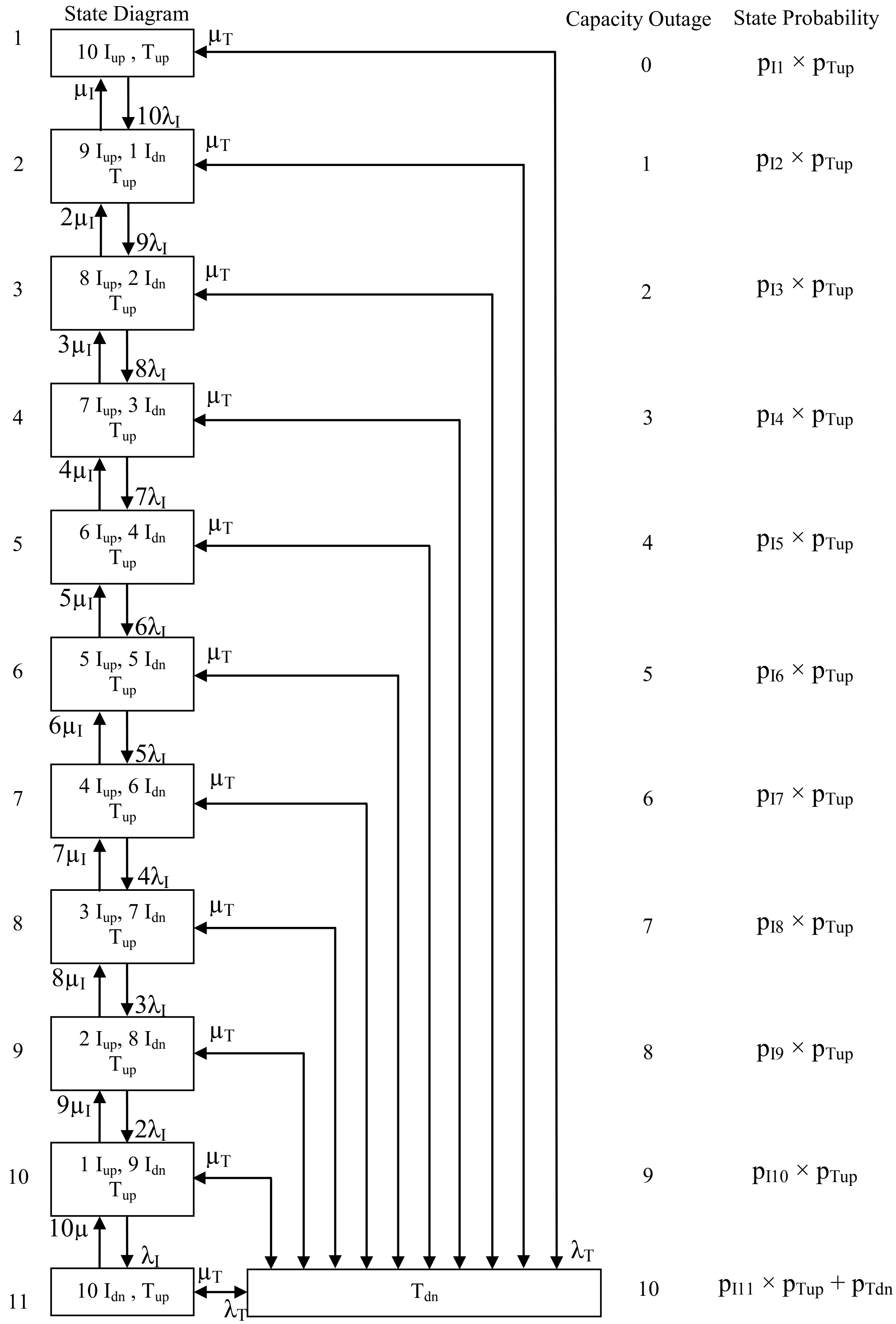

Figure 8 - State transition diagram for *10*-inverter & transformer PV unit

Transformer failure causes full capacity outage. Therefore, a transformer down-state is added to the last state corresponding to the full capacity outage. All other capacity outage levels are achieved if the transformer is in up-state. So the state probabilities are multiplied by the transformer up-state probability.

For the frequency calculations, in addition to transition from one state to another adjacent state, there can also be transition from any state to the last state and vice versa. This happens when the transformer is failed or repaired. The frequency calculations are given in Table 3.

Table 3 - Frequency calculations for *10*-inverter & transformer PV unit

Transition Frequency (Due to Inverter)	Transition Frequency (Due to Transformer)
$f_{12} = f_{21} = p_{I2} \times p_{Tup} \times \mu_I$	$f_{1,11} = f_{11,1} = p_{I1} \times p_{Tdown} \times \mu_T$
$f_{23} = f_{32} = p_{I3} \times p_{Tup} \times 2\mu_I$	$f_{2,11} = f_{11,2} = p_{I2} \times p_{Tdown} \times \mu_T$
$f_{34} = f_{43} = p_{I4} \times p_{Tup} \times 3\mu_I$	$f_{3,11} = f_{11,3} = p_{I3} \times p_{Tdown} \times \mu_T$
$f_{45} = f_{54} = p_{I5} \times p_{Tup} \times 4\mu_I$	$f_{4,11} = f_{11,4} = p_{I4} \times p_{Tdown} \times \mu_T$
$f_{56} = f_{65} = p_{I6} \times p_{Tup} \times 5\mu_I$	$f_{5,11} = f_{11,5} = p_{I5} \times p_{Tdown} \times \mu_T$
$f_{67} = f_{76} = p_{I7} \times p_{Tup} \times 6\mu_I$	$f_{6,11} = f_{11,6} = p_{I6} \times p_{Tdown} \times \mu_T$
$f_{78} = f_{87} = p_{I8} \times p_{Tup} \times 7\mu_I$	$f_{7,11} = f_{11,7} = p_{I7} \times p_{Tdown} \times \mu_T$
$f_{89} = f_{98} = p_{I9} \times p_{Tup} \times 8\mu_I$	$f_{8,11} = f_{11,8} = p_{I8} \times p_{Tdown} \times \mu_T$
$f_{9,10} = f_{10,9} = p_{I10} \times p_{Tup} \times 9\mu_I$	$f_{9,11} = f_{11,9} = p_{I9} \times p_{Tdown} \times \mu_T$
$f_{I10,11} = f_{I11,10} = p_{I11} \times p_{Tup} \times 10\mu_I$	$f_{T10,11} = f_{T11,10} = p_{I10} \times p_{Tdown} \times \mu_T$

3.3.2 CSP Units

There are a number of ways in which a CSP unit may experience failures:

- Reflector failure
- Receiver failure
- Tracking system failure

- Thermal unit failure.

A failure in reflector, receiver, or tracking system does not affect the entire system. It only reduces the amount of heat being generated. Consequently, the reflector and the receiver failures are not considered in CSP unit modeling.

Therefore, a CSP unit failure is mainly due to failure in the steam generator. These generators are the same as the conventional generators and are modeled same as the conventional units. Therefore, the *2*-state unit model is also used for CSP units.

CHAPTER IV

GENERATION SYSTEM MODELING

Once units are modeled, these need to be combined to obtain the generation system model for each subsystem. The generation system model for each subsystem has several states. It is important to know the capacity outage level, the cumulative probability, and the cumulative frequency of occurrence for each state.

4.1 Generation System Model Elements

Generation systems are modeled by three arrays: capacity outage levels (***X***), cumulative probability of capacity outages (***P***), and cumulative frequency of capacity outages (***F***) as follows:

- X_i = one of the discrete capacity outage levels
- P_i = probability of capacity outage greater than or equal to X_i
- F_i = frequency of capacity outage greater than or equal to X_i.

The generation system model is arranged in a tabular form with capacity outage levels sorted in ascending order. Table 4 indicates a generation system model in a tabular form. Index *i* is the number of capacity outage level in the generation system model.

Table 4 - Generation system model

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	X_1	P_1	F_1
2	X_2	P_2	F_2
3	X_3	P_3	F_3
…	…	…	…

There are number of ways to construct the generation system model. The most common method used is called unit addition algorithm. This algorithm is used for embedding a unit model in the generation system model. This method is explained in the following section.

4.2 Unit Addition Algorithm

Let's assume that the generation system model is available in the tabular form as Table 5. We add an *n*-state unit to this model. Let Y_i be the capacity outage level in state *i*. This is shown in Table 6.

Table 5 - Existing generation system model

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	X_1	P_1	F_1
2	X_2	P_2	F_2
3	X_3	P_3	F_3
…	…	…	…
l	X_l	P_l	F_l
…	…	…	…
k	X_k	P_k	F_k
…	…	…	…
j	X_j	P_j	F_j
…	…	…	…
i	X_i	P_i	F_i
…	…	…	…

Table 6 - Capacity outage levels of the unit being added

i	Cap outage levels of the new unit
1	Y_1
2	Y_2
…	…
n	Y_n

The addition of an *n*-state unit, results in *n* subsets of states:

$S_1=\{X_i+Y_1\}$
$S_2=\{X_i+Y_2\}$
…
$S_{n-1}=\{X_i+Y_{n-1}\}$
$S_n=\{X_i+Y_n\}$.

These *n* subsets, arranged as *n* columns in Table 7, have an equal number of states and in each the capacity outages are arranged in an ascending order.

Table 7 - Capacity outage levels after unit addition

S_1	S_2	…	S_{n-1}	S_n
X_1+Y_1	X_1+Y_2	…	X_1+Y_{n-1}	X_1+Y_n
X_2+Y_1	X_2+Y_2	…	X_2+Y_{n-1}	X_2+Y_n
X_3+Y_1	X_3+Y_2	…	X_3+Y_{n-1}	X_3+Y_n
…	…	…	…	…
X_l+Y_1	X_l+Y_2	…	X_l+Y_{n-1}	X_l+Y_n
…	…	…	…	…
X_k+Y_1	X_k+Y_2	…	X_k+Y_{n-1}	X_k+Y_n
…	…	…	…	…
X_j+Y_1	X_j+Y_2	…	X_j+Y_{n-1}	X_j+Y_n
…	…	…	…	…
X_i+Y_1	X_i+Y_2	…	X_i+Y_{n-1}	X_i+Y_n
…	…	…	…	…

Assuming that a capacity equal to or greater than *X* is defined by states equal to and greater than *i*, *j*, …, *k*, *l* in S_1, S_2, …, S_{n-1}, S_n:

$$P(X) = P_i\, p_1 + P_j\, p_2 + \ldots + P_k\, p_{n-1} + P_l\, p_n$$

$$F(X) = G(X) + N(X)$$

where

$$G(X) = F_i\, p_1 + F_j\, p_2 + \ldots + F_k\, p_{n-1} + F_l\, p_n$$

$N(X) = (P_j - P_i) f_{21} + (P_k - P_i) f_{31} + (P_k - P_j) f_{32} + \ldots + (P_l - P_i) f_{k1} + (P_l - P_j) f_{k2}$

$+ \ldots + (P_l - P_k) f_{k(k-1)}$

Pi = probability of capacity outage equal to or greater than Xi

Fi = frequency of capacity outage equal to or greater than Xi.

G(X) represents the frequency due to change in the states of the existing units and *N(X)* represents the frequency due to change in the states of the added unit.

4.3 Simplified Unit Addition Algorithm for Subsystems

The above algorithm is explained for general *n*-state case. This, however, can be simplified for conventional and CSP subsystems since *2*-state units are employed. For PV subsystem, we still have *n*-state, but the state transition frequency calculations can be simplified. These are discussed in subsequent sections.

4.3.1 Conventional and CSP Subsystems

These subsystems are composed of *2*-state units. Addition of these units into existing system will result in two subsets of states:

$S_1 = \{X_i+Y_1\}$
$S_2 = \{X_i+Y_2\}$

where Y_i is the capacity outage level of a *2*-state unit being added. These capacity outage levels can be represented by $Y_1 = 0$ and $Y_2 = C$, where *C* is the capacity of the unit being added. Therefore,

$S_1 = \{X_i\}$
$S_2 = \{X_i+C\}$.

These two subsets, arranged as two columns in Table 8, have an equal number of states and in each the capacity outages are arranged in an ascending order.

Table 8 - Capacity outage levels after *2*-state unit addition

S_1	S_2
X_1	X_1+C
X_2	X_2+C
X_3	X_3+C
…	…
X_j	X_j+C
…	…
X_i	X_i+C
…	…

Assuming that a capacity equal to or greater than *X* is defined by states equal to and greater than *i* and *j* in S_1 and S_2:

$P(X) = P_i\, p_1 + P_j\, p_2$

$F(X) = G(X) + N(X)$

where

$G(X) = F_i\, p_1 + F_j\, p_2$

$N(X) = (P_j - P_i)\, f_{21}$

Pi = probability of capacity outage equal to or greater than Xi

Fi = frequency of capacity outage equal to or greater than Xi.

4.3.2 PV Subsystem

PV units have multiple number of states, so it is required to use the original *n*-state unit addition algorithm to build the generation subsystem model. However, we can simplify the frequency calculations since we can only have transitions from one state to another adjacent state or from any state to state *n* in case of transformer failure.

Here as before, the addition of a *n*-state unit, results in *n* subsets of states:

$S_1 = \{X_i+Y_1\}$
$S_2 = \{X_i+Y_2\}$
…
$S_{n-1} = \{X_i+Y_{n-1}\}$
$S_n = \{X_i+Y_n\}$

where Y_i is the capacity outage levels of a *n*-state unit being added.

These *n* subsets, arranged as *n* columns in Table 9, have an equal number of states and in each the capacity outages are arranged in an ascending order.

Table 9 - Capacity outage levels after *n*-state unit addition

S_1	S_2	…	S_{n-1}	S_n
X_1+Y_1	X_1+Y_2	…	X_1+Y_{n-1}	X_1+Y_n
X_2+Y_1	X_2+Y_2	…	X_2+Y_{n-1}	X_2+Y_n
X_3+Y_1	X_3+Y_2	…	X_3+Y_{n-1}	X_3+Y_n
…	…	…	…	…
X_l+Y_1	X_l+Y_2	…	X_l+Y_{n-1}	X_l+Y_n
…	…	…	…	…
X_k+Y_1	X_k+Y_2	…	X_k+Y_{n-1}	X_k+Y_n
…	…	…	…	…
X_j+Y_1	X_j+Y_2	…	X_j+Y_{n-1}	X_j+Y_n
…	…	…	…	…
X_i+Y_1	X_i+Y_2	…	X_i+Y_{n-1}	X_i+Y_n
…	…	…	…	…

Assuming that a capacity equal to or greater than *X* is defined by states equal to and greater than *i*, *j*, …, *k*, *l* in $S_1, S_2, \ldots, S_{n-1}, S_n$:

$$P(X) = P_i\, p_1 + P_j\, p_2 + \ldots + P_k\, p_{n-1} + P_l\, p_n$$

$$F(X) = G(X) + N(X)$$

where

$G(X) = F_i\, p_1 + F_j\, p_2 + \ldots + F_k\, p_{n-1} + F_l\, p_n$

$N(X) = (P_j – P_i)\, f_{21} + (P_k – P_j)\, f_{32} + \ldots + (P_l – Pk)\, f_{In(n-1)} + (P_l – Pk)(f_{n1} + f_{n2} + \ldots$

$+ f_{Tn(n-1)})$

Pi = probability of capacity outage equal to or greater than Xi

Fi = frequency of capacity outage equal to or greater than Xi.

Let's assume that we want to add the *11*-state PV unit that was modeled in Chapter III to an existing generation system. The capacity outage levels and state probabilities of this unit are given in Table 10 and the state transition frequencies are given in Table 11.

Table 10 - Capacity outage levels and state probabilities of an *11*-state PV unit

i	Capacity outage levels (MW)	State probabilities
1	0	p_1
2	1	p_2
3	2	p_3
4	3	p_4
5	4	p_5
6	5	p_6
7	6	p_7
8	7	p_8
9	8	p_9
10	9	p_{10}
11	10	p_{11}

Table 11 - State transition frequency of an *11*-state PV unit

Frequency (I)	Frequency (T)
f_{21}	$f_{11,1}$
f_{32}	$f_{11,2}$
f_{43}	$f_{11,3}$

Table 11 - Continued

Frequency (I)	Frequency (T)
f_{54}	$f_{11,4}$
f_{65}	$f_{11,5}$
f_{76}	$f_{11,6}$
f_{87}	$f_{11,7}$
f_{98}	$f_{11,8}$
$f_{10,9}$	$f_{11,9}$
$f_{I11,10}$	$f_{T11,10}$

Assume that the existing generation system has 21 states. In this case, addition of an *11*-state unit results in 11 subset of states. This is indicated in Table 12. In this case, a capacity equal to or greater than *15* MW is defined by states equal to and greater than *16, 15, 14, …, 6* in $S_1, S_2, \ldots, S_{11}$:

$$P(15) = P_{16}\, p_1 + P_{15}\, p_2 + P_{14}\, p_3 + P_{13}\, p_4 + P_{12}\, p_5 + P_{11}\, p_6 + P_{10}\, p_7 + P_9\, p_8 + P_8\, p_9 + P_7\, p_{10} + P_6\, p_{11}$$

$$F(15) = G(15) + N(15)$$

where

$$G(15) = F_{16}\, p_1 + F_{15}\, p_2 + F_{14}\, p_3 + F_{13}\, p_4 + F_{12}\, p_5 + F_{11}\, p_6 + F_{10}\, p_7 + F_9\, p_8 + F_8\, p_9 + F_7\, p_{10} + F_6\, p_{11}$$

$$N(15) = (P_{15} - P_{16})\, f_{21} + (P_{14} - P_{15})\, f_{32} + (P_{13} - P_{14})\, f_{43} + (P_{12} - P_{13})\, f_{54} + (P_{11} - P_{12})\, f_{65} + (P_{10} - P_{11})\, f_{76} + (P_9 - P_0)\, f_{87} + (P_8 - P_9)\, f_{98} + (P_7 - P_8)\, f_{10,9} + (P_6 - P_7)\, f_{I11,10} + (P_6 - P_7)\, (f_{11,1} + f_{11,2} + f_{11,3} + f_{11,4} + f_{11,5} + f_{11,6} + f_{11,7} + f_{11,8} + f_{11,9} + f_{T11,10}).$$

The stair case in Table 12 is used to indicate the frequency of transition from capacity outages greater than 15 MW to capacity outages less than 15 MW.

Table 12 - Addition of an *11*-state unit to *21*-state generation system

	Subsets	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}
i	Cap Out (MW)	0	1	2	3	4	5	6	7	8	9	10
1	0	0	1	2	3	4	5	6	7	8	9	10
2	1	1	2	3	4	5	6	7	8	9	10	11
3	2	2	3	4	5	6	7	8	9	10	11	12
4	3	3	4	5	6	7	8	9	10	11	12	13
5	4	4	5	6	7	8	9	10	11	12	13	14
6	5	5	6	7	8	9	10	11	12	13	14	15
7	6	6	7	8	9	10	11	12	13	14	15	16
8	7	7	8	9	10	11	12	13	14	15	16	17
9	8	8	9	10	11	12	13	14	15	16	17	18
10	9	9	10	11	12	13	14	15	16	17	18	19
11	10	10	11	12	13	14	15	16	17	18	19	20
12	11	11	12	13	14	15	16	17	18	19	20	21
13	12	12	13	14	15	16	17	18	19	20	21	22
14	13	13	14	15	16	17	18	19	20	21	22	23
15	14	14	15	16	17	18	19	20	21	22	23	24
16	15	15	16	17	18	19	20	21	22	23	24	25
17	16	16	17	18	19	20	21	22	23	24	25	26
18	17	17	18	19	20	21	22	23	24	25	26	27
19	18	18	19	20	21	22	23	24	25	26	27	28
20	19	19	20	21	22	23	24	25	26	27	28	29
21	20	20	21	22	23	24	25	26	27	28	29	30

4.4 Impact of Solar Radiation on Solar Plants

Solar plant power generation depends on solar radiation. This has to be included in the subsystem generation model. The vector containing capacity outage levels in the PV and CSP subsystem generation model needs to be modified to include the effect of solar radiation. The solar plant power generation, however, needs to be evaluated in correlation with load. There is a common mistake to obtain the probability of various power output levels of solar plants based on the solar radiation, without considering the load. In order to consider the correlation between solar plants power level and the load, the power output of these plants is evaluated on hourly basis. Therefore, the capacity outage level vector of solar plants needs to be modified on hourly basis.

4.4.1 PV Plants

The PV plant power output directly depends on the solar radiation intensity. The solar radiation that contributes to PV plant power generation is called global solar radiation. Global radiation consists of direct radiation, diffuse radiation, and reflected radiation. This radiation has to be measured at a surface perpendicular to the PV modules.

The PV power plant rating is based on global solar radiation of 1000 W/m^2. The hourly global solar radiation in the plant location is divided by 1000 to obtain the power output coefficient. For example, if the hourly radiation is 783 W/m^2, the power output coefficient in that hour would be 0.783. This coefficient can also be greater than one, up to around 1.15, if the global solar radiation is greater than 1000 W/m^2. The power output coefficient, denoted by POC, is obtained hourly for the period under study:

$$POC_k = \frac{average\ global\ solar\ radiation\ at\ hour\ k\ in\ \frac{W}{m^2}}{1000}.$$

Vector $\boldsymbol{G_k}$ is created to indicate hourly power output as follows [5]:

$\boldsymbol{G_k} = \boldsymbol{A} \times POC_k$

where $\boldsymbol{A}$ is the available capacity vector of the generation system model of the PV subsystem.

The available capacity vector is the total plant capacity minus the capacity outage vector:

$$\boldsymbol{A} = C - \boldsymbol{X}$$

where C is the total plant capacity. Therefore, the available capacity has the same number of levels as the capacity outage.

Once $\boldsymbol{G_k}$ is obtained, the capacity outage vector **X** has to be modified hourly to include the effect of fluctuating solar radiation. This is accomplished by creating a modified capacity outage level vector $\bar{\mathbf{X}}$ for each hour of the period under study:

$$\bar{\mathbf{X}}_{\mathbf{k}} = \mathrm{C} - \boldsymbol{G_k}.$$

4.4.2 CSP Plants

The CSP plants usually have heat storage capability. Therefore, while CSP plant daily energy output depends on daily solar radiation, its power output is not directly affected due to the storage capability. As a result, the methodology applied to PV plants to obtain the power output coefficient is not applicable to CSP plants. The solar radiation that contributes to CSP plant power generation is direct normal solar radiation. Other radiations such as diffused or reflected do not contribute to CSP power generation. Since CSP plants have tracking system, they can align their reflectors such that they receive direct normal radiation during hours at which sun is available. The number of hours at which sun is available affects CSP plant availability. Average daily radiation is calculated to determine the average power output. This average is calculated for hours from sunrise to sunset. The daily plant power output is considered to be constant during hours of plant operation. The CSP power plant rating is based on direct normal solar radiation of 1000 W/m^2. The hourly power output coefficient for hours between sunrise and sunset is calculated as:

$$POC_k = \frac{total\ daily\ direct\ normal\ solar\ radiation\ \frac{W}{m^2}}{number\ of\ hours\ from\ sunrise\ to\ sunset \times 1000}.$$

From sunset to sunrise the plant output is set to be zero since no direct normal radiation is available. Therefore, power output coefficient for hours between sunset to sunrise is 0.

Once POC_k is obtained for the period under study, the modified capacity outage level vector $\bar{\mathbf{X}}$ can be calculated in the same manner as PV subsystem. Table 13 indicates generation system model of solar plants after radiation effect consideration.

Table 13 - Generation system model of solar plants

i	$\bar{X}_i$ = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	$\bar{X}_1$	P_1	F_1
2	$\bar{X}_2$	P_2	F_2
3	$\bar{X}_3$	P_3	F_3
…	…	…	…

CHAPTER V

RELIABILITY INDICES CALCULATION AND CAPACITY CREDIT EVALUATION

5.1 Load Modeling

In order to calculate the reliability indices, load model needs to be developed. The load model is the forecasted hourly load for the period under study. This forecast can be based on historical data and other contributing factors.

In order to develop a load model, a weekly peak load is developed first. Consumer’s electricity consumption varies during different weeks of a year. This weekly peak load varies by season. Appliances used in summer are different than those used in winter and they have different power consumptions. After weekly peak load, daily peak load is developed. This reflects consumer’s consumption during different days of week. Next, hourly peak load is developed. This indicates consumer’s consumption at different hours of a day. This hourly peak load again depends on the season. Therefore, we can have hourly peak load for different seasons.

Once weekly, daily, and hourly peak loads are developed, we can obtain the hourly peak load for each year. Sometimes, loads are classified in different power levels and probability of each is obtained. In this thesis, however, hourly load data is used so we can consider its correlation with solar radiation.

5.2 Reliability Indices Calculation

Once generation model and load model are constructed, system reliability can be evaluated. As discussed in Chapter II, the reliability indices used for generation system reliability evaluation are LOLE, Frequency of capacity deficiency, and EUE. The calculations of these indices are explained subsequently.

5.2.1 LOLE

The loss of load expectation is found using the following equation for conventional subsystem [7]:

$$LOLE = \Delta T \sum_{i=1}^{N_t} P_c(k_i) \tag{5.1}$$

where

- ΔT is the time step duration
- N_t is the total number of time steps
- P_c is cumulative probability of the conventional subsystem
- k_i is defined such that $X(k_i)$ is the smallest capacity outage that would cause capacity deficiency.

More precisely,

$$C - X(k_i) < L_i$$

$$C - X(k_i - 1) \geq L_i$$

where C is the total plant capacity. The time step duration used is normally 1 hour ($\Delta T=1$). In this case, N_t is 8760 for one year. Sometimes for simplicity, year is taken to be 364 days, which is integer multiple of 7, in which case, N_t would be 8736. The k_i is obtained with regard to the hourly load model. In order to include the effect of intermittent sources, an extra summation is added for every intermittent source [7]. For each capacity outage level of CSP subsystem, LOLE is calculated on hourly basis:

$$LOLE_{i,n} = \sum_{m=1}^{N_{pv}} p_{pv}(m) p_{csp}(n) P_c(k_i) \tag{5.2}$$

$$LOLE_i = \sum_{n=1}^{N_{csp}} LOLE_{i,n} \tag{5.3}$$

$$LOLE = \sum_{i=1}^{N_t} LOLE_i \tag{5.4}$$

where

- N_{pv} is the number of capacity outage levels of the PV subsystem
- N_{csp} is the number of capacity outage levels of the CSP subsystem
- p_{pv} is the exact state probability of the PV subsystem
- p_{csp} is the exact state probability of the PV subsystem.

Alternatively, this could be done in one step:

$$LOLE = \sum_{i=1}^{N_t} \sum_{n=1}^{N_{csp}} \sum_{m=1}^{N_{pv}} p_{pv}(m) p_{csp}(n) P_c(k_i). \tag{5.5}$$

5.2.2 EUE

The proposed method in this thesis uses the expected value of the unserved load to obtain EUE. This EUE is obtained as [7]:

$$EUE = \Delta T \sum_{i=1}^{N_t} U(L_i) \tag{5.6}$$

where L_i is the load at hour i and $U(L_i)$ is the expected value of unserved load during time interval i. If the time interval is taken to be one hour, the expected value of unserved load is calculated in hourly basis. In order to calculate $U(L_i)$, the load model and generation model is used.

$$U(L_i) = \sum_{k=k_i}^{N_c} \left[L_i - \left(C - X(k)\right)\right] p_c(k) \tag{5.7}$$

where p_c is the exact state probability of the conventional subsystem. (5.7) can be rewritten as:

$$U(L_i) = \sum_{k=k_i}^{N_c} [L_i - C] p_c(k) + \sum_{k=k_i}^{N_c} X(k)\, p_c(k). \tag{5.8}$$

(5.8) can be expressed as:

$$U(L_i) = [L_i - C] P_c(k_i) + H(k_i) \tag{5.9}$$

where $H(k_i)$ is defined as:

$$H(k_i) = \sum_{k=k_i}^{N_c} X(k)\, p_c(k). \tag{5.10}$$

The quantity $H(k_i)$ is the expected value or mean value of all capacity outages which would cause capacity deficiency during time interval i. Therefore, using (5.6), EUE can be expressed as:

$$EUE = \sum_{i=1}^{N_t} [H(k_i) + (L_i - C)P_c(k_i)] \quad (5.11)$$

where ΔT is considered to be 1. In order to obtain EUE for generation systems including intermittent sources such as solar, it is required to find the expected value of the unserved load first. This is done by adding an extra summation in (5.7) for each solar subsystem:

$$U(L_i) = \sum_{k=k_i}^{N_c} \sum_{n=1}^{N_{csp}} \sum_{m=1}^{N_{pv}} p_{pv}(m) p_{csp}(n) \left[L_i - \left(C_c + C_{i,pv} + C_{i,csp} - X(k)\right)\right] p_c(k) \quad (5.12)$$

where

- C_c is the total capacity of the conventional subsystem
- $C_{i,pv}$ is the hourly total capacity of the PV subsystem
- $C_{i,csp}$ is the hourly total capacity of the CSP subsystem.

Note that the PV and CSP subsystem capacities depend on *i*. That means these capacities are changing hourly. These hourly capacities can be obtained using power output coefficient that was explained in Chapter IV:

$$C_{i,pv} = C_{pv} \times POC_i^{pv} \quad (5.13)$$

$$C_{i,csp} = C_{csp} \times POC_i^{csp} \quad (5.14)$$

where

- C_{pv} is the total installed capacity of the PV subsystem
- C_{csp} is the total installed capacity of the CSP subsystem
- POC_i^{pv} is the hourly power output coefficient of the PV subsystem

- POC_i^{csp} is the hourly power output coefficient of the CSP subsystem.

As before, (5.12) can be written as:

$$U(L_i) = \sum_{n=1}^{N_{csp}} \sum_{m=1}^{N_{pv}} p_{pv}(m) p_{csp}(n) \left[\left[L_i - C_c - C_{i,pv} - C_{i,csp} \right] p_c(k_i) \ + \ H(k_i) \right]. \quad (5.15)$$

Once the expected value of unserved load is obtained, EUE can be found using (5.6):

$$EUE = \sum_{i=1}^{N_t} \sum_{n=1}^{N_{csp}} \sum_{m=1}^{N_{pv}} p_{pv}(m) p_{csp}(n) \left[\left[L_i - C_c - C_{i,pv} - C_{i,csp} \right] P(k_i) \ + \ H(k_i) \right] \quad (5.16)$$

where ΔT is considered to be 1.

5.2.3 Frequency of Capacity Deficiency

The capacity deficiency can change due to different changes in the system. These are:

- Changes in the conventional subsystem
- Changes in the PV subsystem
- Changes in the CSP subsystem
- Changes in the load.

All these changes can contribute to the frequency of capacity deficiency. The effect of these are calculated individually and then added together to obtain the overall frequency of capacity deficiency.

The frequency calculation due to changes in the conventional subsystem for each hour is:

$$Fc_i = \sum_{m=1}^{N_{pv}} \sum_{n=1}^{N_{csp}} p_{pv}(m) p_{csp}(n) F_c(k_i). \quad (5.17)$$

The frequency calculation due to changes in the PV subsystem for each hour is:

$$Fpv_i = \sum_{j=1}^{N_c} \sum_{n=1}^{N_{csp}} p_c(j) p_{csp}(n) F_{pv}(k_i). \quad (5.18)$$

The frequency calculation due to changes in the CSP subsystem for each hour is:

$$Fcsp_i = \sum_{j=1}^{N_c} \sum_{m=1}^{N_{pv}} p_c(j) p_{pv}(m) F_{csp}(k_i). \quad (5.19)$$

The above equations are the frequency calculations due to changes in the generation system. These frequencies are added together for the period under study:

$$F_g = \sum_{i=1}^{N_t} (Fc_i + Fpv_i + Fcsp_i). \quad (5.20)$$

The frequency calculation due to changes in the load for each hour is:

$$Fl_i = LOLE_{i+1} - LOLE_i. \quad (5.21)$$

The Fl_i has positive and negative components. Only positive components contribute to the frequency of capacity deficiency due to changes in the load. The positive components are added together for the period under study:

$$F_l = \sum_{i=1}^{N_t} (postive\ components\ of\ Fl_i). \quad (5.22)$$

Finally the total frequency of capacity deficiency for the period under study due to changes in generation and load system is calculated:

$$F = F_g + F_l. \tag{5.23}$$

5.3 Capacity Credit Evaluation

In addition to reliability indices calculation, it is important to evaluate the capacity credit of power plants. This is particularly interesting for renewable power plants since their sources are intermittent. “The capacity value of any generator is the amount of additional load that can be served at the target reliability level with the addition of generator in question [9].” Adding solar power to the grid has the effect of increasing the reliability of the generating system. Therefore, a reduction in conventional power can be achieved. This reduction is taken as a measure of the capacity credit of solar power [9][10][16][19]. Capacity credit should not be confused with capacity factor, which measures the ratio of actual power production of a generator over its nameplate rating for a period of time.

The reliability index used for capacity credit calculation is LOLE [9][10][17][18]. The LOLE of a given generation system is calculated first. This is called the base case LOLE. After adding the solar power to the generation system, the LOLE reduces. The peak load is increased iteratively such than the base case LOLE is achieved. This peak load increase is referred to as effective load carrying capability (ELCC) [9][10][18]. The ELCC is considered to be the capacity credit of the solar power plant. This methodology can be shown graphically as indicated in Fig. 9.

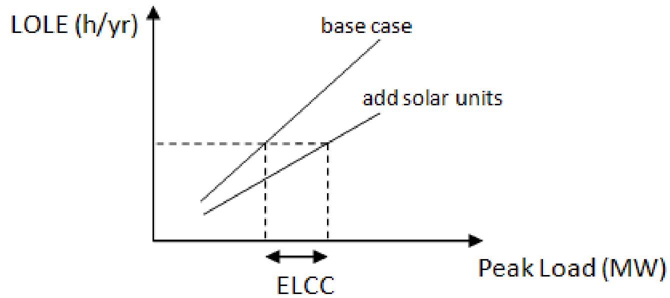

Figure 9 - Capacity credit evaluation method

The capacity value of solar power plant depends on a number of factors:

- Solar radiation at the plant location
- Solar plant components failure rate
- Penetration level of solar power
- Load model.

The solar radiation is the key factor in capacity value of solar plants. Consequently, solar plants are constructed at locations with high levels of solar radiation to increase its capacity value. The penetration level of solar power is also important factor in capacity credit calculations. It is expected that higher penetration levels reduces the capacity credit of solar plants. This is evaluated in case study of Chapter VI. The load model is another important factor in capacity value of solar plants. Correlation between load and solar radiation increases capacity value of solar plants.

CHAPTER VI

CASE STUDY

6.1 Introduction

The methodology developed in this thesis is evaluated in this chapter. In order to compare the generation system reliability with and without solar power, a test system is needed. The test system used in this thesis is IEEE Reliability Test System (IEEE-RTS). This test system has generation and load data and it serves as our base system. The generation system consists of conventional units. The solar power system is evaluated within this system for five and twenty percent penetration levels. For this purpose, five and twenty percent of the conventional power plants are replaced with the solar plants. The reliability indices of the base case are compared with that of five and twenty percent penetration of solar plants. In addition, capacity credits of solar power plants are evaluated for five and twenty percent penetration levels.

6.2 IEEE Reliability Test System

The IEEE-RTS describes a load model, generation system and transmission network which can be used to test or compare methods for reliability analysis of power systems [20]. Since in this thesis, transmission network is not considered, we only use the load model and the generation system.

6.2.1 Load Model

The annual peak load for the test system is 2850 MW. The weekly, daily, and hourly peak loads as percentage of annual peak load are given in the Tables 14, 15, and 16. From these tables, we obtain the hourly load for the whole year. The year is considered to be 52 weeks, which is 364 days. Therefore, the number of hours per year is 7836.

Table 14 - Weakly peak load in percent of annual peak

Week	Peak Load	Week	Peak Load
1	86.2	27	75.5
2	90.0	28	81.6
3	87.8	29	80.1
4	83.4	30	88.0
5	88.0	31	72.2
6	84.1	32	77.6
7	83.2	33	80.0
8	80.6	34	72.9
9	74.0	35	72.6
10	73.7	36	70.5
11	71.5	37	78.0
12	72.7	38	69.5
13	70.4	39	72.4
14	75.0	40	72.4
15	72.1	41	74.3
16	80.0	42	74.4
17	75.4	43	80.0
18	83.7	44	88.1
19	87.0	45	88.5
20	88.0	46	90.9
21	85.6	47	94.0
22	81.1	48	89.0
23	90.0	49	94.2
24	88.7	50	97.0
25	89.6	51	100.0
26	86.1	52	95.2

Table 15 - Daily peak load in percent of weekly peak

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

Table 16 - Hourly peak load in percent of daily peak

	Winter Weeks 1-8 & 44-52		Summer Weeks 18-30		Spring/Fall Weeks 9-17 & 31-43	
Hour	Wkdy	Wknd	Wkdy	Wknd	Wkdy	Wknd
0-1	67	78	64	74	63	75
1-2	63	72	60	70	62	73
2-3	60	68	58	66	60	69
3-4	59	66	56	65	58	66
4-5	59	64	56	64	59	65
5-6	60	65	58	62	65	65
6-7	74	66	64	62	72	68
7-8	86	70	76	66	85	74
8-9	95	80	87	81	95	83
9-10	96	88	95	86	99	89
10-11	96	90	99	91	100	92
11-12	95	91	100	93	99	94
12-13	95	90	99	93	93	91
13-14	95	88	100	92	92	90
14-15	93	87	100	91	90	90
15-16	94	87	97	91	88	86
16-17	99	91	96	92	90	85
17-18	100	100	96	94	92	88
18-19	100	99	93	95	96	92
19-20	96	97	92	95	98	100
20-21	91	94	92	100	96	97
21-22	83	92	93	93	90	95
22-23	73	87	87	88	80	90
23-24	63	81	72	80	70	85

6.2.2 Generation System

Table 17 gives a list of the generating unit ratings and reliability data.

Table 17 - Base system generation units

Generating Unit Reliability Data				
Unit Size (MW)	Number of Units	Forced Outage Rate	MTTF (hrs.)	MTTR (hrs.)
12	5	0.02	2940	60
20	4	0.10	450	50
50	6	0.01	1980	20
76	4	0.02	1960	40
100	3	0.04	1200	50
155	4	0.04	960	40
197	3	0.05	950	50
350	1	0.08	1150	100
400	2	0.12	1100	150

MTTF = mean time to failure

MTTR = mean time to repair

Forced Outage Rate = $\frac{MTTR}{MTTF + MTTR}$.

The generating units are of conventional type. This generation system consists of 9 distinct types of generating units and the total of 32 units. The total generation capacity is 3405 MW.

This generation system serves as our base system. This generation system model is constructed using unit addition algorithm. There are 3180 capacity outage levels in this generation system model. The cumulative probability and frequency of each capacity outage level is calculated. The results are tabulated as it is shown in Table 18. A table with more capacity outage levels is available at Appendix.

Table 18 - Generation system model of the conventional subsystem

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	0	1	0
2	12	0.7636	58.18
…	…	…	…
3180	3405	1.21×10^{-48}	8.51×10^{-45}

6.3 Generation System with Solar Units

In order to have a generation system with five and twenty percent solar penetration, it is required to replace five and twenty percent of the conventional generation capacity for the base system with solar power:

- 5% of the total capacity = 3405×0.05 = 170.25 MW
- 20% of the total capacity = 3405×0.20 = 681 MW.

We round the above capacity to 150 MW and 600 MW respectively for convenience. These are for both PV and CSP units. The individual capacity for PV and CSP plants for each penetration level is indicated in Table 19.

Table 19 - Solar power capacity used for different penetration levels

	PV Capacity (MW)	CSP Capacity (MW)
5% Penetration	50	100
20% Penetration	200	400

The generation system model is constructed for conventional, PV, and CSP subsystems for five and twenty percent solar penetration levels.

6.3.1 Conventional Subsystem

For five percent penetration, the conventional subsystem capacity is 3255 MW. In the base case generation system of IEEE-RTS, a 50 MW and a 100 MW unit is removed and the generation system model is constructed again. The results are tabulated as it is shown in Table 20.

Table 20 - Generation system model of the conventional subsystem for 5% solar penetration

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	0	1	0
2	12	0.7513	58.31
…	…	…	…
3030	3255	3.20×10^{-45}	1.94×10^{-41}

For twenty percent penetration, the conventional subsystem capacity is 2805 MW. In the base case generation system of IEEE-RTS, two 50 MW, a 100 MW, and a 400 MW unit is removed and the generation system model is constructed again. The results are tabulated as it is shown in Table 21.

Table 21 - Generation system model of the conventional subsystem for 20% solar penetration

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	0	1	0
2	12	0.7145	63.40
…	…	…	…
2580	2805	2.52×10^{-42}	1.49×10^{-38}

6.3.2 PV Subsystem

The PV unit failure depends on the inverter failure or the transformer failure. The reliability data for the inverter and the transformer is given in Table 22. This data is estimated from values given in [4] and rounded off for simplicity. The accuracy of this data is not critical in reliability evaluation of PV units; rather the PV plant configuration is more important.

Table 22 - PV unit reliability data

	Unit Size (MW)	Number of Units	Forced Outage Rate	MTTF (hrs.)	MTTR (hrs.)
Inverter	1	10	0.0909	2400	240
Transformer	10	1	0.0909	24000	2400

Unlike the conventional case, where the generating unit is a *2*-state unit, the PV unit is an *11*-state unit. The PV unit capacity outage level is given in Table 23.

Table 23 - PV unit capacity outage levels

i	Capacity Outage Level
1	0
2	1
3	2
4	3
5	4
6	5
7	6
8	7
9	8
10	9
11	10

For five and twenty percent solar penetration levels, different number of PV units is used as given in Table 24.

Table 24 - Number of PV units for different penetration levels

PV Units			
Sola Penetration Level	PV Size (MW)	Unit Size (MW)	Number of Units
5%	50	10	5
20%	200	10	20

For five percent penetration level, five PV units are used. The generation system model is constructed for the PV subsystem and tabulated as Table 25 (complete table is available in Appendix).

Table 25 - Generation system model of the PV subsystem for 5% solar penetration

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	0	1	0
2	1	0.9932	0.9856
…	…	…	…
51	50	6.21×10^{-6}	7.50×10^{-3}

For twenty percent penetration level, twenty PV units are used. The generation system model is constructed for the PV subsystem and tabulated as Table 26.

Table 26 - Generation system model of the PV subsystem for 20% solar penetration

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	0	1	0
2	1	0.9984	0.0304
…	…	…	…
201	200	1.48×10^{-21}	1.62×10^{-18}

6.3.3 CSP Subsystem

The CSP unit is treated in the same manner as conventional units. Therefore, we use the same reliability indices as the conventional unit. This is given in Table 27.

Table 27 - CSP unit reliability data

CSP Unit Reliability Data						
Solar Penetration Level	CSP size (MW)	Unit Size (MW)	Number of Units	Forced Outage Rate	MTTF (hrs.)	MTTR (hrs.)
5%	100	100	1	0.04	1200	50
20%	400	400	1	0.12	1100	150

For five percent penetration level, a 100 MW unit is used. The generation system model is constructed for the CSP subsystem and tabulated as Table 28.

Table 28 - Generation system model of the CSP subsystem for 5% solar penetration

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	0	1	0
2	100	0.04	6.99

For twenty percent penetration level, a 400 MW unit is used. The generation system model is constructed for the CSP subsystem and tabulated as Table 29.

Table 29 - Generation system model of the CSP subsystem for 20% solar penetration

i	X_i = Capacity Outage Levels	P_i (Capout≥X_i)	F_i (Capout≥X_i)
1	0	1	0
2	400	0.12	6.99

6.4 Solar Radiation Effect

Once generation system model is constructed for PV and CSP subsystems, the effect of solar radiation needs to be considered. For this purpose, hourly radiation data at plant location is measured. In this thesis, the radiation data is obtained from National Renewable Energy Laboratory (NREL) solar radiation data. These measurements are conducted by Solar Radiation Research Laboratory (SRRL). The measurement type used is called Base Measurement System (BMS) that provides solar radiation data from instruments at the NREL South Table Mountain site in Golden, Colorado. The latitude, longitude, and elevation of the site are 39.74 °N, 105.18 °W, and 1829 m, respectively. The measurements used in this case study are hourly solar radiation for year 2012.

There are different types of solar radiation data. As discussed in Chapter IV, for PV plants global solar radiation is needed. This radiation measurement is available at different angles. Since PV panels are tilted at a fixed angle proportional to the site latitude, hourly global solar radiation on a 40-degree south facing surface is used to measure the PV plant output power. For CSP plants, hourly direct normal solar radiation is used to measure the CSP plant output power.

Once these measurements are obtained, the generation system model for PV and CSP subsystems are modified to incorporate the effect of radiation. This was explained is Chapter IV.

6.5 Reliability Indices Calculation

Once the load model and the generation system model for each subsystem are constructed, the reliability indices can be obtained by the methods developed in Chapter V. This is done for the base case system, five percent solar penetration, and twenty percent solar penetration.

6.5.1 Results

The reliability indices are calculated and the results are summarized in Table 30.

Table 30 - Reliability indices calculation

	LOLE (h/year)	EUE (MWh)	Freq (/year)
Base Case	9.39	1,176	1.83
5% Penetration	19.06	2,716	3.84
20% Penetration	90.40	20,884	85.47

6.5.2 Discussion

Based on the results obtained above, the reliability of generation system is reduced after replacing solar generators with conventional generators. This is as expected since solar generators are not dispatchable and their power generation depends on solar radiation that is intermittent in nature. As the penetration level of solar power increases, the reliability is reduced further. This reduction is more intense for higher penetration levels.

6.6 Capacity Credit Evaluation

After reliability indices are calculated, capacity credit of solar power plants can be evaluated using the LOLE index.

6.6.1 Results

In order to evaluate the capacity credit of solar plant for five percent solar penetration, the LOLE of the conventional subsystem for five percent solar penetration is calculated first. Then, the solar units are added for five percent penetration level to this conventional subsystem and the LOLE is calculated. The results are given in Table 31.

Table 31 - LOLE before and after adding solar units for 5% penetration

Conventional Capacity (MW)	Conventional LOLE (h/yr)	LOLE after adding solar units (h/yr)
3255	26.12	19.06

For capacity credit evaluation, the peak load is iteratively increased until the conventional LOLE is achieved. The results are given in Table 32:

Table 32 - Peak load increase for capacity credit evaluation

Peak Load Increase (MW)	LOLE (h/yr)
53	26.16
52	26.02

Based on above data, capacity credit of 150 MW solar power plant is between 53 to 52 MW. Since the LOLE corresponding to 53 MW peak load increase is closer to conventional LOLE, the capacity value is considered to be 53 MW. This is about 35.33% of the plant rated value.

In order to evaluate the capacity credit of solar plant for twenty percent solar penetration, the LOLE of the conventional subsystem for twenty percent solar penetration is calculated first. Then, the solar units are added for twenty percent penetration level to this conventional subsystem and the LOLE is calculated. The results are given in Table 33.

Table 33 - LOLE before and after adding solar units for 20% penetration

Conventional Capacity (MW)	Conventional LOLE (h/yr)	LOLE after adding solar units (h/yr)
2805	204.92	90.40

For capacity credit evaluation, the peak load is iteratively increased until the conventional LOLE is achieved. The results are given in Table 34:

Table 34 - Peak load increase for capacity credit evaluation

Peak Load Increase (MW)	LOLE (h/yr)
172	205.87
171	204.70

Based on above data, capacity credit of 600 MW solar power plant is between 172 to 171 MW. Since the LOLE corresponding to 171 MW peak load increase is closer to conventional LOLE, the capacity value is considered to be 171 MW. This is 28.5% of the plant rated value.

6.6.2 Discussion

Based on above calculations, capacity value of solar power plants reduces as penetration levels of solar plants increase. In this experiment, other factors affecting the capacity credit such as radiation, components failure, and load remained to be constant.

CHAPTER VII

CONCLUSION

This thesis developed a methodology for quantitative reliability study of generation systems with solar power and to evaluate capacity credit of solar power plants. This methodology assists power system planners in designing generation systems with renewable power, in particular solar power, which meets the required reliability standards. Peaking units required to backup renewable power plants can be determined using this method. It also helps to compare the cost of conventional power plants with the effective value of renewable power plants.

The primary step in reliability evaluation of solar power plant is modeling the solar generation units. This was done separately for PV and CSP units. PV units were modeled as a multistate unit depending on the number of inverters. CSP units were modeled same as conventional units. After unit models were developed, the generation system model was constructed for each subsystem. These generation subsystem models were used along with load model to calculate the reliability indices of the generation system with solar power for different penetration levels. In addition, capacity credit of solar power plants was evaluated for different penetration levels.

The reliability of electric power generation system deteriorates if conventional generators are replaced with solar generators. This deterioration is more severe for larger penetrations of solar units. On the other hand, addition of solar generators improves reliability of the generation system, but this improvement is less than their plant ratings.

From this improvement, the capacity credit of solar power plants was evaluated. This capacity credit was about 35.33% of plant rating for five percent penetration level and 28.5% of plant rating for twenty percent penetration level. Knowledge of this capacity value is important for electric power system generation planning. The conventional practice is to have a peaking unit as a backup for every MW of solar or any renewable unit. This is applicable if capacity value of the renewable plant is zero. However, using capacity value of solar plants, the need for peaking unit as a backup is less than the solar plant rating and can be quantitatively calculated.

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APPENDIX

Generation system model of conventional subsystem (first 100 capacity outage levels) is given in Table A-1. Generation system models of PV subsystem for 5% solar penetration and 20% solar penetration are given in Tables A-2 and A-3.

Table A-1 Generation system model of conventional subsystem

i	Capacity Outage	P	F(/yr)
1	0	1	0
2	12	0.763602474	58.18169865
3	20	0.739482306	60.53445631
4	24	0.634416739	65.99626029
5	32	0.633432631	65.94598186
6	36	0.622712557	64.90269193
7	40	0.622692623	64.90644287
8	44	0.605181696	62.41728874
9	48	0.604744315	62.35788851
10	50	0.604744112	62.31006777
11	52	0.590416989	59.51493109
12	56	0.58863031	58.99288943
13	60	0.58862145	58.9919778
14	62	0.587324345	58.55578456
15	64	0.585862516	58.05339953
16	68	0.585789619	58.03200657
17	70	0.585789596	58.02134665
18	72	0.579421986	55.5428983
19	74	0.579289594	55.47844619
20	76	0.579229951	55.44908387
21	80	0.559930695	55.89738987
22	82	0.559894664	55.87827624
23	84	0.559244963	55.52839037
24	86	0.559239563	55.5255628
25	88	0.559238355	55.52525711
26	90	0.557269356	55.27791644
27	92	0.556208088	54.65881416
28	94	0.556204407	54.65630756

Table A-1 Continued

i	Capacity Outage	P	F(/yr)
29	96	0.556177899	54.64101193
30	98	0.547601003	53.17540163
31	100	0.547600991	53.17249797
32	102	0.517609169	54.8149456
33	104	0.517500885	54.73553068
34	106	0.517500735	54.7354068
35	108	0.517500198	54.73511465
36	110	0.516625089	54.45492318
37	112	0.516546477	54.39380245
38	114	0.513492914	54.11013312
39	116	0.513488496	54.10688729
40	118	0.512059029	53.58512186
41	120	0.512059028	53.5844751
42	122	0.498729329	51.73061972
43	124	0.498721305	51.72317346
44	126	0.498596769	51.68918679
45	128	0.497427117	51.20029226
46	130	0.497281266	51.12517256
47	132	0.497279082	51.12305069
48	134	0.495921943	50.73244786
49	136	0.495921616	50.7321321
50	138	0.495813207	50.6729212
51	140	0.495693874	50.60527958
52	142	0.493472257	49.8652309
53	144	0.493472034	49.86498056
54	146	0.493416691	49.84605291
55	148	0.492896879	49.52788076
56	150	0.492886045	49.51415516
57	152	0.491085414	48.83008864
58	154	0.490268474	48.60298918
59	155	0.490268465	48.60297766
60	156	0.450868878	49.33652124
61	158	0.450864815	49.3339766
62	160	0.450811778	49.29359477
63	162	0.450647214	49.20681307
64	164	0.45046389	49.11010183
65	166	0.45039439	49.08460305
66	167	0.450307756	49.01475678
67	168	0.446287728	48.49232667

Table A-1 Continued

i	Capacity Outage	P	F(/yr)
68	170	0.446287425	48.49070572
69	172	0.445487144	48.03155175
70	174	0.445207828	47.91682222
72	176	0.427689424	44.83809449
73	178	0.425245021	44.42847511
74	179	0.425236181	44.42002232
75	180	0.425072164	44.37432852
76	182	0.425067592	44.37102886
77	184	0.424986115	44.31216482
78	186	0.424958642	44.29712943
79	187	0.424952074	44.29064367
80	188	0.423165395	43.71029251
81	190	0.422916206	43.63152969
82	191	0.422782826	43.52912365
83	192	0.422779504	43.528993
84	194	0.422735279	43.50286247
85	195	0.422731956	43.50028148
86	196	0.419813468	42.42146644
87	197	0.418727137	42.02867894
88	198	0.381401212	44.35043594
89	199	0.381400555	44.34931788
90	200	0.381327658	44.32283382
91	202	0.380040994	44.13578911
92	203	0.379991612	44.10038871
93	204	0.379991578	44.09241089
94	205	0.379987094	44.08909699
95	206	0.37759924	43.08000414
96	207	0.377598995	43.07974221
97	208	0.377301215	42.92499035
98	209	0.377190465	42.86843487
99	210	0.375920982	42.46820007
100	211	0.373372137	42.52998463

Table A-2 Generation system model of PV subsystem for 5% solar penetration

i	Capacity Outage	P	F(/yr)
1	0	1	0
2	1	0.993195889	0.985616365

Table A-2 Continued

i	Capacity Outage	P	F(/yr)
3	2	0.966103362	4.477472954
4	3	0.900963951	10.24042233
5	4	0.79735258	15.49899255
6	5	0.675882592	17.39271743
7	6	0.56424722	15.39446755
8	7	0.480568047	11.16953877
9	8	0.427987459	6.819318776
10	9	0.399731489	3.569965819
11	10	0.386547279	3.761736379
12	11	0.374108163	10.12203007
13	12	0.344648796	20.33133567
14	13	0.290584017	27.60970596
15	14	0.222818697	27.50539363
16	15	0.160300093	21.3209216
17	16	0.115326349	13.36515875
18	17	0.089101543	6.957522015
19	18	0.076366235	3.066373509
20	19	0.071113505	1.160990736
21	20	0.069245997	2.581290193
22	21	0.065097902	7.074146904
23	22	0.054281082	10.57771531
24	23	0.038802345	10.28446068
25	24	0.024389424	7.249345462
26	25	0.014666936	3.780856545
27	26	0.009612459	1.635342526
28	27	0.007506664	0.565394894
29	28	0.00678472	0.164891065
30	29	0.006577168	0.101058495
31	30	0.006526434	0.842467254
32	31	0.005593307	1.655095441
33	32	0.003748998	1.592059173
34	33	0.001998969	0.974974239
35	34	0.000949252	0.425123271
36	35	0.000503167	0.123559024
37	36	0.000360425	0.031726856
38	37	0.00032474	0.006512952
39	38	0.000317603	0.001084955
40	39	0.000316444	0.018420809
41	40	0.000316289	0.131948276

Table A-2 Continued

i	Capacity Outage	P	F(/yr)
42	41	0.000196686	0.127638936
43	42	7.71683E-05	0.056557922
44	43	2.33857E-05	0.015426124
45	44	9.04373E-06	0.002736297
46	45	6.53388E-06	0.000333486
47	46	6.2327E-06	2.82525E-05
48	47	6.2076E-06	1.64206E-06
49	48	6.20616E-06	6.26443E-08
50	49	6.20611E-06	0.002033123
51	50	6.20611E-06	0.007544914

Table A-3 Generation system model of PV subsystem for 20% solar penetration

i	Capacity Outage	P	F(/yr)
1	0	1	0
2	1	0.998448062	0.030433052
3	2	0.997611989	0.046494569
4	3	0.996785211	0.059763479
5	4	0.996035882	0.07062748
6	5	0.995355802	0.080958464
7	6	0.9947263	0.095761263
8	7	0.994111927	0.12660491
9	8	0.993439105	0.196240136
10	9	0.992567785	0.342078959
11	10	0.991262775	0.623093576
12	11	2.339071402	-11.6590125
13	12	1.335543111	8.776376538
14	13	1.137723788	6.873206412
15	14	1.014834232	4.993592251
16	15	0.970538375	5.090803982
17	16	0.952221413	5.940407374
18	17	0.937672454	6.799774538
19	18	0.922429083	7.487406932
20	19	0.906232069	8.057104922
21	20	0.889193527	5.034664631
22	21	0.961990233	13.17122156
23	22	0.851407085	10.76474778

Table A-3 Continued

i	Capacity Outage	P	F(/yr)
24	23	0.829459246	12.37120591
25	24	0.804707113	14.18258138
26	25	0.777026295	15.90751278
27	26	0.746848558	17.23679097
28	27	0.715089132	17.96987816
29	28	0.682872607	18.10720979
30	29	0.65115937	17.86228062
31	30	0.620426254	17.58070942
32	31	0.590536711	17.59394436
33	32	0.560877205	18.07347043
34	33	0.530683857	18.94958186
35	34	0.499437936	19.93598883
36	35	0.467149405	20.65073144
37	36	0.434410862	20.78056464
38	37	0.402202096	20.21592733
39	38	0.371534453	19.0970207
40	39	0.343090509	17.75140223
41	40	0.317011458	16.55224744
42	41	0.292914353	15.76152885
43	42	0.270120214	15.42861524
44	43	0.247979786	15.3863589
45	44	0.226153208	15.3409309
46	45	0.204729094	15.00944229
47	46	0.184148922	14.24186903
48	47	0.164988453	13.0759751
49	48	0.147702984	11.70734621
50	49	0.132447243	10.39482487
51	50	0.11903726	9.348034825
52	51	0.107053739	8.647499694
53	52	0.096026369	8.228775345
54	53	0.085611015	7.93003424
55	54	0.075687159	7.574432787
56	55	0.066347267	7.04709763
57	56	0.057799903	6.334730799
58	57	0.050240913	5.516568146
59	58	0.043751446	4.717652739
60	59	0.038260786	4.049727951
61	60	0.033578726	3.566787925
62	61	0.029472115	3.252140238

Table A-3 Continued

i	Capacity Outage	P	F(/yr)
63	62	0.025745835	3.037492708
64	63	0.022293575	2.8403219
65	64	0.019103244	2.600172033
66	65	0.016223953	2.298701012
67	66	0.013716176	1.958272245
68	67	0.011609062	1.623929423
69	68	0.009880884	1.339512363
70	69	0.008465753	1.129037053
71	70	0.007278183	0.990160666
72	71	0.006241357	0.900075093
73	72	0.005306386	0.828696345
74	73	0.004456543	0.751926561
75	74	0.003698244	0.659398422
76	75	0.003045671	0.554814661
77	76	0.00250688	0.450537551
78	77	0.002076597	0.360016105
79	78	0.001736917	0.291649879
80	79	0.001463601	0.246249246
81	80	0.001233895	0.218241936
82	81	0.001032175	0.199164638
83	82	0.000851555	0.181408563
84	83	0.000691849	0.160654768
85	84	0.000555693	0.136411182
86	85	0.000444914	0.110962613
87	86	0.000358518	0.087562877
88	87	0.000292614	0.068778004
89	88	0.000241736	0.055590537
90	89	0.000200597	0.047382554
91	90	0.000165413	0.042514561
92	91	0.000134329	0.039093197
93	92	0.000107026	0.035617642
94	93	8.39107E-05	0.031341551
95	94	6.53373E-05	0.026298958
96	95	5.11655E-05	0.021046766
97	96	4.07092E-05	0.016282324
98	97	3.29691E-05	0.012526121
99	98	2.69583E-05	0.009972695
100	99	2.19536E-05	0.008493624
101	100	1.75822E-05	0.00773229

Table A-3 Continued

i	Capacity Outage	P	F(/yr)
102	101	1.3757E-05	0.007249309
103	102	1.05331E-05	0.006681898
104	103	7.97055E-06	0.005858076
105	104	6.05569E-06	0.004812339
106	105	4.6893E-06	0.003707577
107	106	3.72143E-06	0.002726661
108	107	3.00179E-06	0.001995362
109	108	2.41891E-06	0.001551553
110	109	1.91421E-06	0.001347495
111	110	1.47261E-06	0.001277646
112	111	1.10113E-06	0.001227006
113	112	8.08656E-07	0.001119722
114	113	5.94588E-07	0.000940864
115	114	4.47032E-07	0.000722514
116	115	3.4737E-07	0.00051185
117	116	2.76769E-07	0.000345793
118	117	2.21213E-07	0.000240916
119	118	1.73337E-07	0.000192973
120	119	1.31239E-07	0.0001817
121	120	9.5786E-08	0.000181002
122	121	6.81194E-08	0.000171252
123	122	4.82998E-08	0.000146306
124	123	3.51348E-08	0.000111516
125	124	2.67016E-08	7.63065E-05
126	125	2.10516E-08	4.7982E-05
127	126	1.67408E-08	2.97923E-05
128	127	1.30203E-08	2.1408E-05
129	128	9.70896E-09	1.9782E-05
130	129	6.90799E-09	2.05775E-05
131	130	4.74157E-09	2.02601E-05
132	131	3.22579E-09	1.75457E-05
133	132	2.25926E-09	1.31896E-05
134	133	1.67652E-09	8.68069E-06
135	134	1.31136E-09	5.09422E-06
136	135	1.04202E-09	2.81032E-06
137	136	8.06814E-10	1.75578E-06
138	137	5.92728E-10	1.57892E-06
139	138	4.10129E-10	1.756E-06
140	139	2.70357E-10	1.82412E-06

Table A-3 Continued

i	Capacity Outage	P	F(/yr)
141	140	1.75242E-10	1.60089E-06
142	141	1.17361E-10	1.17682E-06
143	142	8.48526E-11	7.35659E-07
144	143	6.61224E-11	4.00099E-07
145	144	5.2828E-11	1.95477E-07
146	145	4.08756E-11	1.01427E-07
147	146	2.95767E-11	8.72842E-08
148	147	1.98174E-11	1.09395E-07
149	148	1.24516E-11	1.23305E-07
150	149	7.61396E-12	1.09803E-07
151	150	4.82943E-12	7.78747E-08
152	151	3.39248E-12	4.5234E-08
153	152	2.65134E-12	2.21976E-08
154	153	2.14976E-12	9.59505E-09
155	154	1.67056E-12	3.91091E-09
156	155	1.18892E-12	2.97472E-09
157	156	7.65793E-13	4.73725E-09
158	157	4.53125E-13	6.13522E-09
159	158	2.5763E-13	5.55583E-09
160	159	1.52784E-13	3.70872E-09
161	160	1.03914E-13	1.92222E-09
162	161	8.23094E-14	8.09177E-10
163	162	6.87016E-14	2.94563E-10
164	163	5.39948E-14	1.04995E-10
165	164	3.7672E-14	4.34285E-11
166	165	2.30314E-14	1.24482E-10
167	166	1.25784E-14	2.17018E-10
168	167	6.49611E-15	2.00891E-10
169	168	3.54513E-15	1.1956E-10
170	169	2.32882E-15	5.06875E-11
171	170	1.89656E-15	1.64125E-11
172	171	1.66588E-15	4.59408E-12
173	172	1.33935E-15	1.55986E-12
174	173	9.10103E-16	8.16294E-13
175	174	5.15845E-16	4.74766E-13
176	175	2.50651E-16	5.10497E-12
177	176	1.12881E-16	4.96499E-12
178	177	5.54747E-17	2.22355E-12
179	178	3.58217E-17	5.9362E-13

Table A-3 Continued

i	Capacity Outage	P	F(/yr)
180	179	3.0166E-17	1.05571E-13
181	180	2.87835E-17	2.14772E-14
182	181	2.43105E-17	1.67369E-14
183	182	1.5894E-17	1.44127E-14
184	183	7.94067E-18	8.47099E-15
185	184	3.17271E-18	3.56753E-15
186	185	1.14672E-18	1.06433E-13
187	186	4.98432E-19	2.82227E-16
188	187	3.36364E-19	5.6367E-17
189	188	3.03951E-19	9.1554E-18
190	189	2.98684E-19	3.36658E-17
191	190	2.97981E-19	2.252E-16
192	191	1.83614E-19	2.1172E-16
193	192	6.93332E-20	9.27428E-17
194	193	1.79095E-20	2.45046E-17
195	194	4.19661E-21	4.26465E-18
196	195	1.79686E-21	5.1039E-19
197	196	1.50889E-21	4.24885E-20
198	197	1.48489E-21	2.4279E-21
199	198	1.48352E-21	9.11083E-23
200	199	1.48347E-21	4.85986E-19
201	200	1.48347E-21	2.64046E-18