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Generation System Reliability with Wind and Solar Power

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Declaration

I declare that this thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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List of abbreviations

PV	Photovoltaic
COPT	Capacity outage probability table
MCS	Monte Carlo simulation
WTG	Wind turbine generator
FOR	Forced outage rate
LOLE	Loss of load expectation
LOEE	Loss of energy expectation
LOLF	Loss of load frequency
LOLD	Loss of load duration
DPLVC	Daily peak load variation curve
MTTF	Mean time to failure
MTTR	Mean time to repair
FF	Fill factor
NOCT	Normal Operating Cell Temperature
RBTS	Roy Billinton Test System
PLCC	Peak load carrying capability
IPLCC	Incremental peak load carrying capability
WECS	Wind energy conversion system
PECS	Solar energy conversion system
RBECR	Risk based equivalent capacity ratio

Acknowledgements

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Abstract

For the purpose of environmental concerns, carbon emission reduction targets are established in Europe. For example, UK National Grid has developed their scenarios such as ‘gone green’, ‘slow progression’ which may change the patterns of UK transmission network operation. As a result, the integrated level of renewable energy such as wind power and solar power will increase. Therefore, it is worth to test and predict the system performance when great amount of conventional generators are substituted by renewable energy. This thesis is focus on evaluating the impacts of utilizing significant amounts of wind or solar energy sources in large on-grid power systems and analyzing the system reliability performance based on probabilistic method.

A capacity outage probability table (COPT) for conventional generating units is introduced first in this thesis. The conventional generator is represented which based on the well-known recursive technique. Then, the sequential Monte Carlo Simulation method is proposed for creating wind turbine output model, and PV solar energy output model. The Roy Test System (RBTS) is selected for this study. Results shown that the reliability decrease a lot when substitute conventional generator by renewable energy. Wind power have better reliability performance compare with solar when same amount of each type of generators substitute the conventional generators. It is also demonstrated that the help of storage system introduced in solar PV plant has a great help in improving the reliability and it is possible to reach the same reliability level of the original network but additional renewable energy need to be added into the system.

Chapter 1 Introduction

1.1 Current Situation of Main Energy Resources

Nowadays, global electric power systems are carrying out a reform throughout each part of the system. It is getting harder and harder for those original electric power systems to expand their market since they are now facing restrictions from political, social, resource and environmental side. All these restrictions just happen to provide a stage for renewable energy systems. However, renewable energy techniques are still not mature enough to replace the conventional plants completely. So, technology improvement, optimization of system configuration, system reliability improvement and reduction of facility cost are now becoming the key factors to renewable energy system. [1]

1.1.1 Global Resources Situation

Following Figure 1 is a pie chart of global energy consumption in 2010 [2], there exit three significantly expandable forms of global electricity generation: Fossil, Hydro power and nuclear power, which occupy a great ratio of the total amount of electricity generation. Compare to the conventional energy sources, renewable energy sources are insufficiently expandable.

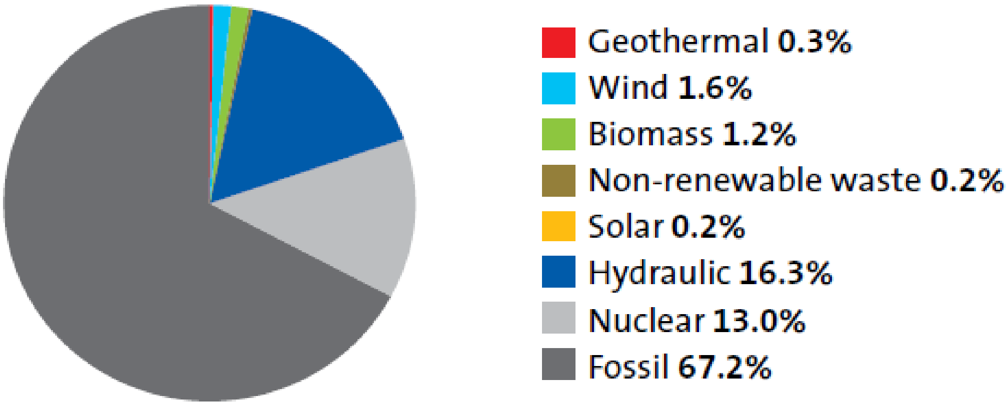


Figure 1 World electricity usage by power source 2010

1.1.2 Defects of Conventional Energy

1) Green house effect

Fossil fuel has its finiteness which is called unsustainable. Moreover, burning all remaining coal and fuel would increase the effect of greenhouse gases to make the planet more un-inhabitable which is the main reason for global warming, climate change and responsible for the large amount of CO_2 emission. Statistic data from Table 1 [3] shows that a coal-fired power plant emits 790-1020g CO_2 per KWh for electricity generation. However, wind and hydroelectric energy only emit 4.2-11.1 g CO_2 per KWh and 17-22 g CO_2 per KWh respectively. It presents a deduced benefit for us if utilizing renewable energies.

Table 1 CO_2 emission levels of four mainly used energies

Coal	Nuclear	Hydroelectric	Wind
790-1020 g CO2 per KWh	16-60 g CO2 per KWh	17-22 g CO2 per KWh	4.2-11.1 g CO2 per KWh

2) Health risk

Sulphur compounds, nitrogen oxides and carbon oxides which are the products from burning coal or fuels would cause coughs, asthma, heart attacks and skins disease. The Environmental Protection Agency (EPA) identifies that 2.4 million people die from air pollution per year. It is quite true that we facing the health problem under the using of coal and fuel energy. The following table shows an average emission levels in the production of 1 MWh of electricity Pounds of Emissions per MWh [4]. Polluted air-emissions from Coal, oil and natural gas maintain at a high level while wind and solar energy produce approximately to 0.

Table 2 Polluted air emissions levels of popular energies

	Coal	Oil	Natural Gas	Wind	Solar
Carbon Dioxide	2249	1672	1135	0	0
Sulfur Dioxide	13	12	0.1	0	0
Nitrogen Dioxide	6	4	1.7	0	0

3) Danger of nuclear waste

Nuclear power, a main kind of power source, generates electricity by using the nuclear fission of uranium to produce heat. It made great contribution on electricity generation in the last decade without a doubt. However, it is still not a perfect choice because it pollutes the environment from its radiation waste and also cause the risk of terrorism and radioactive accident. All of these are comparatively harmful to human beings. Figure 2 shows a real picture of radiation area. (It is from a subsided crater left by a nuclear bomb test at the Nevada Nuclear Test Site, near Yucca Mountain [5].)

Figure 2 A nuclear bomb test at the Nevada Nuclear Test Site

1.2 Need of Renewable Energy

Renewable energy is defined as a kind of technology capture energy resource from solar, wind, water, biomass, or the Earth's core. Due to the disadvantages has been mentioned above, it is quite necessary and important for us to consider alternatives to conventional power supply, which are sustainable, environment friendly and safe so that it will lead to a secure and self-reliant future. Benefits of renewable energies are displayed in the figure below.

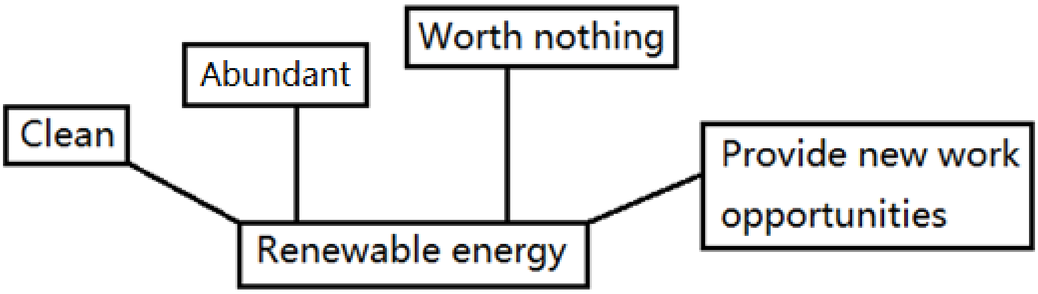


Figure 3 Benefits of renewable energies

1.3 Research Objectives

The main objective of the thesis includes:

- Establish a generation model by using analytical or simulation method, and then combine with load model to calculate conventional generating system reliability
- Create single wind or single solar generating mathematical models and get their reliability index.
- Evaluate the effect of the wind and solar generating unit penetration level, the system load level, the risk based equivalent capacity ratio, the energy storage level and the location sites when wind or solar generating unit integrate into grid-power system

1.4 Thesis Outline

Chapter 1: This chapter introduces the main energy resources, their relative merits and shortcomings. As a comparison, several leading-edge renewable energy resources are listed and the characteristics relative to the environment, resource storage, technical event and commercial opportunity are discussed, especially concentrated in the intermittency of sources and integration problem to the whole power system. The objective and original contributions of this thesis are included as well.

Chapter 2: This chapter explained the basic knowledge of wind and solar generating system from 3 aspects:

1. Categories of wind and solar generating system. The classification of wind turbine from the geographical expression is mainly divided into two parts, onshore and offshore wind turbines. While solar generating system can be divided into solar thermal system and solar photovoltaic system from the technology side. In terms of structure, renewable energy generating system can be categorized as well.

2. System components and generating principle. In typical PV systems, module is its core. It plays a role in absorbing the sunlight and creating a flow of electrons, that is electricity. In wind turbine generating systems, wind turns blades to drive the rotor.

3. International development status in recent years. The United States, Europe and Asia are the 3 biggest Wind energy market. While in the PV industry, it reaches an average annual growth rate of 43% for PV cells production over the past ten years.

Chapter 3: The aim of this chapter is to provide an overview of the generation system reliability background, which is roughly classified into two categories: system adequacy and system security. Further discussion of the deterministic and probabilistic approach will be included in the later sections. A subsection of probabilistic approach in detailed is provided since there are limitations of deterministic method. It is divided into two parts: analytical techniques and stochastic simulation techniques. The former one is normally applied by creating capacity model from capacity outage probability table and load model from load duration curve. The essential parameters involved in it include: system availability, system unavailability, and forced outage rate are included as well. In addition, the later one, stochastic simulation techniques (the widely used method—Monte Carlo simulation) will be discussed since analytical method is unsuitable to wind or solar generating system due to their stochastic operating features and chronological system load model. Furthermore, a brief review of three types of sampling methods is described which are related to Monte Carlo simulation. According to different characteristics between wind and solar resources, different distribution functions combined with Monte Carlo simulation will be mentioned in this chapter. Finally, the most popular reliability indices will be discussed to evaluate the system risk index.

Chapter 4: This chapter involved in the generation system reliability models of power systems using wind energy, solar energy and conventional energy were developed by using Capacity Outage Probability Table (COPT) and Monte Carlo simulation (MCs) approach. The random weather resources, the equipment parameters of the generating unit are the major factors in reliability analyses of power systems especially for wind plant and solar plant. In this thesis, the sequential MCs technique is used to simulate wind speeds. The sequential MCs techniques can be used to simulate wind speeds. The power available from a wind turbine generator can be determined from a function describing the relationship between the wind speed and output power. A widely used solar radiation method, determined by Hottel's equation was associated to MCs techniques to generate solar radiation levels so that the solar radiation data can be calculated by the program in MATLAB. The generated power of a photovoltaic generating unit is then obtained based on the voltage-current characteristics of the generating unit using these data. An energy storage model is also developed for the purpose of system's backup study.

Chapter 5: In this chapter, key parameters that influence the reliability of combined electricity power system, such as the wind or solar penetration level, the system load level, the risk based equivalent capacity ratio, the energy storage level and the location sites are all considered and are illustrated respectively in each single case study. The evaluation criterions of system reliability which examined in terms of the Loss of Load Expectation (LOLE), Loss of Energy Expectation (LOEE) and Loss of Load Frequency (LOLF), have been used to assess the system reliability issues.

Chapter 6: Future work and conclusions.

Chapter 2 Wind and Solar Generating System

2.1 Introduction

The renewable energy sources will have a significant contribution in electric power supply in the future from the overview of chapter 1. So, a well understanding of renewable energy is definitely needed. In this research, wind and solar power will be detailed introduced for renewable energy since these two are the major types of energy used now day. Scenarios of how wind turbine generating system and solar generating system worked are introduced in this study. Both wind turbine generating system and solar generating system can be categorized in terms of structure. Wind turbine generating system can be classified by various locations and solar generating system can be divided as solar thermal system and solar photovoltaic system from the technology side. Thus, it is important to know the characteristics and requirements of different types of these devices so the appropriate representative models can be established and different case studies can be established according to different system structures.

2.1.1 Onshore and Offshore Wind Farm

Wind farm is mainly divided into two categories, which is onshore and offshore wind farm. It is noted that speed of developing onshore wind energy was limit and only 38 GW of Wind Capacity were installed in 2010. Offshore wind energy, by contrast, has been forecasted around 75 GW by 2020 as it is regarded as the energy that has more potential than onshore wind energy [1]. Table 3 [1] describes the cons and pros of both onshore and offshore wind turbine.

Onshore wind turbine has a cheaper foundation, installation cost and lower integration cost if it is connected to grid network since the transmission system is not as complicated as offshore wind farm. But social concerned about the visual and noise impact of onshore wind farm. In term of wind resources, it is still inferior to offshore wind farm.

Offshore wind turbine is located far from city centre so that it will not cause so much visual and noise pollution. Furthermore, it will do no injuries to birds since offshore wind turbines are established in the ocean where birds do not usually fly past. Nevertheless, it has a high capital cost and conflicts with shipping lane, gas platforms and military areas.

Table 3 Comparison of onshore and offshore wind farms

	High capital cost	**Visual and noise pollution**	**Injury to bird**	**Conflicting with shipping lane, gas platforms and military areas**
onshore	×	√	√	×
offshore	√	×	×	√

2.1.2 Solar Thermal and Solar Photovoltaic

Solar powers are typically divided into two parts: Solar photovoltaic (PV) technology and solar thermal technology. Photovoltaic technology transmits sunlight into electricity directly. It mainly depends on sunlight which involved in the hour of sunlight and number of watts of the panel. Few decades ago, photovoltaic technology is only applied in those high-technology areas, such as satellite power system. However, it is now widely designed for megawatt scale power plants or integrated into building system as well. Solar thermal technology, utilize heat or infrared radiation to produce electricity. The key merit is that it can operate at night or even under the no-sunlight situation. Nowadays it mainly used for hot water system, depends on the heat energy from sun. In Figure 4, it shows two types of solar energy technologies.

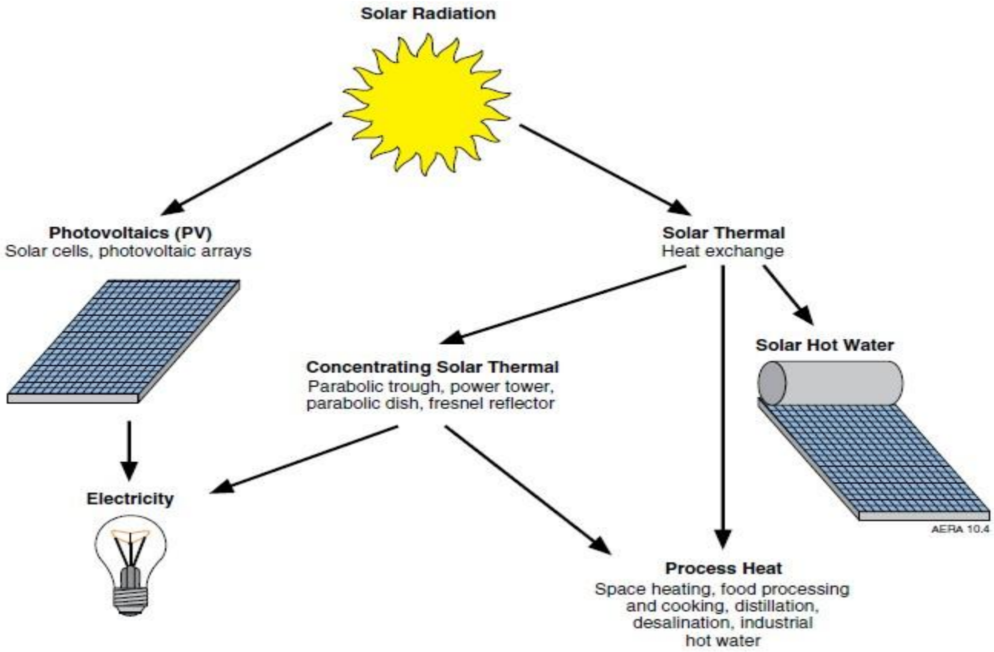


Figure 4 Solar energy techniques

Data from Figure 5 [6] predict for worldwide solar park installation from 2009 to 2014 shows that solar photovoltaic is projected to install 45.2GW by 2014. It will expand by a factor of 37. Solar thermal is projected to install 10.8GW during the same period by contrast. Only a six-fold rise for solar thermal is estimated.

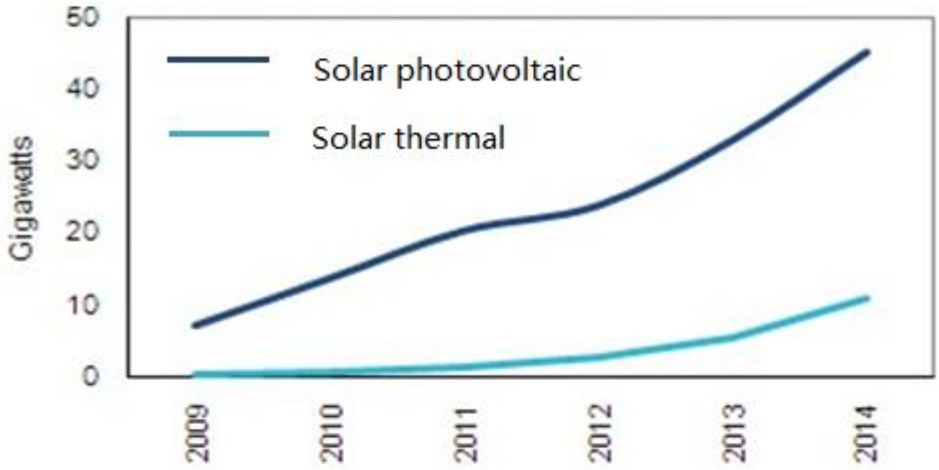


Figure 5 Global annual solar photovoltaic and solar thermal installation

According to this trend, solar PV system will be select for the further study direction.

Considering of cost, PV generation system normally gets a high capital cost, but it will operate silently and environmental friendly in the same time. Besides, the maintenance cost is very low and with the decrease of solar cell's cost, the PV generation system would be more attractive.

2.1.3 Wind and Solar System Structures

In [12], the systems structures can be divided into:

- Wind/solar system without energy storage

Due to its natural intermittent parameter, if one system is entirely depended on wind energy or solar energy to produce electricity, the probability of outrage will be high. Therefore, customer demand cannot always be satisfied with this kind of system structure.

- Wind/solar system with energy storage

To compensate the power imbalance during above conditions, energy storage system is one of the possible answers. Normally, it is implicated in repeater stations for mobile phones or power supply for remote areas. In some rural area, installing such kind of system spends less than the cost used for upgrading the transmission and distribution system to meet rising electricity demand.

- Wind/solar system with storage combined with conventional generation

Usually, the working networks are combining the wind or solar energy with conventional energy to generate electricity. It is satisfactory that not only system reliability can reach a desirable level but also cost can be reduced.

- Wind/solar system integrate to grid network

Renewable energies are supposed to assist utility grid to meet customer demand, reducing fuel costs and CO_2 emissions.

2.2 Wind and Solar Potential Overview

2.2.1 Wind Energy Resource

The theoretical potential for wind is estimated that about 1% – 3% of the energy from the sun is converted into wind energy, which is about 6,000 EJ/yr. Especially in UK; with its long coastlines and low latitude land, UK has been the country which has the largest potential wind energy resource in Europe. Figure 6 [7] is the map of UK wind resources. The literature shows [7] that the potential electricity which be obtained of each year from the wind in UK can achieve 1000TWh, whereas the electricity consumption of the country per year is almost account for one third of it. Even it is not possible to utilize the whole coastlines since taking some sensible restrictions into consideration. The potential electricity generated by wind per year on most effective coastlines and land still achieves an extremely significant number: 50TWh.

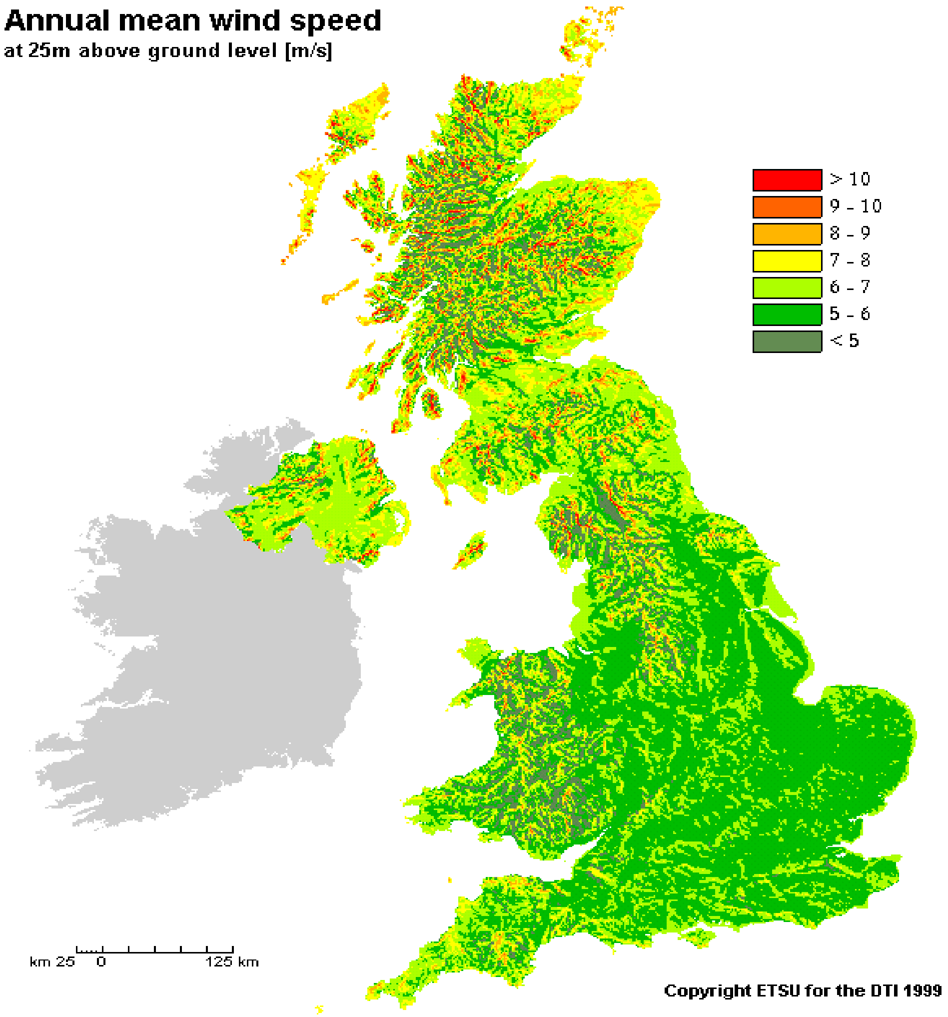


Figure 6 Map of the UK's Wind Resource

2.2.2 Solar Energy Resource

Due to the influence of natural factors such as cloud cover, atmospheric conditions, etc. The amount of solar energy resource varies every year. In spite of this, it is conservative estimated that the average potential of solar energy resource over the world is about 5.6GJ, which is equal to 1.6Mwh/m per year [8]. Such huge amount of energy is far beyond the need of energy required by human beings. As a result, solar energy makes us convinced that there is a great potentiality in the area of energy demand in the future.

Figure 7 [8] is a distribution map of solar energy resources in worldwide scale

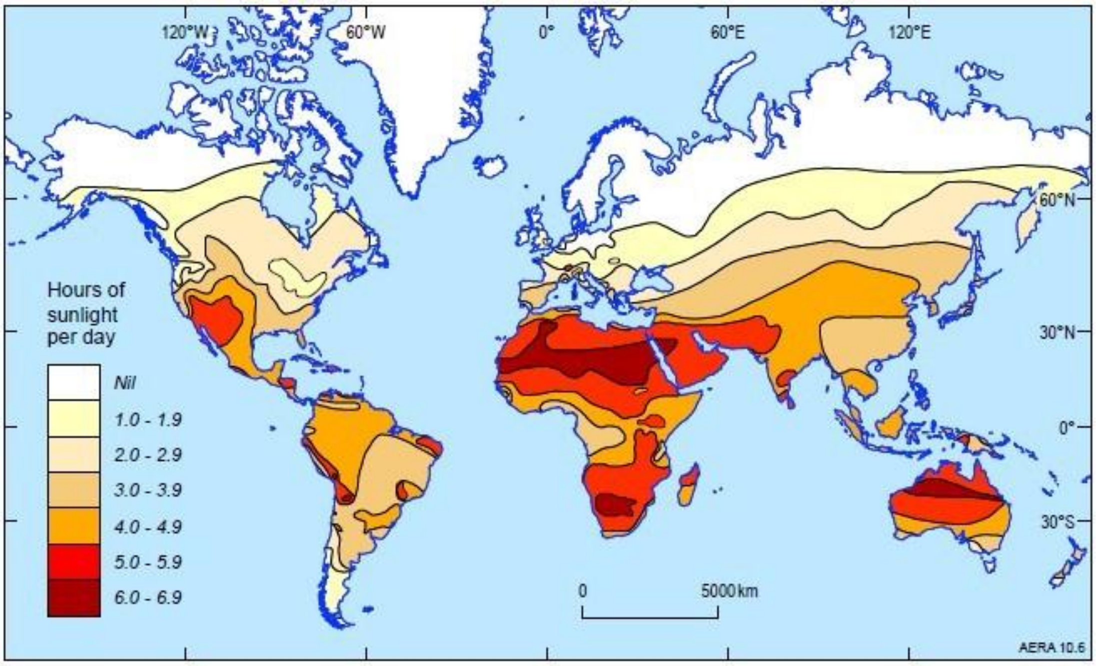


Figure 7 Distribution maps of solar energy resources in worldwide

From Figure 7, red sea areas are founded as the region contains the richest solar energy resources, with Egypt and Saudi Arabia included.

2.3 Components and Generating Principle

2.3.1 Wind Turbine System Components

Figure 8 provides a general structure of the wind turbine system: Rotor blades rotate around a hub which is connected to drive train (gearbox, generator, control system, wind speed and direct monitor included). They are all located inside nacelle, which is on the top of tower.

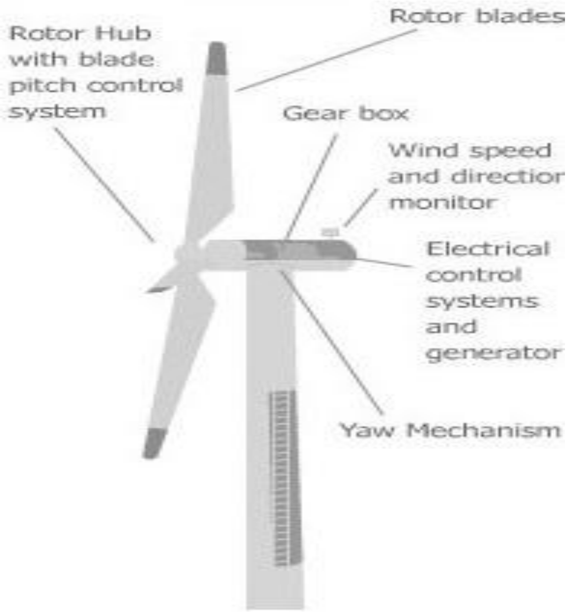


Figure 8 Wind system

2.3.2 Principle of Wind Power Generation

Wind turbine generating systems obtain energy through transforming the kinetic energy of wind to the eclectic power. The principle indicates that wind is the fluid which contains a lot of quickly moved particles. These particles make the blades begin to turn. Then, rotor turns and makes the rotating shaft, which is connected to rotor drive. That’s the whole process of transforming wind energy into electricity.

2.3.3 Photovoltaic System Components

Solar energy defined as “the way sun energy can be directly used into heating, lighting and electricity [8]”. In typical PV structure systems, PV cells are the core of it. It is made of semi-conductor, mostly silicon and plays a role in absorbing the sunlight, creating a flow of electrons, which generate the electricity. These devices only need barely servicing and maintenance with a life-span of 20 years. As each cell generates very little power, they are often wired together into modules. Modules can then be grouped together as panels which encased in glass to protect panels from the outside. These panels could make up even larger arrays. Figure 9 shows the relationship between arrays, modules and cells.

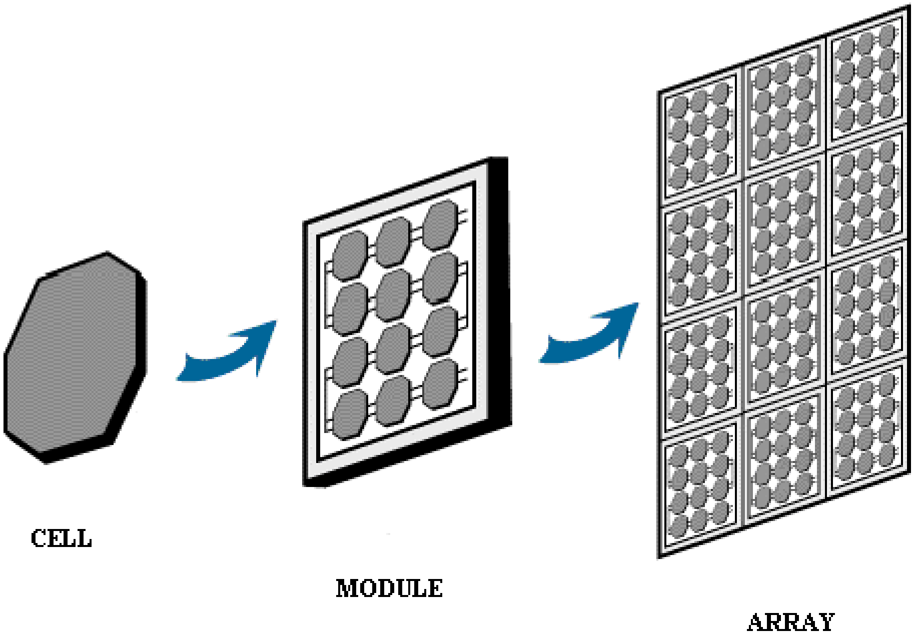


Figure 9 Solar PV production chain

Normally, solar cell's types could be classified into two kinds: monocrystalline type and polycrystalline type. The monocrystalline is produced from a single crystal of silicon and polycrystalline is produced from a piece of silicon consisting of many crystals. Figure 10 shows the two kinds of cell below. Since polycrystalline cells got many crystals, however, they just have a slightly less energy absorbing than monocrystalline cells. On the other hand, the creating silicon for polycrystalline cell is slightly simpler, so price is better and is popular used.

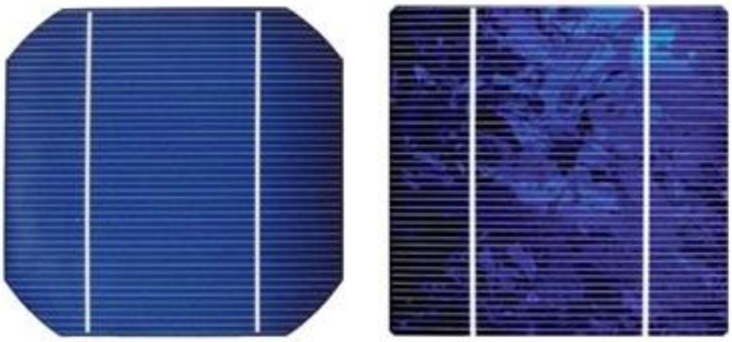


Figure 10 From left to right: a monocrystalline cell and a polycrystalline cell

Figure 11 gives a quick view of other PV system components:

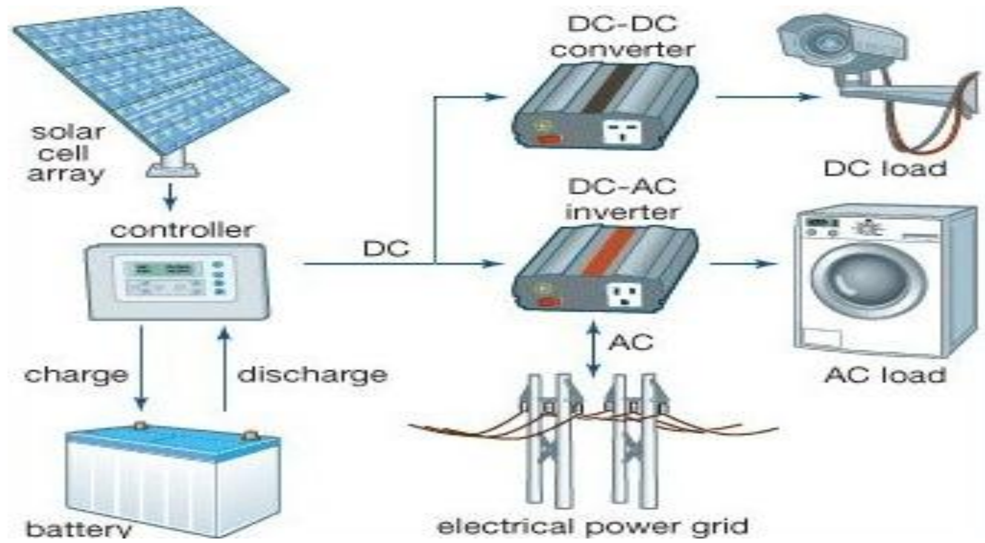


Figure 11 Basic configurations of grid PV system components [14]

- PV panel collector: Collect sun energy and convert it to electricity.
- AC/DC inverter: Used to convert DC power into AC power and transmit it to the grid for consumers.
- Cables and accessories: Used to connect components in safety, especially according to the maximum load current and potential operating temperatures.
- Battery: Accumulate excess energy created by your PV system and store it to be used at night or when there is no other energy input.
- Meter: Show the total generation of electricity at the time.

2.3.4 Working Principle of Photovoltaic Module

The photons exposed from the light firstly prompt the bound electrons into higher energy state. This process will excite free electrons. The free electrons move around in silicon with the holes be collected in the P-layer and electrons collected in the N-layer. The material between N-type layer and P-type layer is called P-N junction. Near the P-N junction the electrons diffuse into the vacant holes named as depletion zone, which is going to preventing other free electrons in the N-type silicon and holes in the P-type silicon from combining. As the vacant holes exist in depletion zone, N region will miss some electrons and has obtained a positive charge. Similar situation will occur in P region and obtained a negative charge. When the outside circuit is closed, electricity flows. Following Figure [12] shows a brief description of the working principle of photovoltaic module.

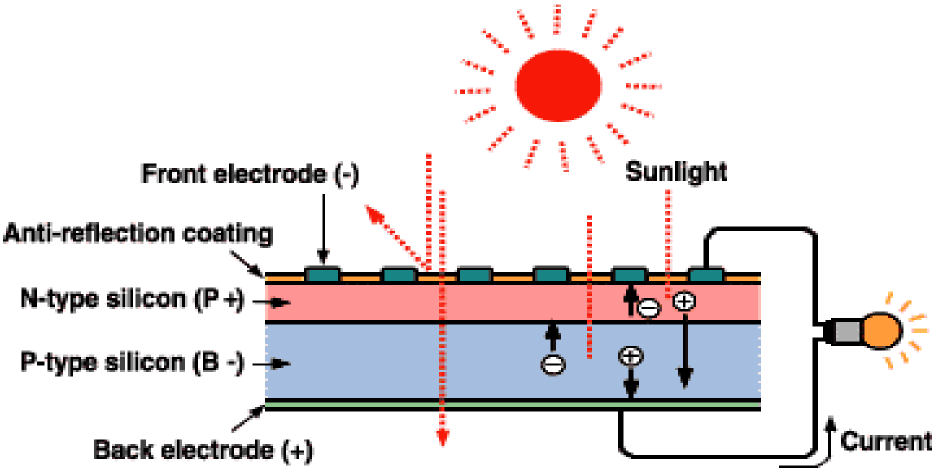


Figure 12 Working principle of photovoltaic module

2.4 World Wind Energy Market

In 2008, data (Figure 13) shows that Europe accounted for 32.8% of global wind market [1]. It is followed by North America which presented 32.6% of it. Asia ranks number three by 31.5% contributions and 1.1% is shared by Latin America and Africa.

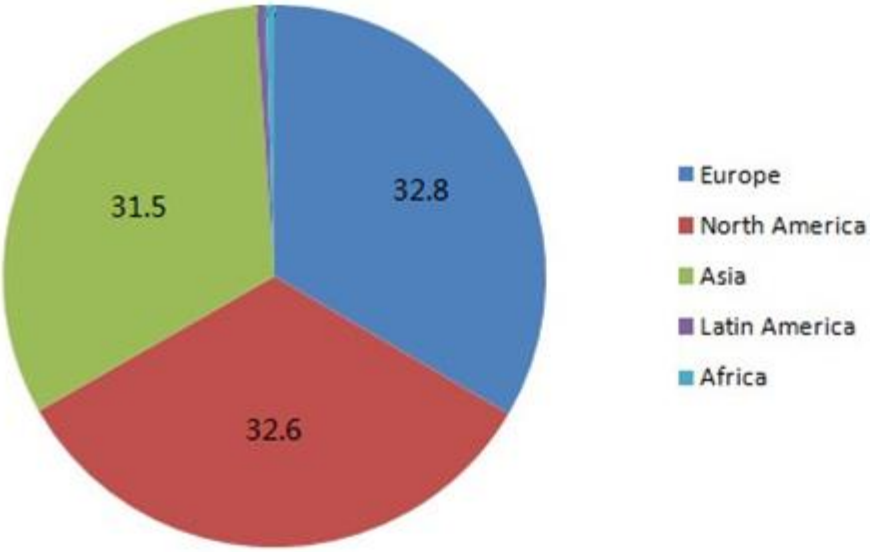


Figure 13 Global wind energy markets 2008

- **The United States**

New capacity installation was over 8,000MW in the United States in 2008, which representing more than 40% of total new electricity generating capacity. It is noted that more and more states realize that wind power technology is critically important in the future development so that the legal frameworks which are benefit for wind energy expanding are under established gradually [1].

- **Europe**

Europe has been the leader in both area of wind technology innovation and capacity installation. Among the Europe countries, Germany accounted for the largest percentage of it. Even more, Germany is still maintaining the increasing at more than 7% of its total consumption. But, there is a tendency that Europe will be surpassed by North America and Asia. Its total capacity installation was kept to 66,160MW in 2008 compare to MW in 200 [1].

- **Asia**

Statistics data shown that 24,439 MW new wind turbines were installed in Asia in

2008 [1]. China and India rank number four and five respectively on the list of countries with the largest installed capacity worldwide. Besides, market share are increasing rapidly for these two countries in recent years, not only reflect by their domestic energy requirement but also turbines export.

2.5 World PV Energy Market

Over the last decade, on the basis of concerning about the air pollution problem and over-reliance on fossil fuels, photovoltaic is increasingly attractive to electricity power industry. The global demand of PV units is shown in Figure 14 as below. The PV industry, reaching an average annual growth rate of 43% for PV cells production over the past ten years [1].

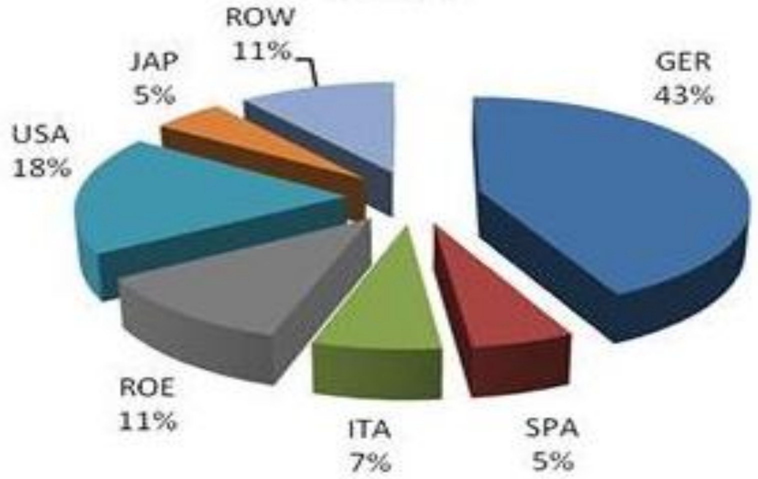


Figure 14 Worldwide PV demand in 2010

A brief review of the situation of PV in most representative countries is in the following description:

- **Europe**

EU PV industry takes a significant proportion in the worldwide PV industry currently, keeping occupancy about 66% of total PV demand. It should also be noticed that PV capacity installed in EU in 2008 was up to 4600MW, nearly half of the total installation of the world. The market is ascending due to the technologies improvement. PV capital investment cost nowadays is lower by 60% when compared to that of 1990 [8]. Moreover, several EU members issued a series of policies and measures, in order to stimulate the extension of PV market. In the 1997 White Paper, the EU commission set a target, indicating that EU total PV capacity to be installed was expected to reach 3000MW before 2010. Actually, the White Paper target had already been approached in 2006. In 2010, total cumulative capacity installed in EU is up to 16000MW. Figure 15 demonstrates the comparison of white paper objectives with recent years PV growth.

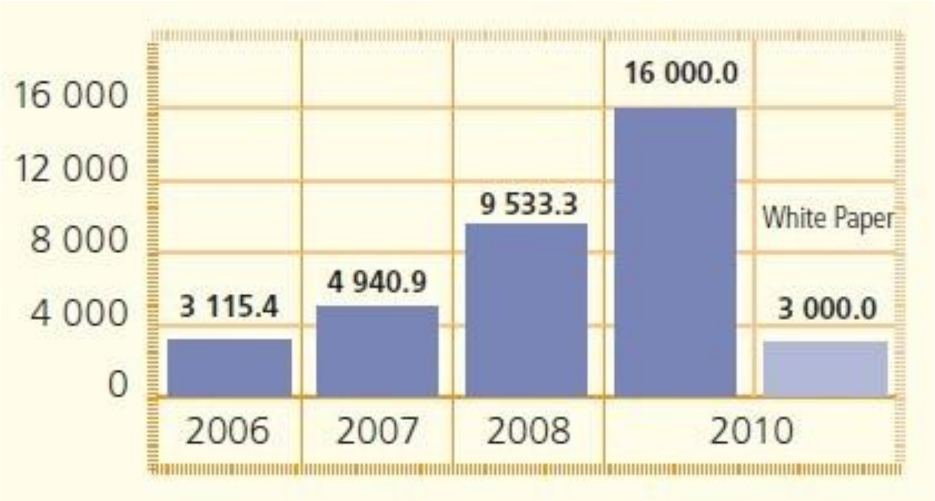


Figure 15 Europe PV installation targets from White paper

- **United States**

Solar energy is growing rapidly in United States. From the data of year [1] 2010, it is demonstrated that PV installation capacity was 1680MW, which is almost doubled than expectation value. Thus, capacity will come up to 6.4GW in 2015 if keeping this rapid growth speed. From another point of view, from 2005, United States remains a growth in this segment of the market. PV account for 5% of global demand in 2010 and increasing to 9% this year. A white paper of 2010 status that demands will be increased to 15% by year-over-year growth.

2.6 Summary

This chapter explained the basic knowledge of wind and solar generating system from following aspects:

Categories of wind and solar generating system

The classification of wind turbine from the geographical expression is mainly divided into two parts, onshore and offshore wind turbines. While solar generating system can be divided as solar thermal system and solar photovoltaic system from the technology side. In terms of structure, renewable energy generating system can be categorized as well.

System components and generating principle

Wind is the fluid which contains a lot of quickly moved particles. These particles make the blades begin to turn. Then, rotor turns and makes the rotating shaft, which is connected to rotor drive. That's the whole process of transforming wind energy into electricity. In typical PV systems, modules are the core of it. It plays a role in absorbing the sunlight and creating a flow of electrons, that is process of generating electricity.

International development status in recent years

United States, European and Asia are the 3 biggest Wind energy market. According to world energy market data in 2008, Europe accounted for 32.8% of global wind market and followed by North America which presented 32.6% of it. Asia ranks number three by 31.5% contributions. Photovoltaic market, whatever in developed countries or developing countries, all has been rapidly expanded in the past few years. PV industry, reaching an average annual growth rate of 43% for PV cells production over the past ten years. All of the data shown that renewable energy will be the most popular and fast developing energy type in the world power energy trends in next few decades.

Chapter 3 Generating System Reliability Evaluation Background

3.1 Introduction

Reliability always plays an important role in electricity power system from section of planning, design, operation to maintenance. What's more, generation system is the most significant part of electricity supply chain. Therefore, with the purpose of ensuring generation system operated under an acceptable reliability, several reliability evaluation methods are studied in this chapter. Additionally, some samples used by probabilistic method to identify the generating system reliability were also provided here.

3.1.1 System Adequacy and System Security

Typically, generation system reliability presently used can be divided into two elements: system adequacy and system security. Adequacy refers to the amount of generating capacity to meet the total system load whereas security refers to the ability of system to withstand disturbances happened in the system, such as loss of a generator, loss of a transmission line, etc. In this thesis, generation system reliability study will be focus on system adequacy. The system therefore can be simply represented by a single bus as shown in Figure 16. System security will not be included [11].

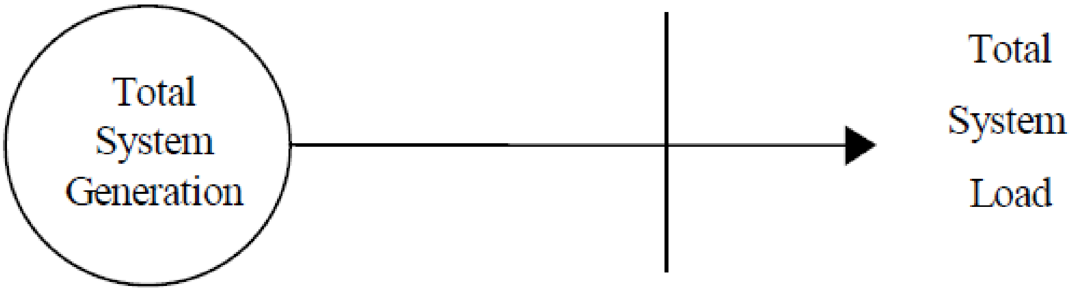


Figure 16 A brief description of system adequacy

3.2 System Adequacy Evaluation Method

The main purpose of generating system adequacy assessment is involved in the following two parts:

- Estimate the generating capacity needed to meet the consumer load.
- Estimate the excess capacity supply for forced outage events.

Generally speaking, generating system adequacy assessment model (Figure 17) can be identified by four essential steps:

1. Build a generation capacity model based on its operating characteristics like failure rate.
2. Create a consumer demand model.
3. Combine the capacity model and demand model together to gain a risk model
4. Observe the system reliability indices according to the risk model

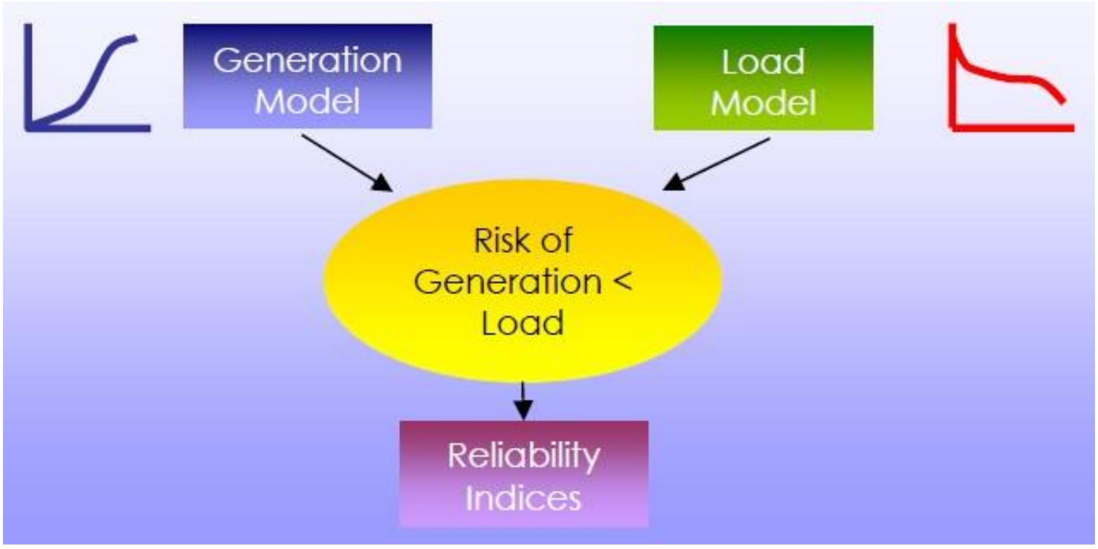


Figure 17 Generating system adequacy assessment model

To define the requirement of capacity, the most fundamental deterministic method which includes percentage reserve or reserve margin method will be introduced later. Probabilistic methods will be demonstrated as well for the reason that it becomes more popular and has a greater advantage in reflecting the parameters of system reliability if compared to deterministic methods.

3.2.1 Deterministic Approach

Deterministic approach, as a part of system adequacy assessment, has been developed for power system planning, design, operation for many years. The most commonly used deterministic criteria is called reserve margin, which will be explained in this chapter later. Figure 18 is a brief description of power system reliability evaluation and system adequacy assessment categories.

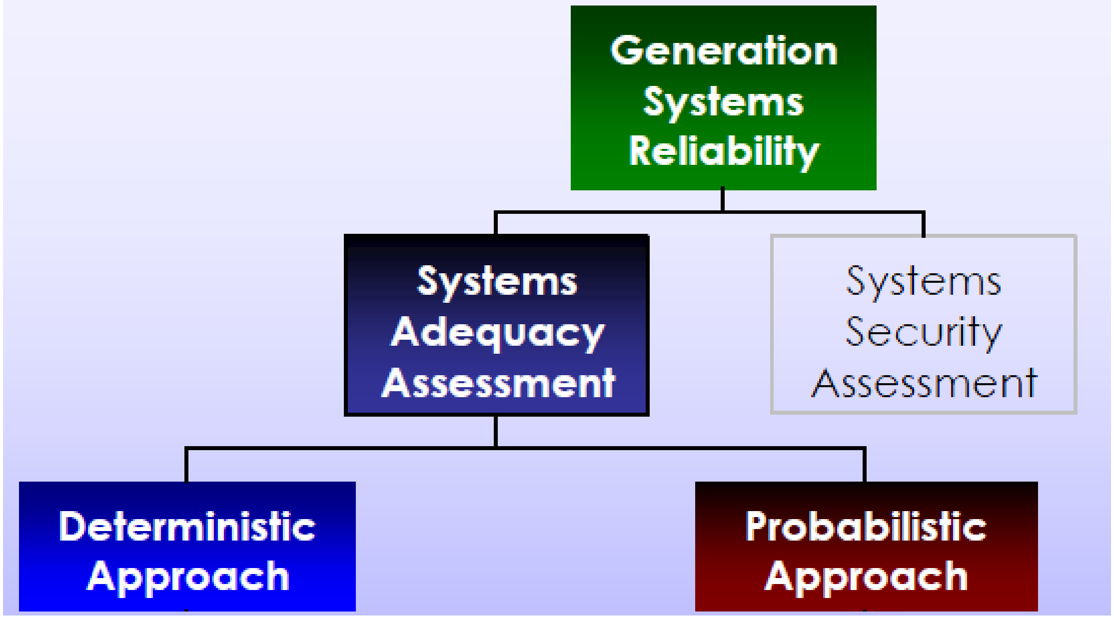


Figure 18 Generation system reliability categories

Reserve margin

For producer, reserve margin refers to the percentage of additional capacity after meeting customer demand over annual peak demand. It is known as a criterion applied in power system reliability assessment, which can be calculated following

Equation (3.1):

$$\text{Reserve margin} = \frac{\text{Installed Capacity (MW)} - \text{Annual Peak Demand (MW)}}{\text{Annual Peak Demand (MW)}} \times 100\% \qquad (3.1)$$

Reserve margin is applied in small generation systems to identify their reserve adequacy. Former experience [12] shows that criteria are generally set between 15% - 20% so that it can help keeping normal operation of system. This approach is quite simple and effective for small generation system but not suitable for large generation system, which is for the reason that it cannot reflect the actual risk of the system, lacking of the determination of probabilistic or stochastic nature of system operation, system demand and component failure. Besides these, it probably can cause over-investment in generation expansion or system reliability insufficiency [13]. So, probabilistic indices are widely used now rather than reserve margin.

3.2.2 Probabilistic Approach

In comparison with deterministic method, probability method is able to provide more useful information on selection of system design, planning and operation. Probabilistic methods are applied in both statistic and stochastic cases. Therefore, it has two main categories, which is analytical method and stochastic simulation method.

In this thesis, capacity outage probability table (COPT) approach represents as a main idea of analytical method, which could measure the power system adequacy through mathematical modeling. Stochastic simulation method, such as Monte Carlo Simulation (MCS) method, simulates the stochastic scenarios and random behaviors of the system by Mat lab performance to calculate the reliability indices. Following figure shows the two sorts of probabilistic approach.

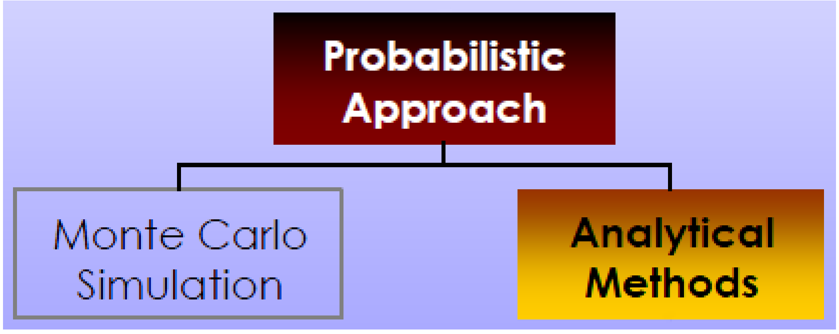
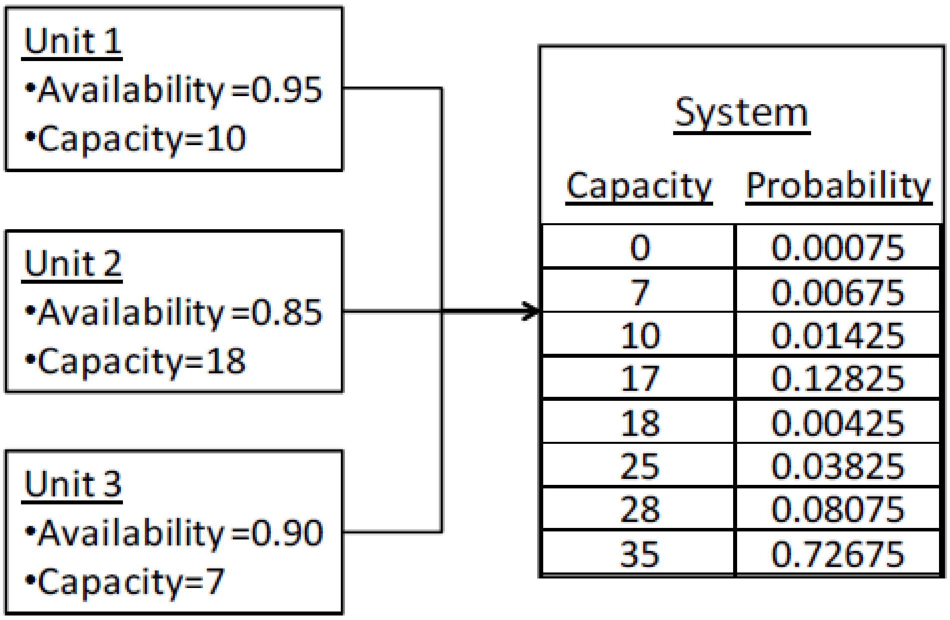


Figure 19 Two sorts of probabilistic approach

3.3 Analytical Techniques

Capacity outage probability table is a table listed all capacity states in an ascending order of outage magnitude in detail. Each capacity state is combined with available and unavailable capacity levels and their corresponding probabilities. In the direct analytical method, the generation model is usually created by the well-known recursive technique to establish the COPT [14]. The load is usually represented by either a daily peak load or an hourly load duration model. Basic COPT table can be constructed considering the parameters shows in Figure 20. The availability and the capacity of each individual generator are the input data.



Unit 1
•Availability=0.95
•Capacity=10

Unit 2
•Availability=0.85
•Capacity=18

Unit 3
•Availability=0.90
•Capacity=7

System

Capacity	Probability
0	0.00075
7	0.00675
10	0.01425
17	0.12825
18	0.00425
25	0.03825
28	0.08075
35	0.72675

Figure 20 A 3-unit system availability and capacity used to calculate the capacity probability table

No derated state model

The concepts of availability and unavailability are associated with the simple 2-state model shown in the figure below:

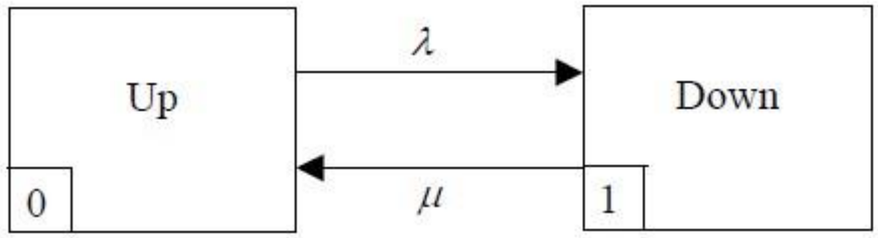


Figure 21 Two-state models for a generating unit

The total number of available (or unavailable) capacity states in an N-unit no derated state system is 2^N. For example, a 3-unit system (each unit can exist in 2 states) will have 2^3 states of available capacity. Each state can be seen from Table 4.

Table 4 Capacity states of a 3-unit no derated state system

	Unit A	Unit B	Unit C
1	Up	Up	Up
2	Up	Up	Down
3	Up	Down	Up
4	Down	Up	Up
5	Down	Down	Up
6	Down	Up	Down
7	Up	Down	down
8	Down	Down	Down

Derated states

In most cases, generating units are not in the states of completely up or completely down. A three or even more state can make them operate less than capacity which is called “derated state”. The state model is shown in Figure 22 as below. Derated state has a critical effect in accurate electricity power system reliability assessment, especially appropriate to intermittent energy generators such as WTG or PV units.

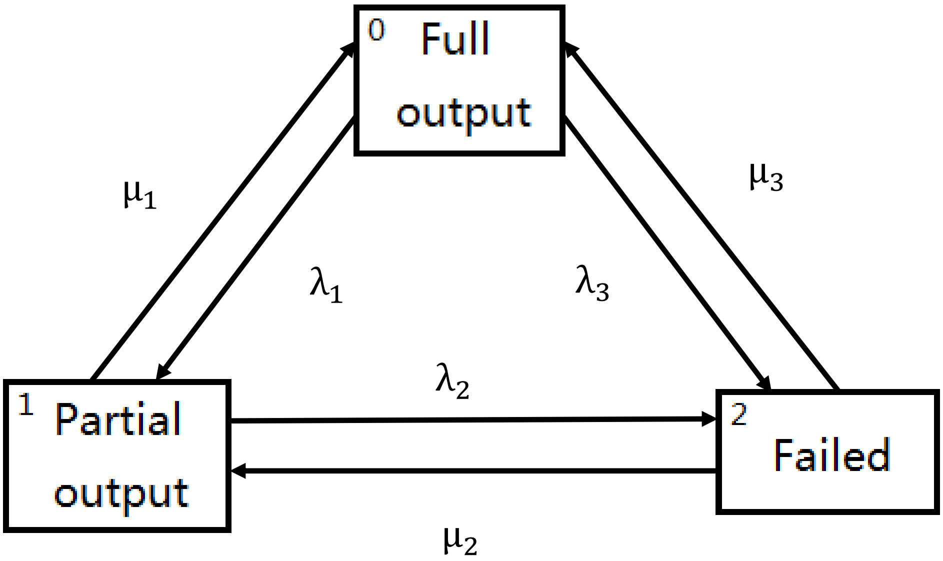


Figure 22 State space diagram of component with partial output state

3.3.1 Forced Outage Rate

Forced outage rate means the occurrence of a component failure or other condition which requires that the generating unit be removed from service immediately. If it is assumed that there are totally two states for the operation of generators, its available probability is called “Availability” and its failure probability on the hand is named as “Unavailability”. It can be noticed that machines are not able to operate all the time without interruption because broken-down cannot be avoid and maintenances are required. Two aspects of system unavailability shown as follow:

Scheduled outage (planned outage): Out of service for maintenance or replacement.

Forced outage (FOR): Out of service for unplanned problems.

Usually, planned outage is ignored in the reliability analysis to simplify the calculation.

Its mathematical formula of forced outage rate then can be defined as below:

$$\mathrm{FOR} = \mathrm{Unavailability} = \frac{\lambda}{\lambda+\mu} = \frac{\mathrm{r}}{\mathrm{m}+\mathrm{r}} = \frac{\mathrm{r}}{\mathrm{T}} = \frac{\mathrm{f}}{\mu} = \frac{\Sigma(\text{down time})}{\Sigma(\text{down time})+\Sigma(\text{up time})} \tag{3.2}$$

Availability can be expressed as,

$$\mathrm{Availability} = \frac{\mu}{\lambda+\mu} = \frac{\mathrm{m}}{\mathrm{m}+\mathrm{r}} = \frac{\mathrm{m}}{\mathrm{T}} = \frac{\mathrm{f}}{\lambda} = \frac{\Sigma(\text{up time})}{\Sigma(\text{down time})+\Sigma(\text{up time})} \tag{3.3}$$

Table 5 Description of parameters

λ	Expected failure rate(f/yr)
μ	Expected repair rate(rep/yr)
m	Mean time to failure=MTTF=$\frac{1}{\lambda}$
r	Mean time to repair=MTTR=$\frac{1}{\mu}$
m+r	Mean time between failures=MTBF=$\frac{1}{f}$
f	Cycle frequency=$\frac{1}{T}$
T	Cycle time$\frac{1}{f}$

3.3.2 Binomial Distribution

If all the units in the system are identical, the COPT can be easily obtained using either the Binomial distribution or the recursive algorithm. It is noted that the recursive technique is not limited to identical unit system but can also be applied in the not identical unit system to produce the final model. In summary, if FOR is known, the probability of system availability can be defined as Equation (3.4).

$$P_r = \frac{n!}{(n-r)!r!}(AV)^{n-r}(FOR)^r \tag{3.4}$$

Where

Pr = probability of r units in the down state

n = number of identical units

r = number of units in the failed state

AV = unit availability

✧ **Example**

Let there be 4 identical generating units, 25 MW, 1% FOR each.

Then, P_0= probability that zero units are in the failed state (i.e., all the 4 are up) =$\frac{4!}{(4-0)!0!}(0.99)^{4-0}(0.01)^0$=0.960596

Similarly, P_1=$\frac{4!}{(4-1)!1!}(0.99)^{4-1}(0.01)^1$=0.0388119

P_2=$\frac{4!}{(4-2)!2!}(0.99)^{4-2}(0.01)^2$=0.00058814

P_3=$\frac{4!}{(4-3)!3!}(0.99)^{4-3}(0.01)^3$=0.00000396

P_4=$\frac{4!}{(4-4)!4!}(0.99)^{4-4}(0.01)^4$=0

Thus,

$\sum_{r=0}^{r=n} P_r = P_0 + P_1 + P_2 + P_3 + P_4$=1

It is extremely unlikely that all the units in a practical system will be identical, and therefore the Binomial distribution has limited application. The units can be combined with basic probability concepts and this approach can be extended to a simple but powerful recursive technique in which the units are added sequentially to produce the final model [15].

There is an example about system availability analysis offered in the following:

Consider a 4-generating unit system with an installed capacity of 100 MW consisting of one 40 MW, 4% FOR unit and three 20 MW, 4% FOR units. Obtain the capacity model in the form of a COPT.

Table 6 Results of capacity outage probability table (a)

State	Capacity out	Capacity in		Probability
1	0	100	0.96*0.96*0.96*0.96	0.8463465
2	20	80	0.96*0.96*0.96*0.04	0.0353894
3	20	80	0.96*0.96*0.04*0.96	0.0353894
4	20	80	0.96*0.04*0.96*0.96	0.0353894
5	40	60	0.96*0.96*0.04*0.04	0.0014746
6	40	60	0.96*0.04*0.04*0.96	0.0014746
7	40	60	0.96*0.04*0.96*0.04	0.0014746
8	40	60	0.04*0.96*0.96*0.96	0.0353894
9	60	40	0.96*0.04*0.04*0.04	0.0000614
10	60	40	0.04*0.04*0.96*0.96	0.0014746
11	60	40	0.04*0.96*0.04*0.96	0.0014746
12	60	40	0.04*0.96*0.96*0.04	0.0014746
13	80	20	0.04*0.04*0.04*0.96	0.0000614
14	80	20	0.04*0.04*0.96*0.04	0.0000614
15	80	20	0.04*0.96*0.04*0.04	0.0000614
16	100	0	0.04*0.04*0.04*0.04	0.0000026

From Table 6 (a), it can be get that Availability1*Availability2 indicates unit1 and unit2 are both in operation while FOR1*FOR2 represents unit1 and unit2 are both out of service. In the same way, AV1*FOR2 means unit1 is in service and unit2 is out of service.

Thus, table can be simplified as following table.

Table 7 Results of capacity outage probability table (b)

State	Capacity out	Capacity in	Probability
1	0	100	0.8493465
2	20	80	0.1061683
3	40	60	0.039813
4	60	40	0.004485
5	80	20	0.0001843
6	100	0	0.0000025

3.3.2 Recursive Algorithm

Recursive algorithm is a powerful algorithm which input values first, then obtained results by applying simple operation to return values for next input. In this case, based on establishing system unit state model, knowing forced outage rate, the system capacity levels and their associated probabilities then could be achieved.

Cumulative probability

The COPT can also be developed using cumulative probability which known as the probability of obtain an unavailability which is equal to or greater than the indicated value. The cumulative probability values decrease as the capacity on outage increases.

For no-derated state, the cumulative probabilities of a capacity outage state of XMW can be determined as:

$$\mathrm{P(X)} = (1 - \mathrm{U}) * \mathrm{P'(X)} + \mathrm{U} * \mathrm{P'(X - C)} \qquad (3.5)$$

Where P’(X) and P(X) are the cumulative probabilities of a capacity outage state of

XMW before and after capacity C is added. Equation is initially set P'(X) =1.0 for X<0 and P'(X) =0 otherwise.

In multi-state (derated state) case, the capacity outage probability of capacity outage state of XMW can be modified as below:

$$P(X) = \sum_{i=1}^{n} P_i * P'(X - C_i) \tag{3.6}$$

Where：n= the number of the added unit state

C_i=capacity outage i for the unit being added

P_i=probability of existence of the unit states

✧ **Example**

The generators' data of Table 8 are used as an example to calculate the cumulative probability by using recursive approach:

Table 8 Forced outage rate to each generator

Unit No.	Capacity (MW)	Forced Outage Rate
1	20	0.02
2	20	0.02
3	80	0.02

1. Adding first unit:

P(0)=(1-0.02)P'(0)+(0.02) P'(0-20)=(0.98)(1)+(0.02)(1)=1

P(20)=(1-0.02) P'(20)+(0.02)P'(20-20)=(0.98)(0)+(0.02)(1)=0.02

The results mean when first unit added, the probability of system outage bigger than

0MW is 100% and it is 2% if bigger than 20MW.

2. Adding second unit:

P(0)=(1-0.02)P’(0)+(0.02)P’(0-20)=(0.98)(1)+(0.02)(1)=1

P(20)=(0.98)P’(20)+(0.02)P’(20-20)=(0.98)(0.02)+(0.02)(1)=0.0396

P(40)=(0.98)P’(40)+(0.02)P’(40-20)=(0.98)(0)+(0.02)(0.02)=0.0004

After second unit added, the generating system then has 3 outage levels with the combination of outage scenarios for each unit. System outage is 0 MW when both units are in ‘up’ state while it is 40 MW when both of them are in ‘down’ state. The last case of 20 MW happens when one is in ‘up’ state and another is in ‘down’ state.

3. Adding the third unit:

P(0)=(1-0.02)P’(0)+(0.02)P(0-80)=(0.98)(1)+(0.02)(1)=1

P(20)=(0.98)P’(20)+(0.02)P(20-80)=(0.98)(0.0396)+(0.02)(1)=0.058808

P(40)=(0.98)P’(40)+(0.02)P(40-80)=(0.98)(0.0004)+(0.02)(1)=0.020392

P(60)=(0.98)P’(60)+(0.02)P(60-80)=0+0.02=0.02

P(80)=(0.98)P’(80)+(0.02)P(80-80)=(0.98)(0)+(0.02)(1)= 0.02

P(100)=(0.98)P’(100)+(0.02)P(100-80)=0+(0.02)(0.0396)=0.000792

P(120)=(0.98)P’(120)+(0.02)P(120-80)=0+(0.02)(0.0004)=0.000008

There are totally 7 outage levels shows in Table 9.

Table 9 Complete capacity outage probability

Capacity out of service (MW)	Capacity in service (MW)	Cumulative probability
0	120	1
20	100	0.058808
40	80	0.020392
60	60	0.02
80	40	0.02
100	20	0.000792
120	0	0.000008

3.4 Stochastic Simulation Techniques

Unlike the fixed generation capacity from conventional generation system, the generation capacity of non-conventional generation system depends largely on resource due to its stochastic nature. Therefore, considering for the random operating feature and chronological system load model, the analytical techniques are not appropriate for non-conventional generation systems. However, those random verities of non-conventional generation capacity model could be reflected by stochastic simulation, normally known as Monte Carlo simulation (MCS).

Component of MCS can be summarized by several parts: 1. Probability distribution functions - system must be described in the form of probability distribution function. 2. Random number generator – need numbers obtained in a completely random way, not deterministic, predictable or repeatable. 3. Sampling rule - a sampling for assuming the availability of random numbers on the unit interval, should be provided.

Two approaches to MCS

MCS is able to be briefly classified into sequential MCS and non-sequential MCS [16, 17]. Sequential method depends on chronological process and each time point is correlative with its neighboring point. Non-sequential method, however, is independent on chronological process and each time point is unrelated on any other points [24]. In this thesis, the sequential MCS method is selected and will be described in details later.

3.4.1 Monte Carlo Simulation Sampling Methods

Sampling is a key factor of describing the generator operating history and determining the system states. The system state in a chronological Monte Carlo simulation is the probability in the operating history. Typically, there are 3 types of MCS sampling methods which are state sampling, state transition sampling and component state duration sampling [18].

3.4.1.1 State Sampling

In state sampling approach, the behavior of each component can be defined by random number which is uniformly distributed in [0, 1]. Each component is supposed to have 2 states: up state and down state. “1” used to represents up state while “0” represents down state [19, 20]. For a good expression, the state of a component is sampled by Equation (3.7).

$$S_i = \begin{cases} 0 & \text{(up)} \qquad U_i \geq FOR_i \\ 1 & \text{(down)} \qquad 0 \leq U_i \leq FOR_i \end{cases} \tag{3.7}$$

Where, S_i=state of ith component

U_i=random number uniformly distributed in [0, 1]

$\mathrm{FOR_i}$=forced outage rate for component i

If random number uniformly distributed in [0, 1] is greater or equal to its FOR, then state of this component is up state. But the converse situation is down state. State sampling method is a relatively simple method because the required data are just $\mathrm{FOR_i}$ and $\mathrm{U_i}$. Although it is proposed for composite system reliability evaluation, state sampling method still restricted from the aspect of system size. As state sampling is a non-sequential sampling approach, it is therefore not applicable to be applied in the calculation of frequency and duration related index.

3.4.1.2 State Transition Sampling

State transition sampling focuses on state transition of individual component in the system. Then, the system state transition is obtained by combining all components state transitions. The chronological state transition process for each component has the form shown in Figure 23. For the purpose of describing the whole system state duration, all system components should apply to uniformed probability distribution function (exponential distribution). As contrasted with state sampling approach, system state transition sampling approach can be used to calculate the actual frequency index without requiring sample or store all the components states. However, if components are unable to be expressed by a uniform probability distribution function (exponential distribution), system state transition sampling then is not allowed to be used [21, 22].

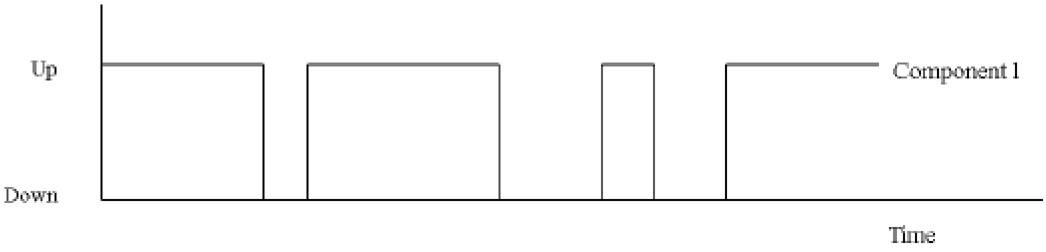


Figure 23 Chronological state transition sampling

3.4.1.3 Component State Duration Sampling

It is a sequential Monte Carlo sampling method which can produce all the operating parameters in the system. It can actually demonstrate the frequency and duration index by any probability distribution functions [18].

A random state residence time of component state duration sampling method can be sampled with following equation:

$$T_i = -\frac{1}{\lambda_i} \ln U_i \tag{3.8}$$

Where U_i is a uniformly distributed random number between [0, 1]. λ represents failure rate when present state is up state otherwise λ represents repair rate.

Generally, simulation methodology can be summarized in the following steps :

- Initialize all system component states, typically is assumed to be up state.
- Compute the duration of each state for all system components. It enquires a probability distribution function (exponential distribution) to calculate the state residence time.
- Generate operating history for each component and obtain the available capacity.
- Superimpose the available capacity of each unit on the chronological operating history with load profile, normally is a chronological hourly load pattern, to obtain the system margin model. Outage occurs when load is higher than system available capacity.

3.4.2 Random Number Generation

Two types of random numbers: Pseudorandom numbers and true random number

Pseudorandom numbers are generated in a limited random way, which means pseudorandom numbers have characteristic such as deterministic, repeatable and predictable manner.

True random numbers are defined as the numbers obtained in a completely random way. They are not deterministic, predictable or repeatable.

It is not viable to generate a true random number using Monte Carlo simulation approach since computer process is deterministic. However, we can generate a good enough random numbers that have properties close to true random numbers.

The random numbers generation strategy should ensures the followings:

- The random number generation should be vectorizable but with low overhead to achieve more efficiency.
- The random numbers should be obtained uniformly. For the purpose of uniformity, the essential correlations between random numbers should not be ignored.
- Once a random number was generated, the repetition should appear only after a long period of random numbers generation.

3.4.3 Probability Distribution

As a considerable number of reliability models used mean values for indices in the past, it ignored the shape of index probability distribution function and loosed the accuracy of indices. It is therefore probability distribution functions are now widely used in stochastic analyses of reliability of systems. In Section 3.4.3.1 and 3.4.3.2 we briefly introduced the normal distribution and the exponential distribution respectively. In section 3.4.3.3 we present the Wei-bull distributions which are popular models in reliability and which can be considered as generalizations of the

Exponential distribution.

3.4.3.1 Normal Distribution

The Normal distribution is a widely used probability distribution in statistics. Generally speaking, it also occurs in quantitative risk assessment, e.g. when risks of investments are under consideration, but its role in reliability is less important.

The Normal distribution has two parameters, $-\infty < \mu < \infty$ and $\sigma^2 > 0$, which are equal to its mean value and variance, so σ is standard deviation and its probability distribution function is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \tag{3.9}$$

Here is the relationship with the two parameters and distribution curves shape.

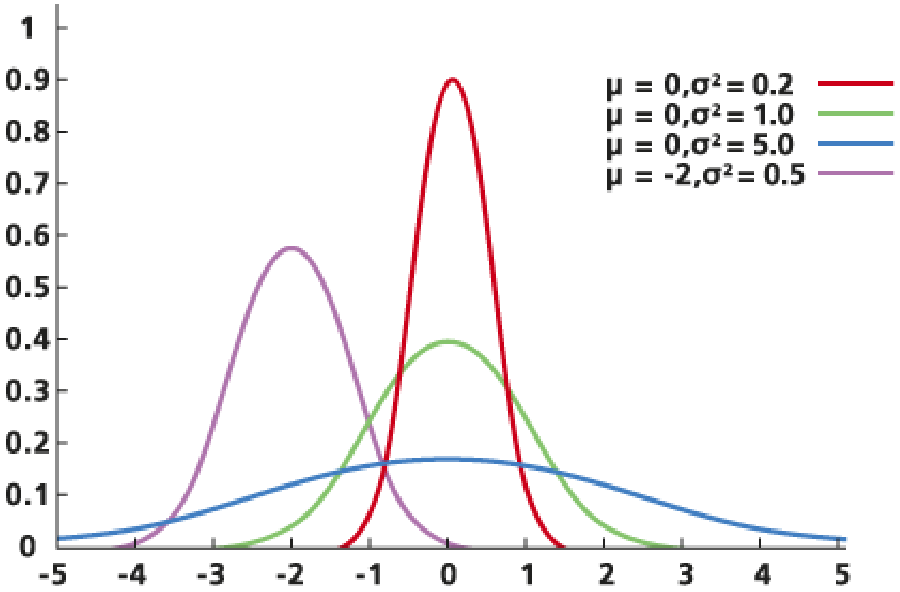


Figure 24 Basic normal distribution curves

3.4.3.2 Exponential Distribution

The Exponential distribution is a continuous probability distribution. It is generally used to model time between events that occur at a constant average rate. As the time increases, there is an exponentially greater chance for the event to occur. The occurrences of the events are independent of one another. The probability distribution in this section is a very popular model for reliability evaluation, because in system reliability evaluation, the failure rate which introduced previously is constant. So its distribution function is expressed as below:

$$f(x) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{3.10}$$

Where, x is the possible number of occurrences for the event.

Following figure shows the distribution curves shape.

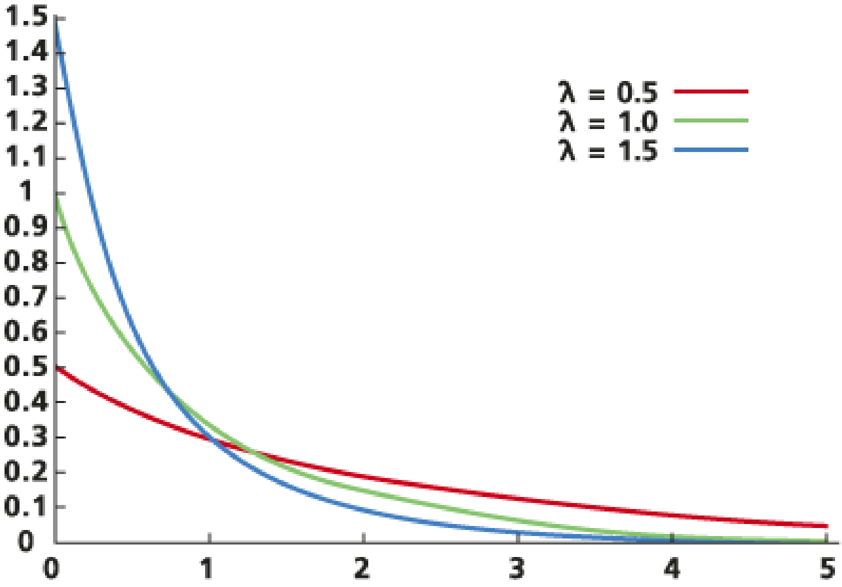


Figure 25 Basic exponential distribution curves

3.4.3.3 Wei-bull Distribution

The expression of Wei-bull distribution is as follows:

$$f(x) = \frac{\beta x^{\beta-1}}{\alpha^{\beta}} \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \tag{3.11}$$

Where x≥ 0, and$\alpha, \beta > 0$. α is the scale parameter andβ is the shape parameter.

Wei-bull distribution can be applied to fit the experimental data which is unable to be described with a particular distribution such as normal distribution or exponential distribution due to its own characteristic: it has not a specific shape. It can be shaped to represent many distributions by modified the value ofα and β, as long as they are positive. Following figure shows the distribution curves shape [23, 24].

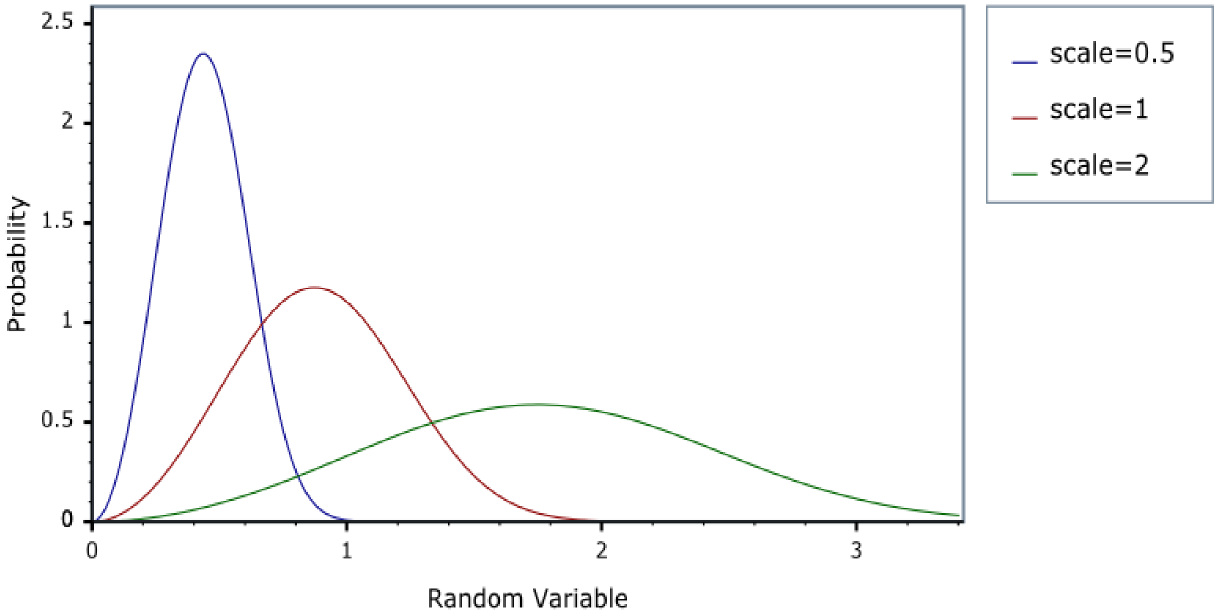


Figure 26 Basic Wei-bull distribution curves

3.4.5 Simulation Convergence and Stopping Criteria

In power generation systems, it is always a long period computing time for its stochastic simulation to simulate the actual operation. The indices with higher level of accuracy need more sampling time to achieve it. However, in actual operation cases, it is unrealistic to carry out a simulation for an extremely large number of samples only for the purpose of obtain indices with extremely accuracy. In order to make the systems stop simulation in an appropriate time, stopping criteria is required to do so. It is aim at ensuring the balance between accuracy of indices and sampling time. There are several kinds of stopping criteria, which can be used to track the simulation convergence. In this research, the stopping criterion is selected as the mathematical expression in the following:

The basic reliability index is

$$\mathrm{E(X)} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{X_i} \tag{3.12}$$

Where

$\mathrm{X_i}$ – The observed value of X in year i

N – The total number of simulated years

The standard deviation of the mean is

$$\sigma[\mathrm{E(X)}] = \frac{\sigma(\mathrm{X})}{\sqrt{\mathrm{N}}} \quad \text{Where} \quad \sigma(\mathrm{X}) = \left[\frac{1}{\mathrm{N}-1} \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{X_i^2} - \mathrm{E^2(X)})\right]^{\frac{1}{2}} \tag{3.13}$$

The stopping criterion is as follows:

When$\frac{\sigma(\mathrm{E(X)})}{\mathrm{E(X)}} < \varepsilon$, the simulation is terminated.

Where ε is the maximum error allowed.

It should be noticed that each sort of indices converge at the different rate. The literature introduced LOEE index need more time to converge than the other indices. It is the reason that LOEE is taken as the base index to check for convergence [25].

3.5 Probabilistic Criteria and Indices

As the capacity model measured by either COPT or MCS approach is sufficient to calculate reliability indices in terms of probability, expected days (hours) of loss of load, and expected unsupplied energy, an excellent understanding of the probabilistic criteria and indices used in generating capacity reliability studies is important. The commonly used probabilistic reliability indices are loss of load expectation (LOLE), loss of energy expectation (LOEE), loss of load frequency (LOLF) ,loss of load duration (LOLD) and loss of load probability (LOLP) which basically expected values of a random variable.

Loss of load expectation (LOLE)

LOLE, the most widely used probabilistic index in deciding future generation capacity which is the average days or hours during a research period which peak load is expected to exceed the available generating capacity. The method is expressed in the followings:

$$\mathrm{LOLE} = \frac{\sum_{y=1}^{Y_s} \mathrm{LLD}_y}{Y_s} \quad \text{(days/yr or hours/yr)} \tag{3.14}$$

Where

Y_s- sampling time

LLD_y- sampled loss of load duration

Loss of energy expectation (LOEE)

LOEE is the expected energy that will not supplied due to the occasions when load exceeds the available generation during a research period. It is presently less used than LOLE but is a more appealing index since it reflects risk more truly and is likely to encompass severity of the deficiencies. The method is expressed in the followings:

$$\mathrm{LOEE} = \frac{\sum_{y=1}^{Y_s} \mathrm{ENS}_y}{Y_s} \quad \text{(MWh/yr)} \tag{3.15}$$

Where

Y_s- sampling time

$\mathrm{ENS_y}$- sampled energy not supplied

Loss of load frequency (LOLF)

LOLF is defined as the expected frequency of generation deficiency during a research period. The method is expressed in the followings:

$$\mathrm{LOLF} = \frac{\sum_{\mathrm{y=1}}^{\mathrm{Y_s}} \mathrm{LLO_y}}{\mathrm{Y_s}} \quad \text{(occurrence/yr)} \tag{3.16}$$

Where

$\mathrm{Y_s}$- sampling time

$\mathrm{LLO_y}$- sampled loss of load occurrence

Loss of load duration (LOLD)

LOLD presents the expected duration of generation deficiency during a research period. The method is expressed in the followings:

$$\mathrm{LOLD} = \frac{\mathrm{LOLE}}{\mathrm{LOLF}} \quad \text{(hours/occurrence)} \tag{3.17}$$

Loss of load probability (LOLP)

LOLP is defined as the expected probability that a system will exceed the available generation capacity during a research period. The mathematical formular for calculation LOLP is shown as below:

$$\mathrm{LOLP} = \sum_{\mathrm{y=1}}^{\mathrm{Y_s}} \mathrm{P_y} = \frac{\mathrm{LOLE}}{\mathrm{Y_s}} \tag{3.18}$$

Where

$\mathrm{Y_s}$- sampling time

P_y- the probability of outage

LLO_y- sampled loss of load occurrence

Frequency and duration criterions are extensions of LOLE. They are frequently mentioned in documents but still not widely used in practice because both of them need more data and complexity analysis and create low effect on the planning decisions compared to LOLE.

3.6 Summary

This chapter briefly describes the various techniques for generating capacity adequacy evaluation and their uses in generation planning have been illustrated. The techniques used by utilities for obtain adequacy evaluation broadly fall into the two categories of deterministic and probabilistic approaches. Deterministic methods cannot completely reflect the risk of a given system, and therefore electric power utilities prefer to use probabilistic criteria.

Two different approaches exist in the probabilistic evaluation of generating capacity adequacy. They can be classified as being either analytical or Monte Carlo simulation approaches. The main disadvantage of the analytical approach is that it is not appropriate for systems having chronological varying behavior or when modeling large complex systems. Monte Carlo simulation, on the other hand, is preferable in such situations.

Indices such as LOLE and LOEE are simply indications of static capacity adequacy which respond to the basic elements that influence the performance of the given system. They can be evaluated by suitably combining the generation model with the load model in both analytical and Monte Carlo simulation approaches.

Chapter 4 Reliability Evaluation Models for Generating System

4.1 Introduction

Since the utilization of wind and solar energy for electric power generation is increasing all over the world, power system planners have to paid more attention to the reliability issues associated with these renewable energy sources due to the lack of suitable modeling and evaluation techniques.

Typically speaking, the renewable energy which could be converted to electricity are mainly affected by the available energy contained in the different weather condition. Due to the consideration for different characteristics of the renewable resources, it is quite different for wind and solar energy systems in modeling and related reliability analyses.

4.2 Representation of Conventional Generating System

4.2.1 Establish COPT approach

It has been already mentioned in chapter 3 that it normally be dozens even hundreds generating units operating in an electrical power system, with two states for each unit at least. Moreover, types and characteristics of each unit are quite different. These effects make the whole process of calculating power system reliability become comparatively complicated by using general method. But now, recursive algorism assisted the calculation much simpler than it used to be.

For each independent generating unit, COPT can be summarized as following form shown in Table 10:

Table 10 Capacity outage probability table

Available Capacity	Outage Capacity	Exact Probability	Cumulative Probability
c	0	1-q	1
0	c	q	q
* c is capacity and q represents for forced outage rate			

4.2.2 Obtain Reliability Index Combined with Daily Peak Load Variation Curve

Figure 27 below shows the relationship between capacity and load where the load model is shown as a continuously declining curve for a period of 365 days. The balance between installed capacity and peak load are saved as reserve. Only capacity outage exceed the reserve will result in the system LOLE.

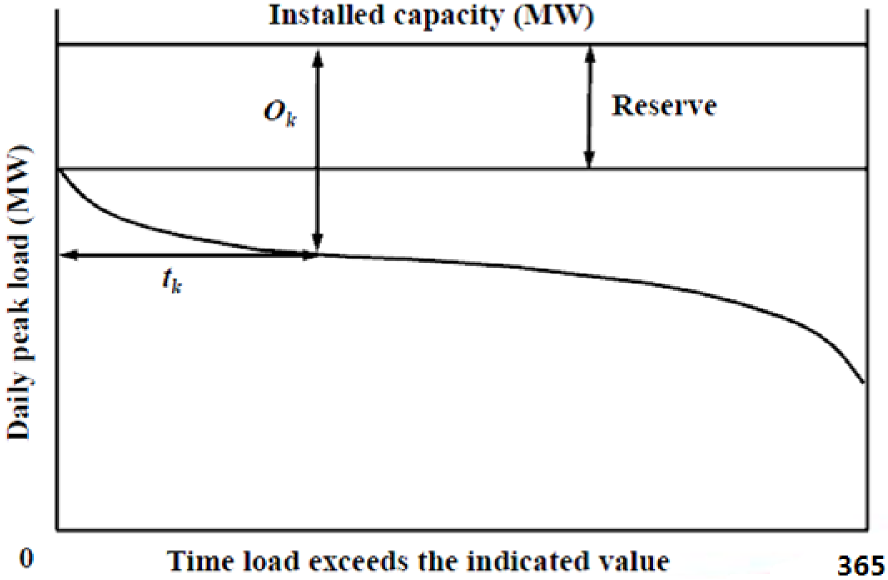


Figure 27 Relationship between load, capacity and reserve

Capacity outage which is less than the reserve will not affect to system indices. Expressed mathematically, the value of the system LOLE captured by capacity outage $O_k$is $P_k t_k$, where P_k is the relatively individual probability of its outage O_k [15]. The mathematical expression of total LOLE for the study is given by Equation (4.1).

$$\text{LOLE}=\sum_{k=1}^{n} P_k t_k \qquad (4.1)$$

Alternatively, the system LOLE can be expressed by using the cumulative probability values from the COPT which is shown in Equation (4.2).

$$\text{LOLE}=\sum_{k=1}^{n} P_k (t_k - t_{k-1}) \qquad (4.2)$$

Where P_k is the cumulative outage probability for its relative outage state O_k.

✧ **Example**

For further study, the application of Equation (4.1) and (4.2) can be illustrated by a simple numerical example. There are 5 generation units contained in a system. The capacity for each unit is 40MW for each capacity and forced outage rate is 1%. The COPT of this system is listed in Table 10. In the following COPT, binomial distribution method has been applied and probability values below 10^{-6} have not been taken into consideration.

The system load model is selected for the annual daily peak load variation curve (DPLVC) shown in Figure 28. Considering simplicity of the calculation, it present as a linear curve in this case, whereas the curve will be non-linear but the concept is still applicable in actual practice.

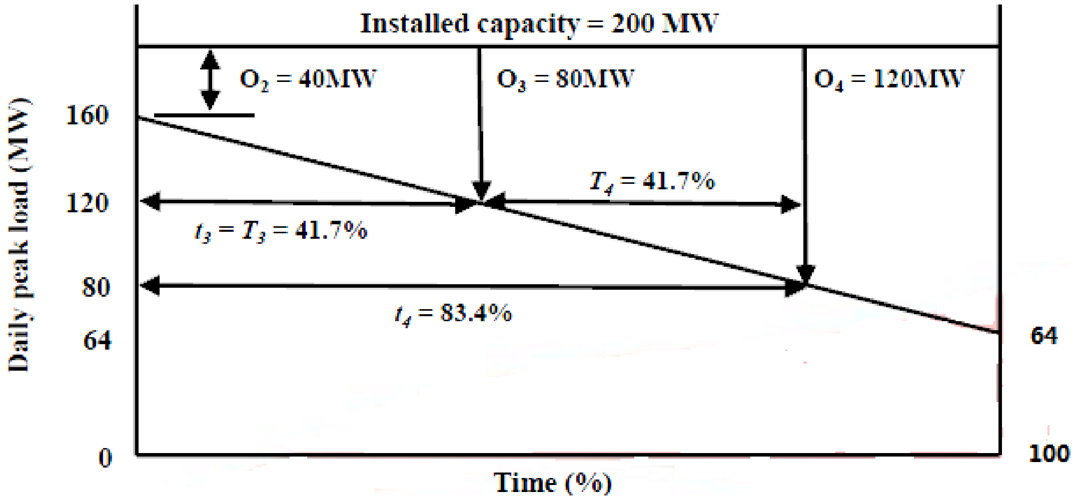


Figure 28 Time period during which loss of load occurs

The LOLE can be evaluated using Equation (4.1) (individual probabilities) or Equation (4.2) (cumulative probabilities), both methods are illustrated here. The time periods $t_k$are calculated using the equation of the straight line DPLVC. The LOLE calculations using Equation (4.1) are shown in Table 11.

Table 11 Obtain LOLE by using individual probabilities

Capacity out of service(MW)	Capacity in service(MW)	Individual probability(P_k)	Total time(t_k)	LOLE($P_k t_k$)
0	200	0.950991	0	0
40	160	0.048029	0	0
80	120	0.000971	41.7	0.040491
120	80	0.000009	83.4	0.000751
		$\sum 1.00000$		$\sum 0.04124$

LOLE = 0.0412413(365/100) = 0.150410 days/yr

If the cumulative probability values are used, the time quantities used are the interval or increases in curtailed time represented by T_k. The calculation results are shown in Table 12.

Table 12 Obtain LOLE by using cumulative probabilities

Capacity out of service(MW)	Capacity in service(MW)	Cumulative probability(P_k)	Time interval(T_k)	LOLE ($P_k t_k$)
0	200	1.000000	0	0
40	160	0.049009	0	0
80	120	0.000980	41.7	0.040866
120	80	0.000009	41.7	0.000375
				$\sum 0.04124$

System LOLE = 0.0412414% (365/100) = 0.15041 d/yr

4.2.2 Monte Carlo Simulation Approach

For conventional generating units, either COPT method of MCS method is appropriate for electricity power system reliability assessment. In sequential MCS, system capacity model descript available capacity by chronological order; load model, in most cases, can be obtained from chronological hourly load profile. The capacity model simulation techniques of conventional generating units are based on component state duration sampling because it can actually reflect the operating frequency and duration index by any probability distribution function. Mean time to failure (MTTF) and mean time to repair (MTTR) are two most crucial parameters of unit operational history which denote “up-time” and “down-time” respectively [26]. Then associated with a uniformed distributed random number between [0, 1], the component state operating history could be obtained and the expression is shown as below:

$$\mathrm{T_i} = -\frac{1}{\lambda_\mathrm{i}} \ln \mathrm{U_i} \tag{4.3}$$

Where: λ is the failure rate when the present state is up state; λ is repair rate when the present state is down state.

The basic simulation procedure of conventional generating units by component state duration sampling can be briefly described as following steps:

1) Initialize system component state, usually it is setting on up-state.

2) Sample the residence time throughout the operating history by generating random number which is uniformly distributed in [0, 1] and associated with component duration probability density function. For power system reliability evaluation, probability density function usually is exponential distribution.

3) Generate operating histories for each component.

4) Combine all the components operating histories together. The finally history is then in the form of chronological up-down-up or up-derate-down-up etc.

5) Obtain system risk model by importing chronological hourly load profile. Outage occurs when load is higher than system capacity at a specific time.

Figure 29 illustrate the marginal model of a two-generator system. Loss of load has been marked by dashed area in the figure.

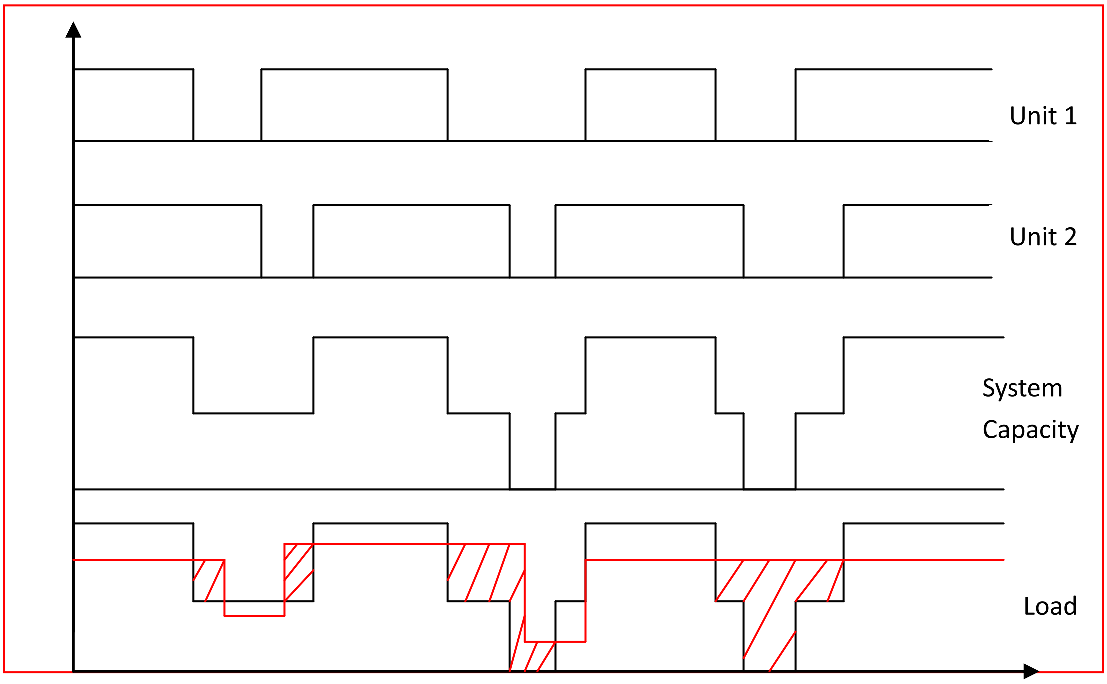


Figure 29 Loss of load of two-generator system

4.3 Representation Model of Wind Turbine Generating System

4.3.1 Wei-bull Distribution

Wind velocity varies in different time and different locations so that wind turbine generation output is fluctuating in most of the time. In order to observe an accurate wind power output model of wind turbine, study on wind speed variation forecasting at different locations is a key of the solution. Normally, wind velocity can be represented by using Wei-bull distribution as it can simulate wind speed variation by modifying parameter α and β. The expression of Wei-bull distribution function is as Equation 4.4 below:

$$f(x) = \frac{\beta \times X^{\beta-1}}{\alpha^{\beta}} \exp\left[-\left(\frac{X}{\alpha}\right)^{\beta}\right] \tag{4.4}$$

Where $\alpha > 0$ is the scale parameter, $\beta > 0$ is the shape parameter and $X > 0$ is wind speed. Usually, the scale of Wei-bull distribution function is determined by α which represents the mean speed of wind when simulating wind speed by Wei-bull distribution function, α normally is set as 7. On other side, shape of Wei-bull distribution function is determined by β, always is set as 2 in simulation.

The cumulative probability distribution function can be expressed as below:

$$f(x) = 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \tag{4.5}$$

And then, by using inverse transform method [17], equation will be deformed as:

$$W_s = x = \alpha \left[\ln(U)^{1/\beta}\right] \tag{4.6}$$

Where: U is a random variety uniformly distributed in [0, 1].

Electrical power output model of wind turbine

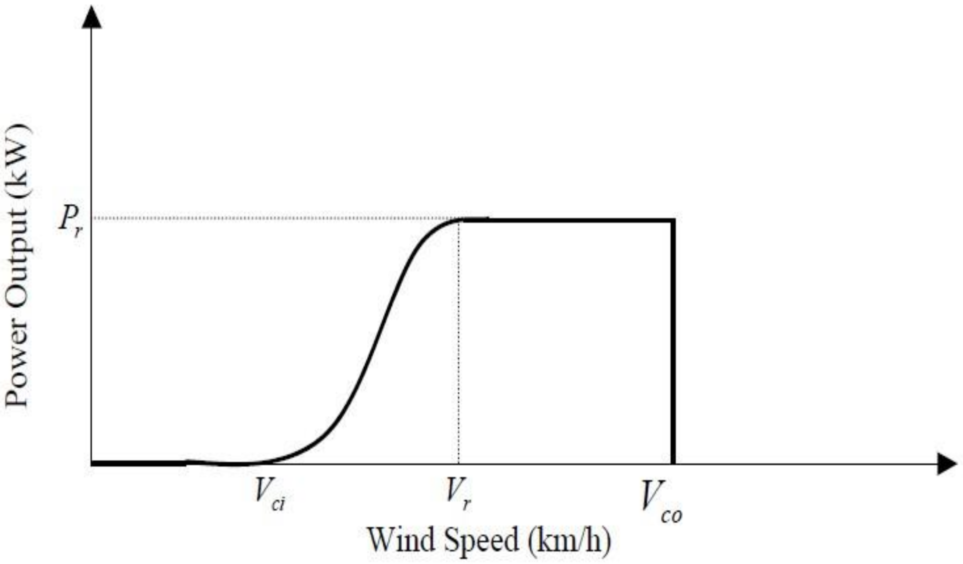


Figure 30 Electrical power output curve of wind turbine

The power curve in Figure 30 describes the relationship between input wind speed and output electrical power of a wind turbine generator. The mathematical expression can be identified as [27, 28]:

$$P_w = \begin{cases} 0 & W_s < V_{ci} \\ (A + B * W_s + C * W_s^2) * P_{wr} & V_{ci} \le W_s < V_r \\ P_{wr} & V_r \le W_s < V_{co} \\ 0 & W_s \ge V_{co} \end{cases} \tag{4.7}$$

A, B, C is constant parameters:

$$A = \tfrac{1}{(V_{ci} - V_r)^2} [V_{ci}(V_{ci} + V_r) - 4V_{ci}V_r(\frac{V_{ci} + V_r}{2V_r})^3] \tag{4.8}$$

$$B = \tfrac{1}{(V_{ci} - V_r)^2} [4(V_{ci} + V_r)(\frac{V_{ci} + V_r}{2V_r})^3 - (3V_{ci} + V_r)] \tag{4.9}$$

$$C = \frac{1}{(V_{ci} - V_r)^2}[2 - 4(\frac{V_{ci} + V_r}{2V_r})^3] \tag{4.10}$$

Where: Ws is wind speed, V_{ci}, V_{co} and V_r is cut-in speed, cut-out speed, rated speed of wind turbine respectively, P_{wr} is rating power output of wind turbine. The non-linear relationship between wind speed and power output can be described as the curve below:

4.3.2 Wind Plant Output Example

The following example simulate a wind turbine generation output by generating wind speed first and then applied with wind power output model (Equation4.6).The cut-in , cut-out, rated wind speed and rating power output of wind turbine generator are given in Table 13. Other technical data about wind turbine is detailed demonstrated in Appendix A.

Table 13 Fundamental parameters of wind turbine

Vci(m/s)	Vco(m/s)	Vr(m/s)	Pwr(KW)
2	24	11	225

Figure 31 illustrate the simulation result for wind velocity. As explained previously, wind velocity can be simulated by Wei-bull distribution function. The corresponding power output under this wind condition is shown in Figure 32.

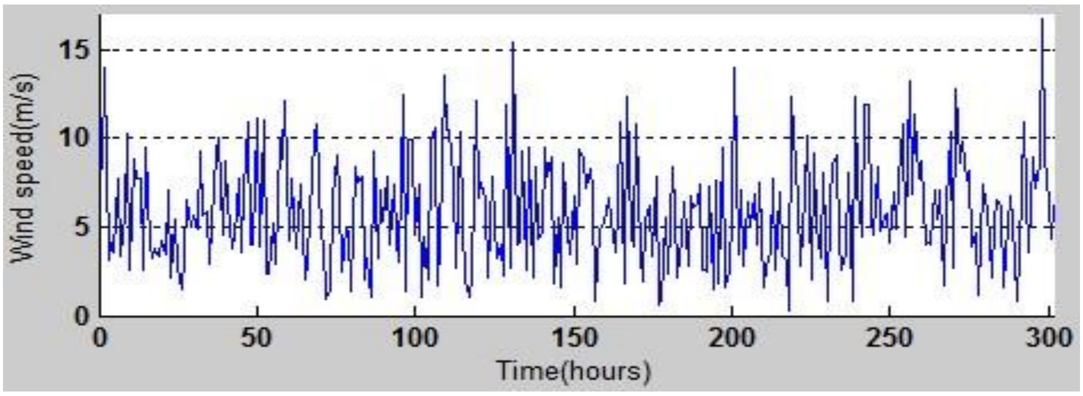


Figure 31 Snap shot of wind velocity

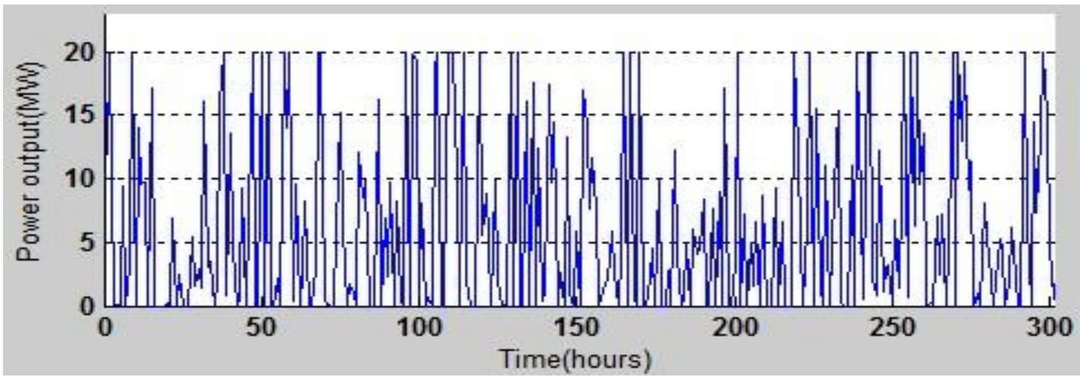


Figure 32 Sample process for power output of wind turbine

4.4 Capacity Model of Photovoltaic Generating System

When PV generation system integrated into utility grid with a large penetration level, its power output is related to the intermittent weather condition and geographical position. Since these factor may affect the power stability. So, it is more essential to study the relationship between them.

4.4.1 Forecast Solar Radiation

Extraterrestrial solar radiation

The output of PV generation system has been estimated by evaluating solar radiation. In order to obtain extraterrestrial radiation at first, Hottel's equation has been applied which is shown below [29]:

$$G_o \text{ (irradiance)} = \frac{T\, I_0}{\pi\, \rho^2} \int_{-\omega_0}^{+\omega_0} (\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega)\, d\omega \qquad (4.11)$$

$$G_o \text{ (irradiance)} = \frac{T\, I_0}{\pi\, \rho^2} (\omega_0 \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_0) \qquad (4.12)$$

Where, G_o= extraterrestrial radiation

T=Time of one day

ϕ=Latitude

ρ=mean sun-earth distance

I_0=Solar constant, usually is $1367 w/m^2$

Solar constant is the total radiant energy on a unit area perpendicular to the beam outside the atmosphere at the mean sun-earth distance.

Typically, the radiation power from the sun depends linearly on the earth-sun distance. Therefore, it is necessary to get accurate earth-sun distance. Nowadays, earth-sun distance of any day in a year is known. In order to simplify the calculation, we always use $\frac{1}{\rho^2}$ to indicate it. The equation is shown as following:

$$\frac{1}{\rho^2}=1.000110+0.034221\cos\theta_0+0.001280\sin\theta_0+0.000719\cos 2\theta_0+0.000077\sin 2\theta_0 \tag{4.13}$$

$$\theta_0=2\pi(d_n-1)/365 \tag{4.14}$$

where, θ_0 =angle of earth revolution

d_n=Day of the year

δ= Declination

It should be noticed that the revolution orbit of earth doesn't meet at right angle with its rotation axis, but 66.5°. The declination of the sun is the angle between a plane perpendicular to a line between the earth and the sun and the earth's axis. According to different declinations, there will be different altitude of noonday sun. It is described as below.

$$\delta = 0.006918 - 0.399912\cos\theta_0 + 0.070257\sin\theta_0 - 0.006758\cos 2\theta_0 + 0.000907\sin 2\theta_0 - 0.002697\cos 3\theta_0 + 0.000148\sin 3\theta_0)\frac{180}{\pi} \tag{4.15}$$

$$\omega_0=\cos^{-1}(-\tan\phi\tan\delta) \tag{4.16}$$

Parameter ω_0 represents hour angle here.

Thus, if we've got T (time of one day), d_n (day of year), ϕ (latitude) and θ_0 (angle of earth revolution), we could solve the extraterrestrial radiation (G_o) out.

Daily clear sky radiation on a horizontal plan

Clear sky radiation on a horizontal plan then could be determined by Hottel's equation and Liu and Jordan's equation [29]:

$$\cos\theta_z=\cos\phi\cos\delta\cos\omega+\sin\phi\sin\delta \tag{4.17}$$

$$\tau_b=a_0+a_1*e^{(-k/\cos\theta_z)} \tag{4.18}$$

Where, θ_z=Zenith angle

τ_b = Atmosphere transmittance for beam radiation

a_0 , a_1 and k are correction factors. They could be calculated by the following equations [28]. Parameter A represents for the altitude.

$$a_0=r_0a_0^* \tag{4.19}$$

$$a_1=r_1a_1^* \tag{4.20}$$

$$k=r_kk^* \tag{4.21}$$

$$a_0^*=0.4237-0.00821(6-A)^2 \tag{4.22}$$

$$a_1^*=0.5055-0.00595(6.5-A)^2 \tag{4.23}$$

$$k^*=0.2711+0.01858(2.5-A)^2 \tag{4.24}$$

Table 14 presents the value of r_0, r_1 and r_k with various climates:

Table 14 Parameters of r_0, r_1 and r_k in different climates

Climate type	r_0	r_1	r_k
Tropic	0.95	0.98	1.02
Mid-latitude	1.00	1.00	1.01
frigid zone	1.05	1.02	1.00

G_{cb} is daily clear sky beam radiation on a horizontal plane:

$$G_{cb} = G_o * \tau_b \tag{4.25}$$

To evaluation the diffuse radiation, Liu and Jordan's equation has been applied again as shown below [27]:

$$\tau_d = 0.271 - 0.294 * \tau_b \tag{4.26}$$

τ_d is Solar diffuse transmission coefficient

$$G_{cd} = \tau_d * G_0 \tag{4.27}$$

G_{cd} is daily clear sky diffuse radiation on a horizontal plane

$$G_c = G_{cb} + G_{cd} \tag{4.28}$$

G_c is daily clear sky radiation on a horizontal plane

Daily solar radiation considering weather change

Using the above method, PV output power can be estimated only in sunny (clear sky) weather. So, in order to calculate PV output in cloudy/rainy weather, the forecasting of solar radiation considering weather condition should be included. It is described from [30]:

$$G = G_c \times F \tag{4.29}$$

Where, G = solar radiation considering probabilistic

F= random number derived from normal distribution considering weather (shown in Table 15)

Table 15 Average and standard deviations of random number considering weather change

Weather	Average	Standard
Sunny	1	0.03
Cloudy	0.5	0.2
Rainy	0.1	0.0003

The overall procedure for generating synthetic solar radiation data in the program is a three-step process, as shown in Figure 33.

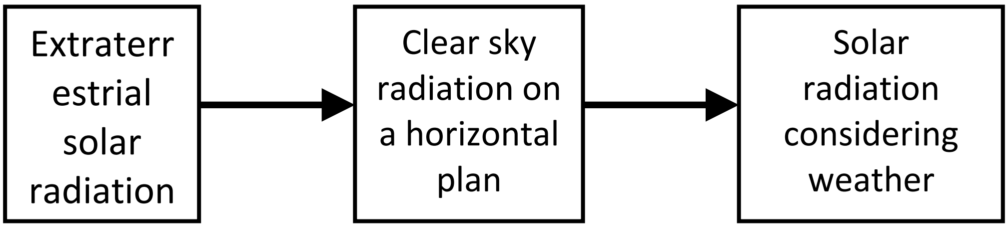


Figure 33 Basic steps involved in solar radiation forecasting

4.4.2 Modelling Photovoltaic Generation Output

The literature [30] introduced that hourly output of a solar panel is typically determined from the cell's current-voltage relationship so that the basic points of solar cell are mainly involved in 3 parameters: maximum power point, short-circuit current and open-circuit voltage.

Maximum power point

Reference maximum power, shown as the area of the shade in Figure 34, is evaluated when the area of rectangle fits under I-V curve is in maximum value.

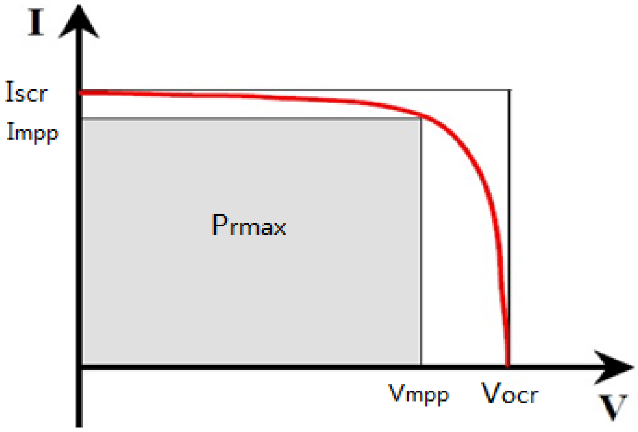


Figure 34 Maximum power delivered by the solar cell

The commonly used fill factor, FF, is obtained by the ratio of P_{rmax} to the rectangle area formed by reference short circuit current (I_{scr}) and (V_{ocr}) which can be expressed by Equation (4.30) [31].

$$FF = \frac{P_{rmax}}{(V_{ocr})(I_{scr})} \tag{4.30}$$

The maximum power can be calculated from the panel I-V curve using Equation (4.31).

$$P_{max} = P_{rmax} \frac{V_{oc} I_{sc}}{V_{ocr} I_{scr}} = FF \times V_{oc} \times I_{sc} \tag{4.31}$$

Short circuit current and open circuit voltage

Short circuit current (I_{sc}) is the maximum value of current under short circuit conditions: V=0. Likewise, open circuit voltage (V_{oc}) corresponds to the voltage cross the p-n junction under open circuit conditions: I=0.

Open-circuit voltage depends on cell temperature while short-circuit current is related to irradiance. The Figure 35 shows the temperature dependence of the

I-V characteristic of a solar cell [32]:

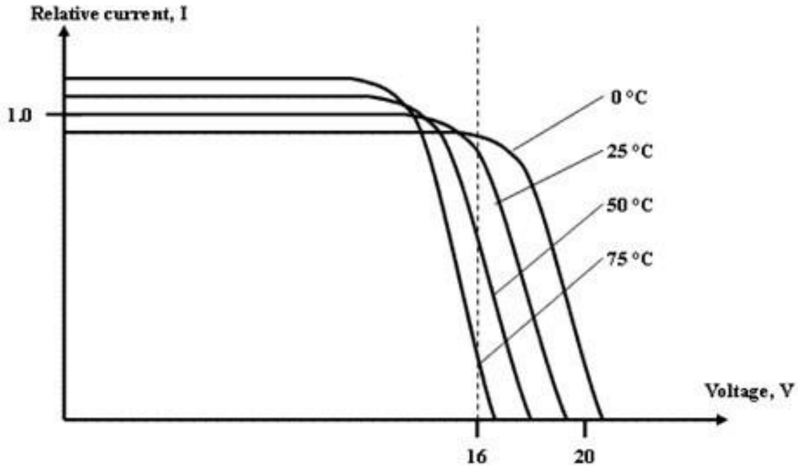


Figure 35 Temperature dependence of the I-V characteristic of a solar cell

From the graph, we can see that temperature could affect power output directly. The short circuit current slightly increased with temperature. Typically, the decrease of voltage is 2.3mV/°C. So, it is determined that temperature coefficient for open-circuit voltage is about -2.3mV/°C for a cell [32].

Voltage variation with temperature, for an individual module consisting of n cells connected in series is set equal to:

$$ {}^{dV_{oc}}\!/_{dT} = -2.3 \times \mathrm{nc\ mV/°C} \tag{4.32} $$

Short-circuit current (I_{sc}) of a module is proportional to the irradiance and open circuit voltage increases slightly with the ambient irradiance. It is shown in the Figure 36 that current will increase when irradiance increases [32]:

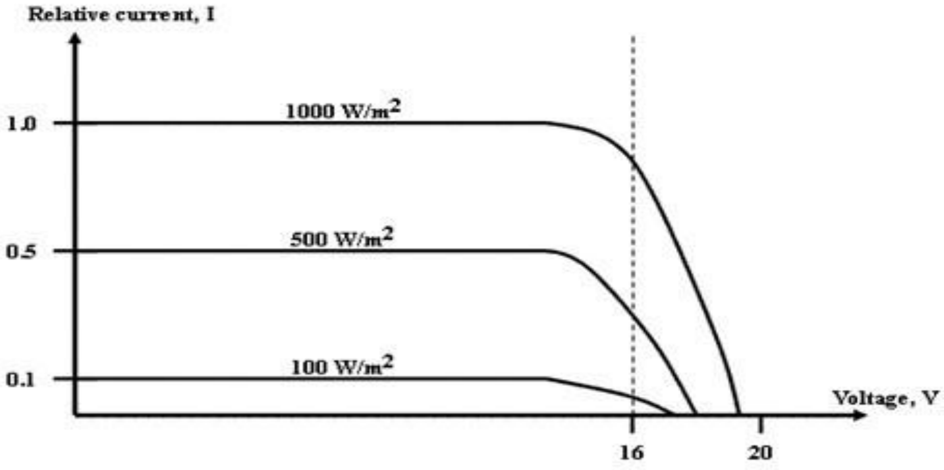


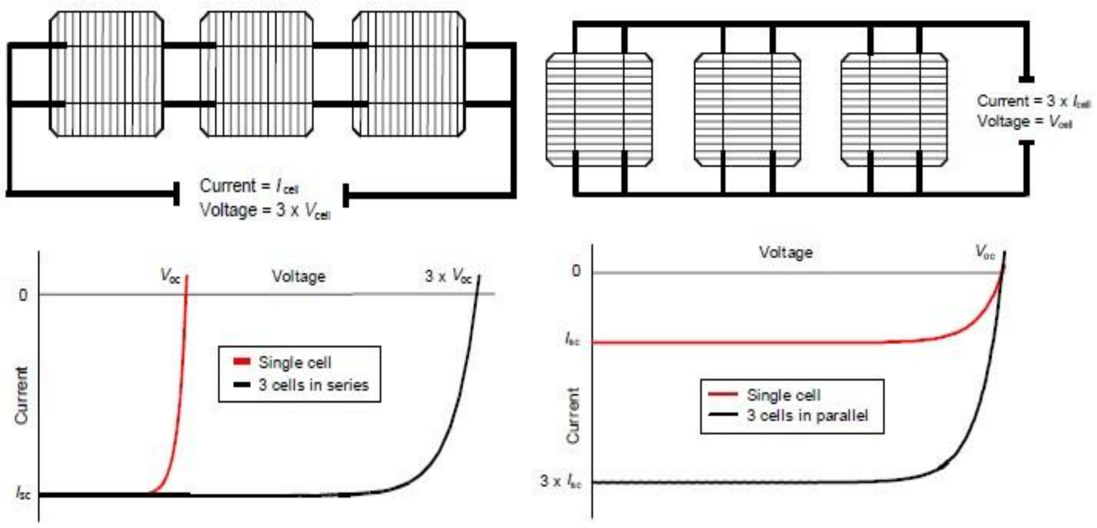
Figure 36 Irradiance dependence of the I-V characteristic of a solar cell

Equation (4.33) shows the design of PV generator current proportional to the irradiance:

$$\mathrm{I_{sc}(G) = I_{sc}(at\ 1\ kW/m^2) \times G(in\ kW/m^2)} \qquad (4.33)$$

I-V curve of series or parallel connected solar modules

Practically, solar modules could be made up of series connected cells or parallel connected cell. More recently, large modules have begun to be produced for building integrated systems and more cells are incorporated in each module. Figure 37 presents how the I-V curve is modified in the case when two solar cells are connected in series or in parallel [31].



a b

Figure 37 solar cells modules: (a) series connected (b) parallel connected

Figure 37 (a) shows three individual cells connected as a series string. The current output of the string is the same as the current of a single cell, whereas the voltage output of the string is 3 times as much as cells. Typically speaking, cell's number in a module in serious is around 33-36 solar cells due to the allowing voltage permitted by module manufacture.

Figure 37 (b) shows three individual cells connected as a parallel string. In this case, the current output of the string is equivalent to 3 times as much as current from each cell, whereas the voltage output of the string is equal to that of a single cell.

In current practice, the PV module parameters specified by manufacturer are mainly determined under special conditions, such as nominal or standard conditions. Table 16 gives the details of these conditions:

Table 16 PV module parameters

Reference conditions	**Standard conditions**
Irradiation: $G_{a,ref}$=800W/m^2	Irradiation: $G_{a,0}$=1000W/m^2
Ambient temperature: $T_{a,ref}$=20℃	Cell temperature: $T_{c,0}$=25℃
Wind speed: 1m/s	

Under reference condition, the following parameters are displayed:

- The ambient irradiation $G_{a,ref}$
- The ambient temperature $T_{a,ref}$

Under standard conditions, the following parameters are determined:

- The ambient irradiation $G_{a,0}$
- The cell temperature $T_{c,0}$

The fill-factor (FF) could be defined by maximum power, open-circuit voltage and short-circuit current which is expressed by Equation (4.34) [9].

$$p_{max} = v_m I_m = FF\, V_{oc} I_{sc} \tag{4.34}$$

The characterization of the PV module is completed by measuring the Normal Operating Cell Temperature (NOCT) which is defined as the cell temperature when the module operates under the reference conditions.

NOCT (usually between 42 and 46) is then used to determine the solar cell temperature T_c during module operation. [9]

$$T_c - T_a = \frac{NOCT-20}{0.8} G(kW/m^2) \tag{4.35}$$

Where T_a is ambient temperature

$$P_{max}(G, T_c) = FF \times I_{sc} \times V_{oc} \tag{4.36}$$

Thus, the result of PV output has been presented. Figure 38 summarizes the calculation of module parameters under operating conditions:

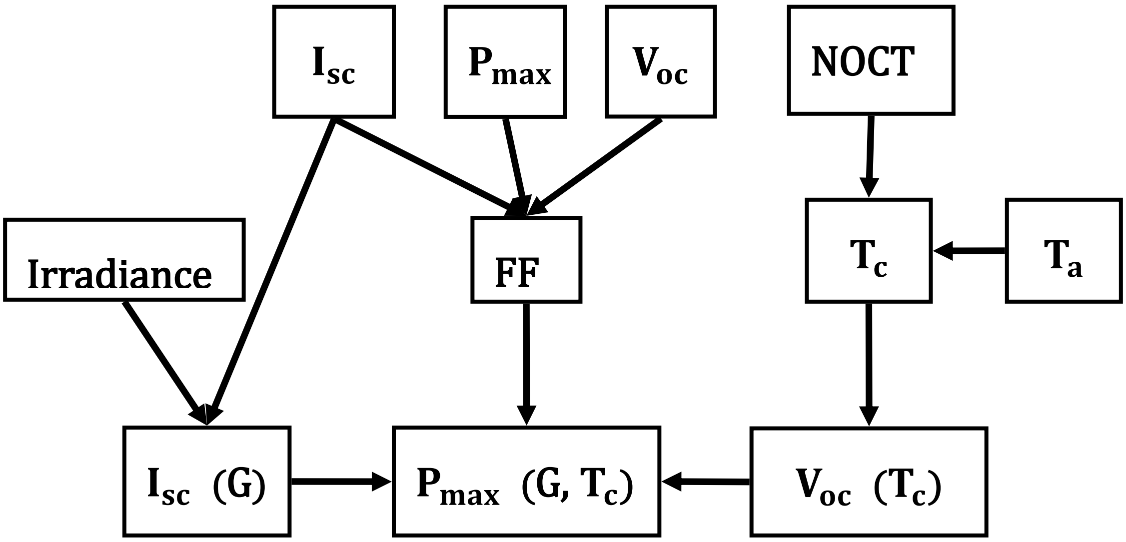


Figure 38 Calculation of the module operation parameters

4.4.3 The Procedure of Photovoltaic Output

The computer program in this research is designed in MATLAB to achieve the mathematical model for calculating the various components of the system. The program is run with the following steps:

1. Predict G_0 (G_0 is extraterrestrial radiation).

2. Determine G_{cb} , G_{cd} and G_c (G_{cb} Clear sky beam radiation; G_{cd} Clear sky diffuse radiation; G_c Clear sky radiation)

   $G_{cb}=G_0 * \tau_b$ (τ_b Beam transmission coefficient)

   $G_{cd}=G_0 * \tau_d$ (τ_d Diffuse transmission coefficient)

   $G_c=G_{cb}+G_{cd}$

3. Calculate solar radiation G considering weather. (Including clear sky days, cloudy days and rainy days)

$G=G_c * F$ (F is random number derived from normal distribution considering weather)

4. Input ambient temperature T_a, and then generate solar cell temperature.

$$T_c = \frac{\text{Normal operating cell temperature(NOCT)}-20}{0.8} + T_a$$

5. Set the number of cells in series and in parallel.

$$N_s = \frac{\text{Manufacture's voltage of a module}}{\text{Manufacture's voltage of a cell}}$$

$$N_p = \frac{\text{Manufacture's current of a module}}{\text{Manufacture's current of a cell}}$$

6. Determine short-circuit current and open-circuit voltage of a module

$I_{sc} = I_{sc}$ (manufacture's value under standard condition at 1 kW/m^2) $*$ G (in kW/m^2)

$V_{oc}(T_c) = V_{oc}$ (manufacture's value under standard condition) -0.00023 $* N_s * (T_c\text{-}25°\text{C})$

7. Calculate fill factor FF

$$FF = \frac{\text{Maximum power point}}{I_{sc}\,V_{oc}}$$

8. Output maximum power point

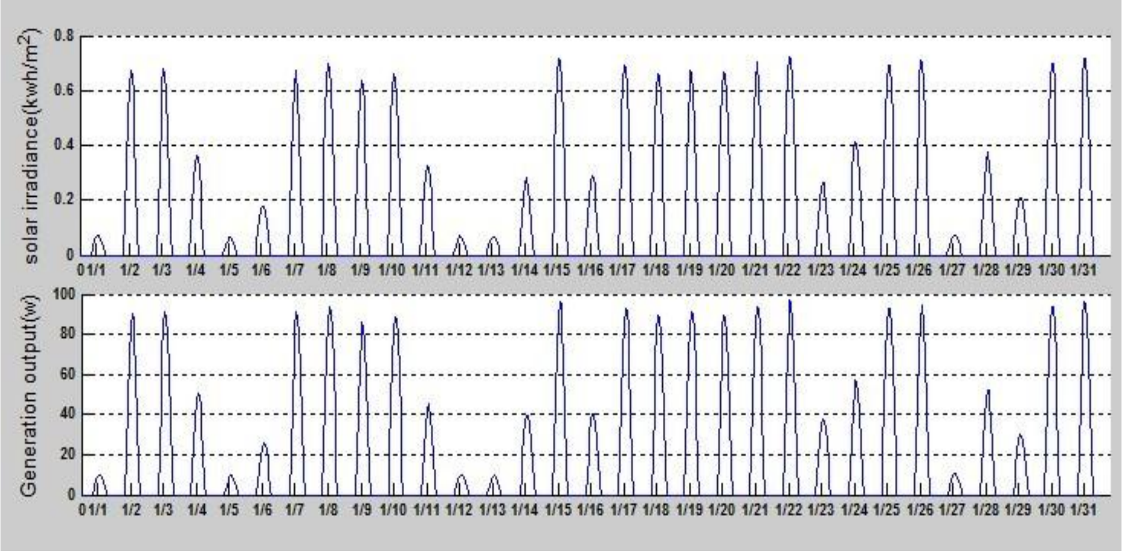
$$P_{max} = FF * V_{oc}(T_c) * I_{sc}$$

4.4.4 Simulation Results

As solar radiation is relative to Geographical location and seasonal difference, it is essential to select two cities with great difference in latitude and longitude for the modeling. Seasonal difference will also be considered. The necessary parameters defining the current-voltage relationship of a CANROM30 solar panel are provided in Appendix B. These data are used in all of the PV related analyses in this thesis. Honolulu and Seattle are chosen as two cities for modeling and the corresponding geographical data are shown as the following table.

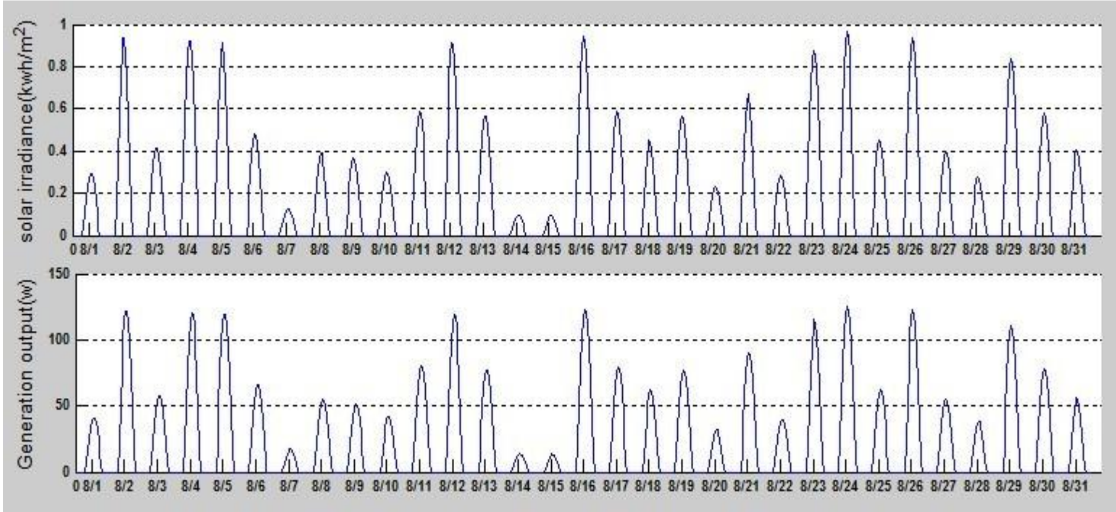
Table 17 Honolulu and Seattle's geographical location and climate type

city	latitude	longitude	altitude	Climate type
Honolulu	21°6'	157°31'	2m	Tropic
Seattle	47°36'	122°19'	123m	Mid-latitude



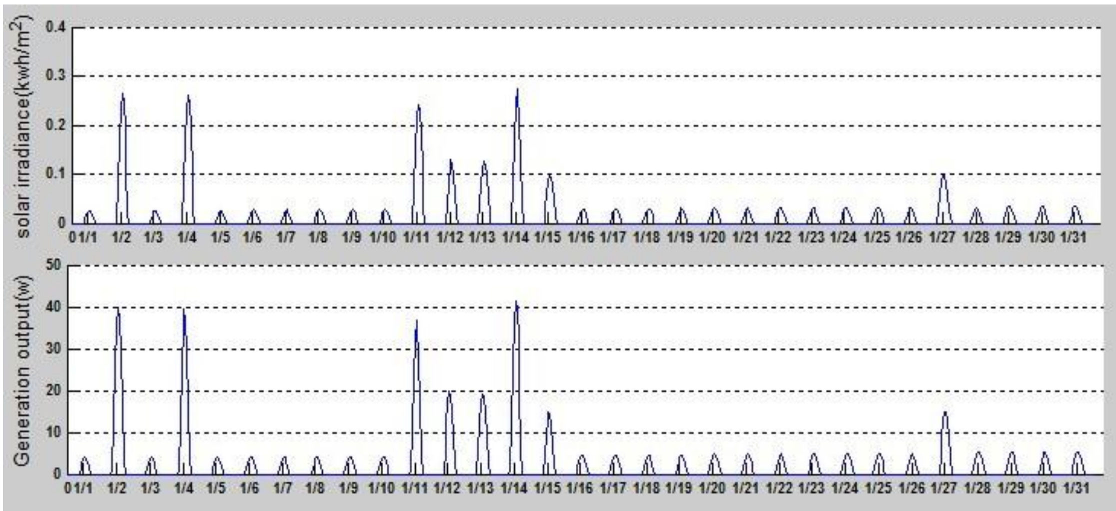
Monthly PV output

Figure 39 Hourly solar irradiance and generation output in Honolulu on January



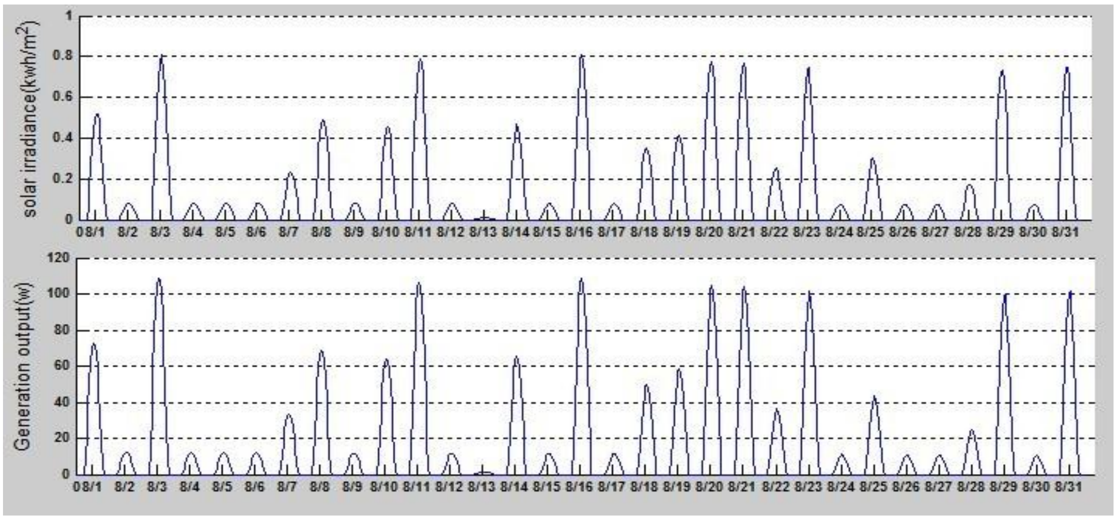
Monthly PV output

Figure 40 Hourly solar irradiance and generation output in Honolulu on August



Monthly PV output

Figure 41 Hourly solar irradiance and generation output in Seattle on January



Monthly PV output

Figure 42 Hourly solar irradiance and generation output in Seattle on August

As depicted in Figure 39-42, solar radiation started in the morning of one day and then achieves the daily peak value at noon. Finally, it turns to zero after the sunset time. The seasonal difference is existed in Honolulu but not palpable. In Seattle, the peak radiation in summer is almost more than twice as that in winter. It also shows solar radiation in Honolulu is much more than that of Seattle in the same season. Even in winter, it is a bit more of Honolulu than that of Seattle in summer.

Figures 43 and 44 show the monthly solar radiations. It is obviously that solar radiations in Seattle vary a lot from winter to summer while it is not so significant in Honolulu.

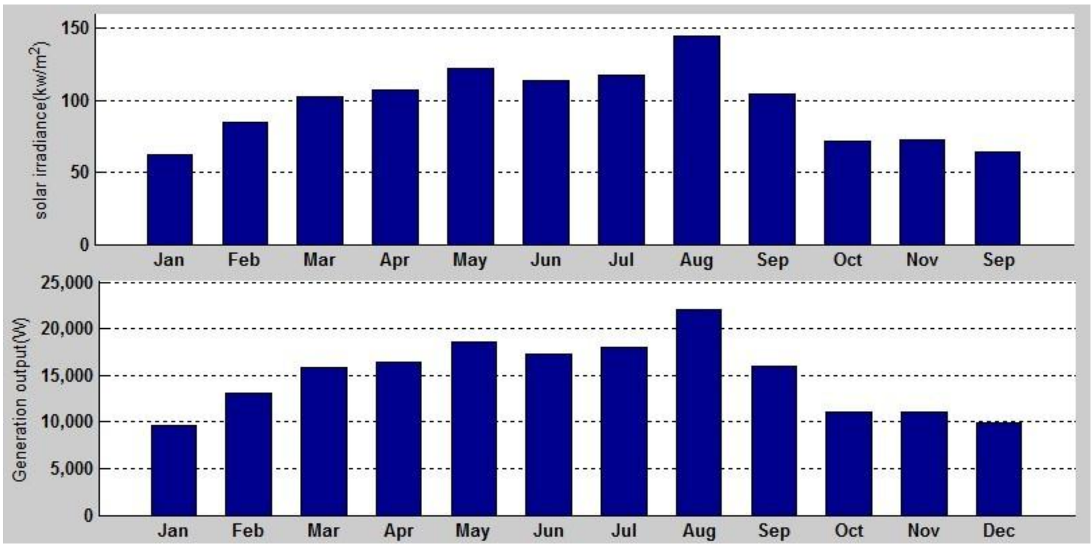


Figure 43 Monthly solar irradiance and generation output in Honolulu of the year

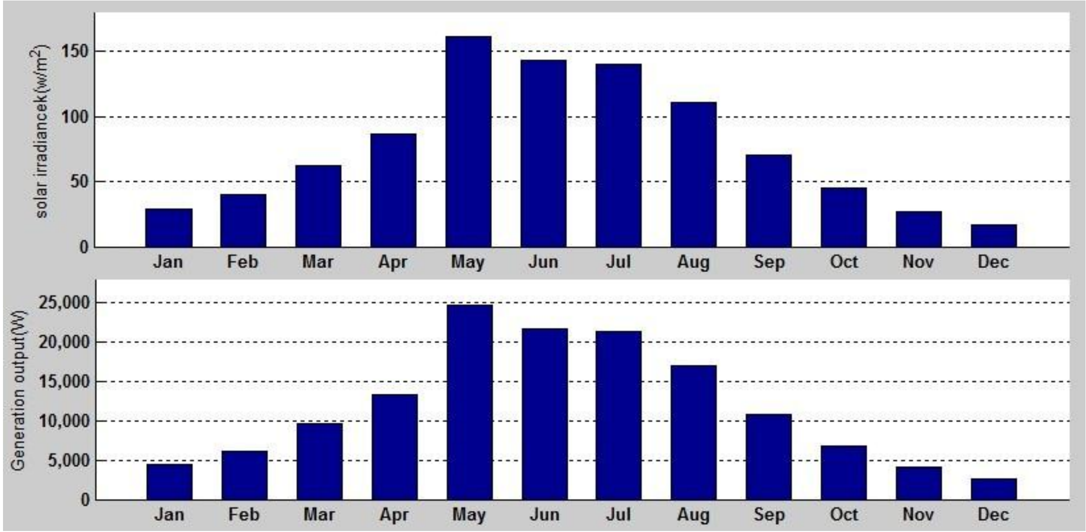


Figure 44 Monthly solar irradiance and generation output in Seattle of the year

4.5 Representation of Load Models

Hourly load duration curve

When the load curve is arranged in the order of descending magnitude, the curve thus obtained is determined as a load duration curve. Figure 45 shows representations of the hourly load curve and hourly load duration curve.

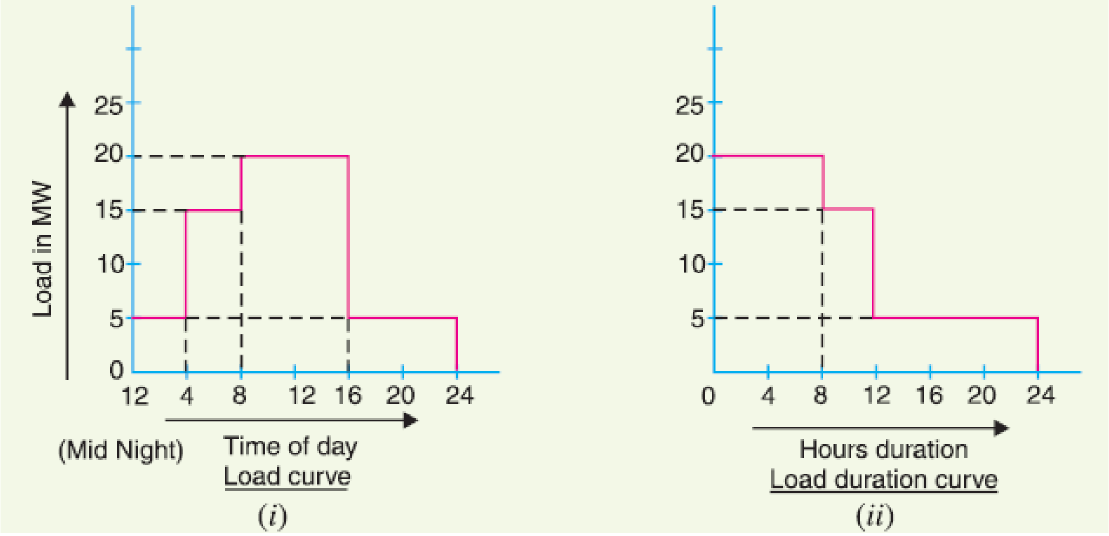


Figure 45 Load curve and load duration curve

It is clear from load duration curve that load maintains 20MW for 8 hours, 15MW for 4 hours and 5MW for 12 hours.

Daily peak load variation curve

Daily peak load model means the load for each day is represented by its daily peak load. When the daily peak load is arranged in the order of descending magnitude, the curve thus obtained is determined as a daily peak load variation curve. (Figure 46)

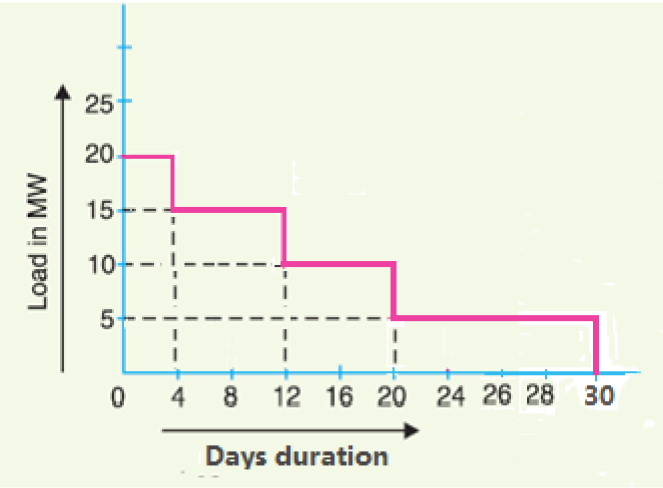


Figure 46 Daily peak load variation curve

Load model for RBTS

The Roy Reliability Test System (RBTS) [33] contains a very useful load model which expressed in a chronological mode so that hourly, daily, weekly and seasonal patterns can be developed (Appendix C).

The weekly load is presented in terms of the percentages of the annual peak load; daily load in terms of the percentages of weekly peak load; hourly load in terms of the percentages of daily peak load. Once the annual peak load, weekly percentage of load of each week in per year, daily percentage of load in each week and 24-hour percentage of load in each day are determined, the annual hourly load curve can be developed. The RBTS load model has been used in the simulation analyses in this research.

4.6 Energy Storage Model

The outputs of wind turbine generators or photovoltaic generators are intermittent because wind or sunlight resources which are used to produce electricity cannot be gained all the time. Therefore, it is obviously that the energy storage system plays an important role in some of wind and solar energy generating system, especially in small stand-alone systems. Up to now the energy storage technologies applied in electric power systems typically includes: flywheels, pump storage and storage batteries.

The operating principle of the energy storage facility can be summarized: When generation output exceeds load demand, the excess energy will be stored into energy storage system until it achieves the maximum allowable storage capacity. Contrarily, when generation output cannot satisfy load demand, the energy storage system will discharge until it reduced to the minimum allowable storage capacity.

The energy storage state could be calculated using the following steps [34]:

1. Compute the surplus generation from load and generation by the equation below:

$$\mathrm{SG_t} = \mathrm{G_t} - \mathrm{L_t} \tag{4.37}$$

Where, t is the time serious. If $\mathrm{SG_t}$ is positive, means the energy storage system is under charged or maintain its maximum storage capacity, if $\mathrm{SG_t}$ is negative, the energy storage system will discharge to provide extra energy to improve the balance of power output and loads.

2. Determine the energy storage state by using following equation:

$$\mathrm{ES_{t+1}} = \begin{cases} \mathrm{ES_{min}} & \mathrm{ES_t + SG_t \le ES_{min}} \\ \mathrm{ES_t + SG_t} & \mathrm{ES_{min} < ES_t + SG_t \le ES_{max}} \\ \mathrm{ES_{max}} & \mathrm{ES_{max} < ES_t + SG_t} \end{cases} \tag{4.38}$$

Where $\mathrm{ES_{min}}$ and $\mathrm{ES_{max}}$ are the minimum and maximum allowable storage levels of the energy storage facility.

4.7 Summary

Generation system reliability models of power systems using wind energy, solar energy and conventional energy are developed by using COPT and MCs approach in this chapter.

The random weather resources and the equipment parameters of the generating unit are the major factors in reliability analyses of power systems while wind energy or solar energy is used. The sequential MCs techniques can be used to simulate wind speeds, then the power available from a WTG can be determined from a function describing the relationship between the wind speed and output power. Also, a widely used solar radiation method, determined by Hottel's equation is associated to MCs techniques to generate solar radiation levels. The generated power of a photovoltaic generating unit is obtained based on the voltage-current characteristics of the generating unit using the simulated solar radiation data generated in MATLAB. In addition, an energy storage model is developed based on the conditions of comparing the output of generators with the load to charge or discharge appropriately in order to improve the probability of the system. The adequacy evaluation of power system with different penetration levels of wind and solar energy (also, with the aid of storage system) is illustrated in next chapter.

Chapter 5 Reliability impact on large scale utilization of wind or solar energy integrated into power grid system

5.1 Introduction

The world-wide demand for renewable energy especially in large grid-connected applications has been growing rapidly owing to the limited fuel resource and environmental impact from large amount carbon dioxide emission over the last two decades. There is a tremendous potential for wind and solar energy projects in grid-connected applications. Therefore, it is important to evaluate the impacts of utilizing significant amounts of wind or solar energy sources in large on-grid power systems.

Key parameters that influence the reliability of combined electricity power system, such as the wind or solar penetration level, the system load level, the risk based equivalent capacity ratio, the energy storage level and the location sites are all considered and are illustrated respectively in each single case study. The evaluation criterions of system reliability which examined in terms of the LOLE, LOEE, and LOLF, have been mentioned in chapter 4.

The conventional generating unit ratings and reliability data from the RBTS are used in the following analyses to illustrate the proposed concepts. RBTS is acronym of Roy Billinton Test System which contains 2 generator bus, 5 load bus, 9 transmission lines and 11 generating units. The annual system peak load of RBTS is 185MW while total installed generating capacity is 240MW [33]. The conventional generating unit ratings and reliability data of the RBTS are given in Appendix C. Load profile are provided in Appendix D. Besides this, a wind farm is assumed to be composed of a number of identical wind turbine generators

(WTG). A solar park is considered to be composed of a number of identical PV generating units, which are composed of a number of identical panels. The necessary parameters of a VESTAS V29 225-50 wind turbine and a CANROM30 solar panel are provided in Appendix B and Appendix C respectively. These data are used in all of the WTG and PV related analyses in this thesis.

5.2 Case study 1: Additional Renewable Energy with Different Penetration Levels Added Based on RBTS

The following case is aims to figure out the relationship between the value of LOLE and additional WTG or PV capacity added to the RBTS. The wind or solar penetration levels are assumed to be 5 hierarchies which displayed in Table 18 from low level to high level. The scenarios are established as follow: 1. Conventional generators; 2. WTG; 3. PV (Honolulu); 4. PV (Seattle), four kinds of energy added separately into RBTS system with the amount of capacity increase from 0 to 50MW. The original generation system data are based on a modified RBTS. The added conventional capacity is in the form of the thermal unit with force outage rate of 0.02 and WTG/PV unit data are come from.

After MCS analysis, the results shown that with the increase levels of expanded capacity, LOLE index decreases and therefore system stability is enhanced. The Figure 47 illustrates that: 1. LOLE in all situations have significant decreases at the beginning regions from 0MW to 10MW. Then it tends to plat toward to the end. In other words, the slop gain of LOLE is gradually descending. If we continue increase the penetration level of energy, finally we will find that the influences of adding more capacity have almost no contribution to the whole system; 2. Wind turbine generator and PV generator produce various reliability indices with an equal increasing capacity due to their different characteristics. Compare with PV generator, wind turbine generator performance better in aspect of improving power system reliability (lower LOLE); 3. According to various insolation data from Honolulu and Seattle, different reliability indices will be observed from PV generators. It can be seen from the Figure 47, PV generator under tropical climate (more sunshine amount) can operate more electricity energy to promote system reliability comparing to it under temperate climate with same total capacity.

Table 18 LOLE of RBTS with different renewable penetration level integrated

Capacity Added (MW)	Penetration level	Conventional Generator	WTG Added	PV Added (Honolulu data)	PV Added (Seattle data)
0	0%	1.383	1.383	1.383	1.383
10	4%	0.473	0.961	1.158	1.284
20	7.69%	0.201	0.801	1.01	1.225
30	11.11&	0.079	0.704	0.919	1.178
40	14.29%	0.035	0.645	0.845	1.142
50	17.24%	0.012	0.605	0.789	1.111

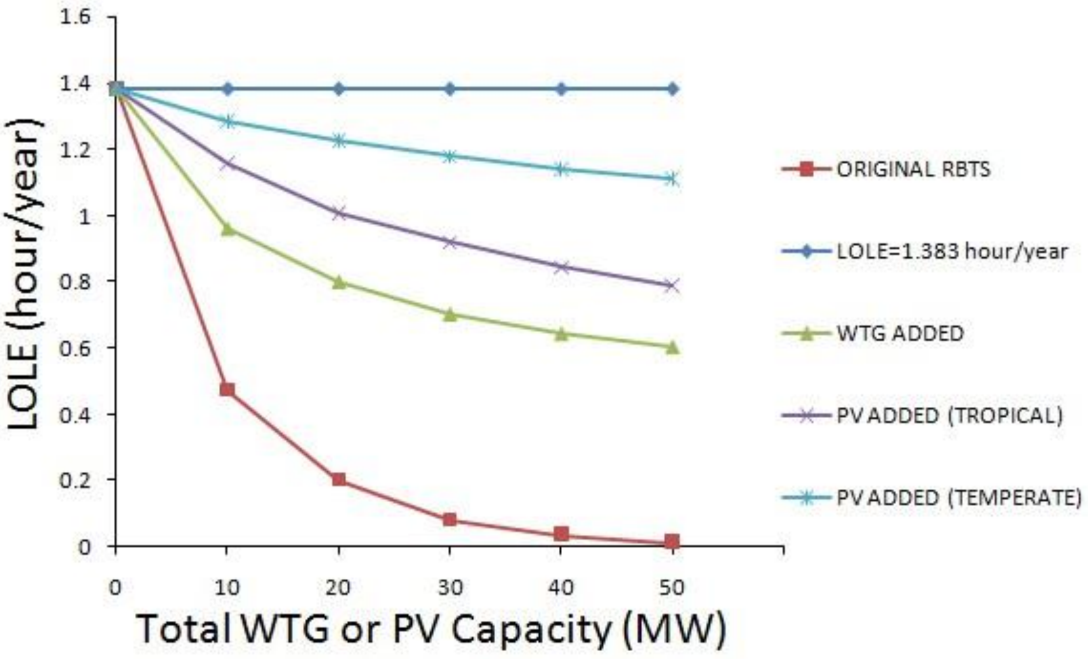


Figure 47 LOLE versus WTG or PV expanded capacity in RBTS

5.3 Case study 2: Incremental Peak Load Carrying Capability

Peak load carrying capability (PLCC), by definition, represents the peak load amount while system reliability is maintaining at a certain level. Where incremental peak load carrying capability (IPLCC) means the increase amount or benefit amount in peak load which the additional generations are supplied while system reliability is maintaining at a certain level. In this case, IPLCC act as a criterion to evaluate the electricity system reliability situation [35].

It can be seen from Figure 48 that LOLE indices of RBTS before and after adding 20MW WTG or PV generators are plotted as functions of annual peak load, which is varied from 170MW to 200MW with each 5MW as an interval. Simulation result shows that the LOLE of original RBTS with 240MW installed capacity and 184MW annual peak load in this case is 1.383 and peak load carrying capability is 184MW at that time [36-38]. LOLE curves of RBTS combined with wind energy conversion system or solar energy conversion system, are plotted and regarded as functions of annual peak load. The corresponding peak load carrying capability is the intersection point between the straight line which is maintaining at 1.383 and each curve shown in Figure 48. The differential section between each peak load carrying capability and original peak load carrying capability 184MW means the load carrying capability benefit.

From simulation data of additional wind energy conversion system (WECS) or solar energy conversion system (PECS), IPLCC of WTG is 4.63 while IPLCCs of PV are approximately 1.38 and 3.32 under temperature data and tropical data used respectively. Furthermore, it can be clearly figured out from the graph that load carrying capability benefits are relatively independent of the risk level criterion because the differences between values of IPLCC at different risk level are relatively small.

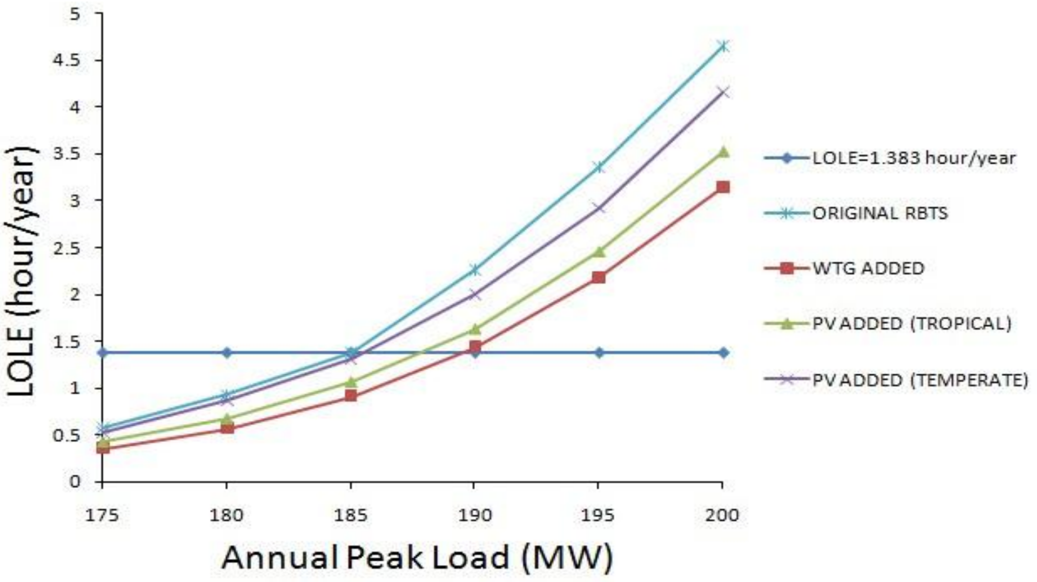


Figure 48 LOLE versus annual peak load

5.4 Case study 3: Renewable Energy Substitute Conventional Generator with Different Penetration Levels Based on RBTS

Case study 3 is tested with replacing conventional generators by WTG with different penetration levels from 0MW to 50 MW. Same procedures are also tested for PV.

It can be seen from Figure 49 that: 1. with the increase of penetration level of non-conventional capacity, LOLE index increases. More renewable energy used to replace conventional generators, worse situation (Higher LOLE) occur as shown according to the graph that LOLE increase fast from 30MW to 50MW. In other words, the slope gain of LOLE is gradually ascending. Power system adequacy will be strongly affected if more WTG or PV generators added; 2. Wind turbine generator and PV generator produce various reliability indices with an equal increasing capacity due to their different characteristics. WTG has lower LOLE than PV generators with same amount of substitution. PV generators under tropical climate have lower LOLE comparing to it under temperate climate with same amount of substitution. This is also the case shown in the above case study 1.

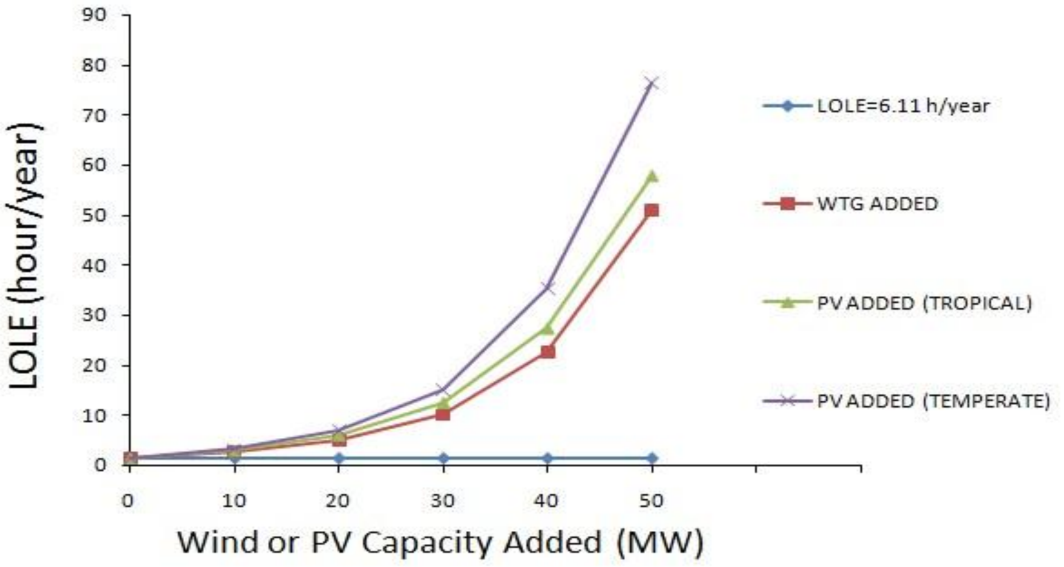


Figure 49 LOLE versus WTG or PV penetration level in RBTS

5.5 Case study 4: Risk Based Equivalent Renewable Capacity Ratio

The equivalence in this case is referred to the ratio of WTG or PV capacity to the conventional unit capacity when their generating capacities are equal to each other. This ratio is called the risk-based equivalent capacity ratio (RBECR) in this thesis. If the RBECR is 5, then 1 unit of conventional generating capacity is equivalent to 5 unit of WTG (or PV) capacity, or 1 unit of WTG (or PV) is equivalent to 0.2 unit of conventional generating unit.

Table 19 Comparison of the reliability indices of RBTS after adding 20MW in renewable energy's or conventional units

Reliability Indices	WTG	PV(Tropical)	PV(Temperate)	Conventional units
LOLE	0.8009	1.0104	1.2249	0.2006
LOEE	7.2434	9.2984	11.685	1.8392
LOLF	0.3356	0.2515	0.2663	0.0445

One comparison has been made between adding additional 20MW conventional generators and WTG/PV generators into RBTS. The results can be seen from the Table 19 that WECS or PVCS does not provide the same reliability contribution as the conventional units does. This kind of comparison is used to learn that renewable energy do less effect on power system stability compare to that of conventional units.

So, new studies should be examined in order to know how much extra WTG or PV units are needed to maintain a specific reliability criterion comparing with conventional generators when adding or replacing energy units into the RBTS.

The tests are based on following conditions: The system LOLE in the original RBTS is 1.383 hours/year. It is assumed that this value of LOLE is acceptable for the system under study and chosen as the risk criterion.

1) One of the 5 MW hydro units is first removed from the RBTS and replaced by WTG and PV units separately. Figure 50 shows the variation of the LOLE when the WTG and PV (both two kinds of climates) units penetrating system. The LOLE criterion of 1.383 hours/year is also shown in this graph and it increases from 1.383 hours/year to 2.029 hours/year after the 5MW hydro unit is removed from the RBTS with no other units added. According the Figure 50 that the LOLE decreases with increasing WTG or PV capacity. The speeds of decrease are not the same when adding wind farm or solar parks. It is not enough for 5MW WTG or 5MW PV units to replace a 5 MW hydro unit in order to have the same LOLE criterion.

Continuing add WTG/PV units in order to get the same LOLE as original system has, results shown in Table 20 that the LOLE is restored to the criterion 1.383 if: 21.51 MW of WTG is added; 38.62 MW PV units which are located at Honolulu is added and not possible for PV plant locate at Seattle. In another words, 21.51 MW (38.62 MW) of WTG (PV tropical climate) is able to replace a 5 MW conventional generating unit in this case.

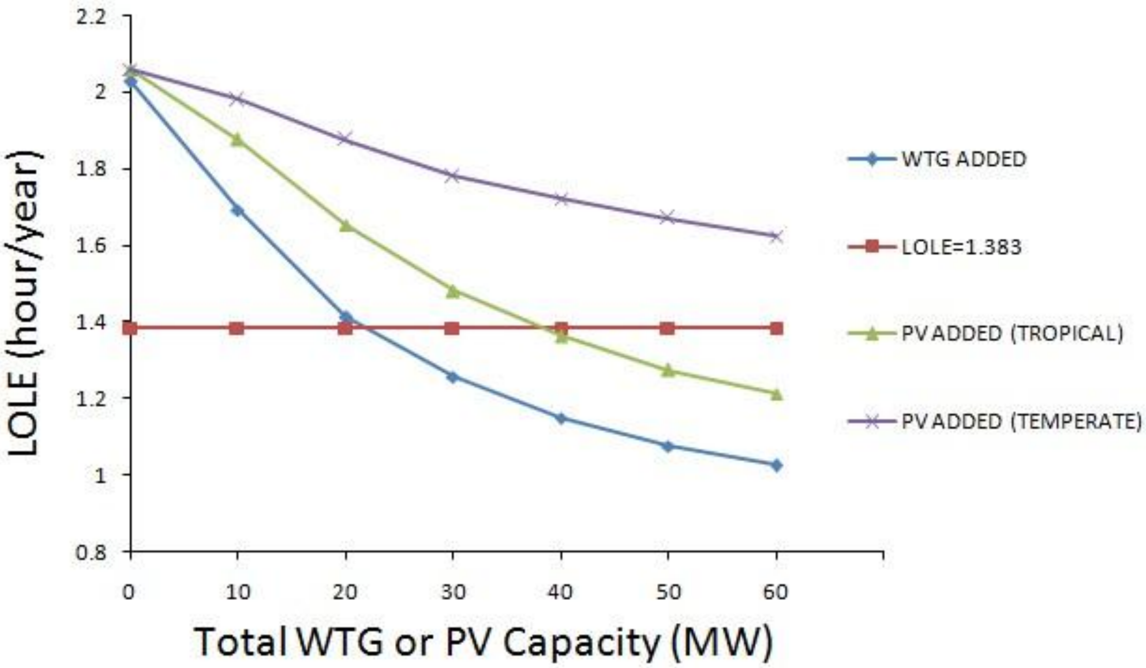


Figure 50 LOLE versus replaced WTG or PV capacity when a 5MW hydro unit is removed from RBTS

Table 20 WTG or PV Capacity relative to a 5 MW conventional generation unit

Case	WTG	PV	PV (Seattle)
Risk based equivalent capacity ratio	2.151	3.862	Not Possible

2) A further study was continued then by removing a 10 MW thermal unit from the RBTS and replaced by renewable energy. The results are shown in Figure 51 and Table 21. It can be seen that when a 10MW thermal unit is replaced, it is not possible to maintain the LOLE reliability criterion of 1.383 hours/year by replacing the conventional unit with PV. The system reliability level can, be reached by adding 122.48 MW of WTG.

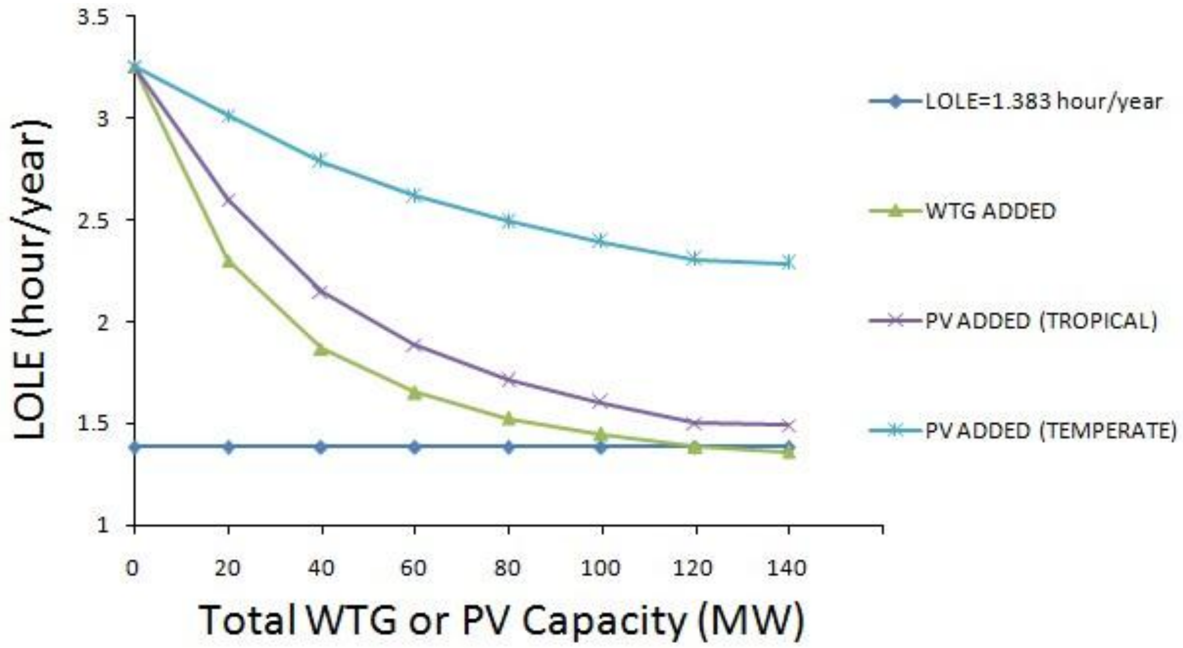


Figure 51 LOLE versus replaced WTG or PV capacity when a 10MW thermal unit is removed from RBTS

Table 21 WTG or PV Capacity relative to a 10 MW conventional generation unit

Case	WTG	PV (Honolulu)	PV (Seattle)
Risk based equivalent capacity ratio	12.248	Not Possible	Not Possible

3) A final study was conducted in which a 10MW thermal unit and a 5MW hydro unit were removed from the RBTS. The results are shown in Figure 52 and Table 22. It can be seen from Figure 52 and Table 22 that if a 15MW conventional generating units are removed from the RBTS, the system reliability level cannot be maintained by adding WTG or PV.

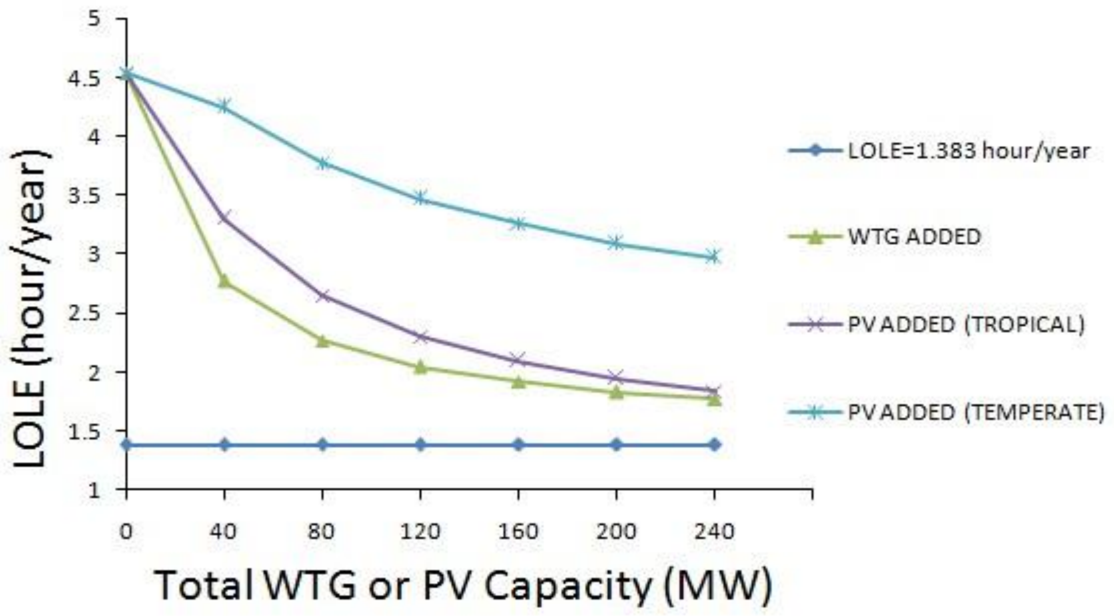


Figure 52 LOLE versus replaced WTG or PV capacity when a 5MW hydro unit and a 10MW thermal unit are removed from RBTS

Table 22 WTG or PV Capacity relative to a 15 MW conventional generation unit

Case	WTG	PV (Honolulu)	PV (Seattle)
Risk based equivalent capacity ratio	Not Possible	Not Possible	Not Possible

5.6 Case study 5: Energy Storage in RBTS Incorporating Solar Energy Conversion System

Storage facility may not utilized in those on-grid solar energy systems because of its very high cost, but it still can be widely used to improve the reliability of small isolated power system [39-43]. It is, however, of interest to investigate the possible impacts of energy storage on large on-grid systems that utilize significant amount of solar energy. In this case, it is assumed that 10% of total PV capacity is proper for its energy storage capacity. Table 16 presents the LOLE in hours/year for the cases when conventional unit is replaced by PV (Seattle data) unit without energy storage system while Table 17 shows the LOLE in hours/year with energy storage system. It can be figure out from Table 17 that the LOLE values reduce for each case with the comparison of non-energy storage system.

It is assumed that there are no restrictions on the energy storage charging and discharging capability. LOLE decreases with the addition of storage capacity. From Tables 23 and 24, it can also be indicated that slight reliability benefits can be obtained by applying energy storage in large on-grid applications. These benefits will, however, have to be evaluated by incorporating the costs and practicality of creating the required storage facilities.

Table 23 Reliability indices for different cases when conventional unit is replaced by PV (Seattle data) unit without energy storage system

Capacity	LOLE	LOEE	LOLF
10MW	3.2567	32.4708	0.6332
20MW	6.9535	76.6711	1.2866
30MW	15.0578	170.8619	2.9923
40MW	35.3315	391.0087	6.8663
50MW	76.3495	888.3117	13.6996

Table 24 Reliability indices for different cases when conventional unit is replaced by PV (Seattle data) unit with energy storage system 10%

Capacity	LOLE	LOEE	LOLF
10MW	2.9632	28.8574	0.5637
20MW	6.1622	69.2456	1.0543
30MW	13.1445	156.1403	2.4664
40MW	30.2635	360.8984	5.5763
50MW	64.9721	827.7575	10.5756

5.7 Summary and Conclusions

From this chapter, we can learn that electric power system reliability of replacing or adding a single wind farm or solar park have various contributions in regard to selected parameters such as system peak load, incremental peak load carrying capability, risk based equivalent renewable capacity ratio, renewable energy penetration levels, site resource availability and energy storage capability. All of these mentioned factors do impacts on the generating system reliability since measured by the reliability indices. In the study shown in this chapter, the system reliability can be maintained if a 5 MW unit is replaced by either WTG or PV units in Honolulu, but the required capacity is not the same for each case considered. If a 10 MW conventional unit is removed from the RBTS, the reliability criterion cannot be maintained by replacing this unit by PV. The system reliability cannot be maintained if a 15 MW unit is replaced by either WTG or PV in the RBTS. The addition of conventional generators contributes much more than that of an equal capacity addition of wind turbine generators or photovoltaic generators. In addition of energy storage system, LOLE slightly decreases with the addition of storage capacity. It can also be indicated that slight reliability benefits can be obtained by utilizing energy storage in large on-grid applications. Furthermore, it can be clearly figured out that load carrying capability benefits are relatively independent of the risk level criterion because the differences between values of IPLCC at different risk level are relatively small.

Chapter 6 Conclusions and Future Work

6.1 Conclusions

Since the utilization of wind and solar energy plays an important role of planning for the future development of the electricity power supply. The encouragement from the policy side appears more and more all over the world and with many producer expected to replace the alternatives for conventional generators, the intermittent nature of renewable resources now are getting a huge impact on the system reliability.

The aim of this project is to analyze and look into the effect of intermittent renewable generation, especially wind and solar, on system reliability and determine their reliability indices.

In this project, all generation system reliability models and simulation processes were developed using Mat lab. Data from the Roy Billinton Test System also used in the system modeling.

This thesis employs capacity outage probability approach and Monte Carlo simulation approach for generating capacity adequacy evaluation of conventional power systems. The conventional generator model works well with both of the two approaches. However, sequential Monte Carlo simulation method also has a good performance in the reliability assessment of wind and solar generators. The technique combines the development of the generation model, the chronological load model and the energy storage model to determine the reliability indices.

In summary, it can be concluded that system peak load, incremental peak load carrying capability, risk based equivalent renewable capacity ratio, renewable energy penetration levels, site resource availability and energy storage capability do varying degrees impacts on the generating system reliability since measured by the reliability indices.

In briefly description, the system reliability can be maintained if a 5 MW unit is replaced by either WTG or PV units in Honolulu, but the required capacity is not the same for each case considered. If a 10 MW conventional unit is removed from the RBTS, the reliability criterion cannot be maintained by replacing this unit by PV. The system reliability cannot be maintained if a 15 MW unit is replaced by either WTG or PV in the RBTS. The addition of conventional generators contributes much more than that of an equal capacity addition of wind turbine generators or photovoltaic generators. In addition of energy storage system, LOLE slightly decreases with the addition of storage capacity. It can also be indicated that slight reliability benefits can be obtained by utilizing energy storage in large on-grid applications. Furthermore, it can be clearly figured out that load carrying capability benefits are relatively independent of the risk level criterion because the differences between values of IPLCC at different risk level are relatively small.

6.2 Future work

Due to the simulation results in this study, loss of load in any part of the system can cause impacts. In order to reduce the frequency and duration of these events, it is necessary to take some aspects into further consideration.

- Load shedding

Load shedding is needed to avoid a huge failure for electricity supply. It shed enough load to relieve the overloaded equipment before there is loss of generation, line tripping, equipment damage, or a chaotic random shutdown of the system.

- Reliability cost and reliability worth

An investment of improving system reliability will be required in the future work to gain some economic benefits. Reliability cost Vs reliability worth (benefit) evaluation can enable utilities to make objective decisions about investments and maintenance for enhancing supply reliability.

- Operating reserve

The operating reserves was not mentioned in this thesis because this study was involved in system adequacy section so that the security criteria was neglected, whereas the operating reserves is needed in the further study since it can be quickly tapped to respond to a system emergency and maintain a reliable supply of electricity.

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Appendix A

TECHNICAL DATA FOR VESTAS V29 225-50, 29 !O! TURBINE

VESTAS-manufacturer
V29-type/version
225-rated power (kW)
50-secondary generator power (kW)
29-rotor diameter (m)
!O!-tower type (tubular)

Appendix B

PARAMETERS DEFINING THE CURRENT-VOLTAGE RELATIONSHIP OF A CANROM30 SOLAR PANEL

DESCRIPTION	VALUE	DESCRIPTION	VALUE
Number of series group in parallel	2	Reference MPP current	2A
Number of modules in series	1	Reference open circuit voltage	19.5V
Area per model	0.5m^2	Reference short circuit current	2.6A
Tracking method	No	Array resistance	0.06Ω
Collector slope	60 degree	Wind speed correction factor	1
Collector azimuth	0 degree	Alpha	0.0025
Reference array operating temperature	25℃	Beta	0.5
Reference radiation level	1000w/m^2	Gamma	0.0029
Reference MPP voltage	16V	Solar cell absorbance	0.9
Front panel emmissivity	0.95	Back panel emmissivity	0.9
Front panel transmittance	0.95	Back panel transmittance	0.9

Appendix C

GENERATING UNIT RATINGS AND RELIABILITY DATA FOR THE RBTS

Rated power	**(MW)**	**Unit type No. of units**	**Failure rate (f/year)**	**Repair time (hour)**	**Forced outage rate (FOR)**
(FOR)	5	hydro	2	45	0.010
0.010	10	thermal	1	45	0.020
0.020	20	hydro	4	55	0.015
0.015	20	thermal	1	45	0.025
0.025	40	hydro	1	60	0.020
0.020	40	thermal	2	45	0.030

Appendix D

LOAD DATA

Weekly peak load as a percentage of annual peak load

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

Daily peak load as a percentage of weekly peak load

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

Hourly peak load as a percentage of daily peak load

Hour	Weekday	Weekend	Weekday	Weekend	Weekend	Weekend
12-1 am	63	75	64	74	67	78
1-2	62	73	60	70	63	72
2-3	60	69	58	66	60	68
3-4	58	66	56	65	59	66
4-5	59	65	56	64	59	64
5-6	65	65	58	62	60	65
6-7	72	68	64	62	74	66
7-8	85	74	76	66	86	70
8-9	95	83	87	81	95	80
9-10	99	89	95	86	96	88
10-11	100	92	99	91	96	90
11-12 pm	99	94	100	93	95	91
12-1	93	91	99	93	95	90
1-2	92	90	100	92	95	88
2-3	90	90	100	91	93	87
3-4	88	86	97	91	94	87
4-5	90	85	96	92	99	91
5-6	92	88	96	94	100	100
6-7	96	92	93	95	100	99
7-8	98	100	92	95	96	97
8-9	96	97	92	100	91	94
9-10	90	95	93	93	83	92
10-11	80	90	87	88	73	87
11-12	70	85	72	80	63	81

Appendix E

Matlab Code Used In the Thesis

Conventional generator ouput

```
while calculationtime<10001
a=1;
a1=1;
a2=1;
a3=1;

out1=zeros(8736,1);
out2=zeros(8736,1);

while a1<8737
   out1(a1,1)=1;
   a1=a1+1;
end
for a2=1:2;
      t1=fix(8691*rand(1));

      a3=t1+1:t1+46;
      a3=fix(a3);
      out1(a3,1)=0;

end
while a<8737
   out2(a,1)=5*out1(a,1);
   a=a+1;
end
```

Hourly duration peak load

```
clc;
peak_load=184;
i_load=1;
j_load=1;
m_load=1;
n_load=1;
x_load=1;
y_load=1;
k_load=1;
out_load=zeros(52,1);
out_load1=zeros(52,1);
out_load2=zeros(7,1);
out_load3=zeros(28,1);
out_load4=zeros(24,1);
out_load5=zeros(8736,1);
out_load6=zeros(24,1);
out_load1(:,1)=[0.862;0.9;0.878;0.834;0.88;0.841;0.832;0.806;0.74;0.737;0.715;
0.727;0.704;0.75;0.721;0.8;0.754;0.837;0.87;0.88;0.856;0.811;0.9;0.887;0.896;0.
861;0.755;0.816;0.801;0.88;0.722;0.776;0.8;0.729;0.726;0.705;0.78;0.695;0.724;
0.724;0.743;0.744;0.8;0.881;0.885;0.909;0.94;0.89;0.942;0.97;1;0.952];
out_load2(:,1)=[0.93;1;0.98;0.96;0.94;0.77;0.75];
out_load4(:,1)=[0.67;0.63;0.60;0.59;0.59;0.60;0.74;0.86;0.95;0.96;0.96;0.95;0.95;
0.95;0.93;0.94;0.99;1;1;0.96;0.91;0.83;0.73;0.63];
out_load6(:,1)=[0.78;0.72;0.68;0.66;0.64;0.65;0.66;0.70;0.80;0.88;0.90;0.91;0.90;
0.88;0.87;0.87;0.91;1;0.99;0.97;0.94;0.92;0.87;0.81];
out_load7(:,1)=[0.63;0.62;0.6;0.58;0.59;0.65;0.72;0.85;0.95;0.99;1;0.99;0.93;0.92
;0.9;0.88;0.9;0.92;0.96;0.98;0.96;0.9;0.8;0.7];
out_load8(:,1)=[0.75;0.73;0.69;0.66;0.65;0.65;0.68;0.74;0.83;0.89;0.92;0.94;0.91;
0.9;0.9;0.86;0.85;0.88;0.92;1;0.97;0.95;0.9;0.85];
out_load9(:,1)=[0.64;0.6;0.58;0.56;0.56;0.58;0.64;0.76;0.87;0.95;0.99;1;0.99;1;1;
0.97;0.96;0.96;0.93;0.92;0.92;0.93;0.87;0.72];
out_load10(:,1)=[0.74;0.7;0.66;0.65;0.64;0.62;0.62;0.66;0.81;0.86;0.91;0.93;0.93;
0.92;0.91;0.91;0.92;0.94;0.95;0.95;1;0.93;0.88;0.8];
while i_load<53
  while i_load<9
        out_load(i_load,1)=out_load1(i_load,1)*peak_load;
        j_load=1;
          for j_load=drange(1:1:5)
                out_load3(m_load,1)=out_load2(j_load,1)*out_load(i_load,1);
                for k_load=drange(1:1:24)
                out_load5(x_load,1)=out_load4(k_load,1)*out_load3(m_load,1);
                x_load=x_load+1;
```

```
                end
                m_load=m_load+1;
            end
            for j_load=drange(6:1:7)
                out_load3(n_load,1)=out_load2(j_load,1)*out_load(i_load,1);
                  for k_load=drange(1:1:24)
                out_load5(x_load,1)=out_load6(k_load,1)*out_load3(n_load,1);
                x_load=x_load+1;
                end
                n_load=n_load+1;
            end
          i_load=i_load+1;
  end

    while i_load>8 && i_load<18
          out_load(i_load,1)=out_load1(i_load,1)*peak_load;
          j_load=1;
            for j_load=drange(1:1:5)
                out_load3(m_load,1)=out_load2(j_load,1)*out_load(i_load,1);
                for k_load=drange(1:1:24)
                out_load5(x_load,1)=out_load7(k_load,1)*out_load3(m_load,1);
                x_load=x_load+1;
                end
                m_load=m_load+1;
            end
            for j_load=drange(6:1:7)
                out_load3(n_load,1)=out_load2(j_load,1)*out_load(i_load,1);
                  for k_load=drange(1:1:24)
                out_load5(x_load,1)=out_load8(k_load,1)*out_load3(n_load,1);
                x_load=x_load+1;
                end
                n_load=n_load+1;
            end
          i_load=i_load+1;
    end

        while i_load>17 && i_load<31
          out_load(i_load,1)=out_load1(i_load,1)*peak_load;
          j_load=1;
            for j_load=drange(1:1:5)
                out_load3(m_load,1)=out_load2(j_load,1)*out_load(i_load,1);
                for k_load=drange(1:1:24)
                out_load5(x_load,1)=out_load9(k_load,1)*out_load3(m_load,1);
                x_load=x_load+1;
```

```
        end
        m_load=m_load+1;
    end
    for j_load=drange(6:1:7)
        out_load3(n_load,1)=out_load2(j_load,1)*out_load(i_load,1);
          for k_load=drange(1:1:24)
        out_load5(x_load,1)=out_load10(k_load,1)*out_load3(n_load,1);
        x_load=x_load+1;
        end
        n_load=n_load+1;
    end
  i_load=i_load+1;
end

while i_load>30 && i_load<44
  out_load(i_load,1)=out_load1(i_load,1)*peak_load;
  j_load=1;
    for j_load=drange(1:1:5)
        out_load3(m_load,1)=out_load2(j_load,1)*out_load(i_load,1);
        for k_load=drange(1:1:24)
        out_load5(x_load,1)=out_load7(k_load,1)*out_load3(m_load,1);
        x_load=x_load+1;
        end
        m_load=m_load+1;
    end
    for j_load=drange(6:1:7)
        out_load3(n_load,1)=out_load2(j_load,1)*out_load(i_load,1);
          for k_load=drange(1:1:24)
        out_load5(x_load,1)=out_load8(k_load,1)*out_load3(n_load,1);
        x_load=x_load+1;
        end
        n_load=n_load+1;
    end
  i_load=i_load+1;
end

  while i_load>43 && i_load<53
  out_load(i_load,1)=out_load1(i_load,1)*peak_load;
  j_load=1;
    for j_load=drange(1:1:5)
        out_load3(m_load,1)=out_load2(j_load,1)*out_load(i_load,1);
        for k_load=drange(1:1:24)
        out_load5(x_load,1)=out_load4(k_load,1)*out_load3(m_load,1);
        x_load=x_load+1;
```

```
          end
          m_load=m_load+1;
      end
      for j_load=drange(6:1:7)
          out_load3(n_load,1)=out_load2(j_load,1)*out_load(i_load,1);
           for k_load=drange(1:1:24)
          out_load5(x_load,1)=out_load6(k_load,1)*out_load3(n_load,1);
          x_load=x_load+1;
          end
          n_load=n_load+1;
      end
     i_load=i_load+1;
    end
end
out_load5(:,1);
```

10MW WTG replace 10MW conventional generator

```
hour=1;
outwind=zeros(8736,2);
i_wind=1;
sumlolp10=0;
sumloee10=0;
sumlf10=0;
%generation output
Pwr=10;
Vci=4;
Vr=10;
Vco=22;
A=(Vci*(Vci+Vr)-4*Vci*Vr*((Vci+Vr)/(2*Vr))^3)/(Vci-Vr)^2;
B=(4*(Vci+Vr)*((Vci+Vr)/(2*Vr))^3-(3*Vci+Vr))/(Vci-Vr)^2;
C=(2-4*((Vci+Vr)/(2*Vr))^3)/(Vci-Vr)^2;

while hour<8737
     outwind(i_wind,1)=i;
    n1= wblrnd(7,2);
    outwind(i_wind,2)=n1;


   if (outwind(i_wind,2)<Vci)
        Pw=0;

    elseif ((Vci<outwind(i_wind,2)) && (outwind(i_wind,2)<Vr))
        Pw=(A+B*outwind(i_wind,2)+C*outwind(i_wind,2)^2)*Pwr;

    elseif ((Vr<outwind(i_wind,2)) && (outwind(i_wind,2)<Vco))
        Pw=Pwr;

            else
        Pw=0;

    end;
 outwind(i_wind,3)=Pw;

i_wind=i_wind+1;
hour=hour+1;

end

%%%%%%%%%%%10 MW%%%%%%%%%%%%%
```

```
i_wind=1;

lole=0;
loee=0;
lf=0;
loeeeachtime=0;
duration=0;
out100(:,1)=out2(:,1)+out4(:,1)+out8(:,1)+out10(:,1)+out12(:,1)+out14(:,1)+out
16(:,1)+out18(:,1)+out20(:,1)+out22(:,1);

while i_wind<8737
        if out100(i_wind,1)+outwind(i_wind,3)<out_load5(i_wind,1)
                lole=lole+1;
                %disp('Loss of load occur at ')
                %disp(i1_solar)
                duration=duration+1;
                loee=loee+out_load5(i_wind,1)-out100(i_wind,1)-outwind(i_wind,3);

loeeeachtime=loeeeachtime+out_load5(i_wind,1)-out100(i_wind,1)-outwind(i_w
ind,3);
        else
        end

        if out100(i_wind,1)+outwind(i_wind,3)>=out_load5(i_wind,1) &&
duration>0
              lf=lf+1;
                %disp('Duration of loss of load without solar energy')
              %disp(durationwithnosolar)
              duration=0;
              %disp('Loss of energy expection without solar energy')
              %disp(loeeeachtime)
              loeeeachtime=0;

      else
      end

        i_wind=i_wind+1;


end
sumlolp10=sumlolp10+lole;
sumloee10=sumloee10+loee;
sumlf10=sumlf10+lf;
```

Incremental peak load carrying capability when 20MW wind power added

```
hour=1;
outwind=zeros(8736,2);
i_wind=1;
sumlolp175=0;
sumloee175=0;
sumlf175=0;

%generation output
Pwr=10;
Vci=4;
Vr=10;
Vco=22;
A=(Vci*(Vci+Vr)-4*Vci*Vr*((Vci+Vr)/(2*Vr))^3)/(Vci-Vr)^2;
B=(4*(Vci+Vr)*((Vci+Vr)/(2*Vr))^3-(3*Vci+Vr))/(Vci-Vr)^2;
C=(2-4*((Vci+Vr)/(2*Vr))^3)/(Vci-Vr)^2;

while hour<8737
        outwind(i_wind,1)=i;
      n1= wblrnd(7,2);
      outwind(i_wind,2)=n1;


    if (outwind(i_wind,2)<Vci)
            Pw=0;

      elseif ((Vci<outwind(i_wind,2)) && (outwind(i_wind,2)<Vr))
            Pw=(A+B*outwind(i_wind,2)+C*outwind(i_wind,2)^2)*Pwr;

      elseif ((Vr<outwind(i_wind,2)) && (outwind(i_wind,2)<Vco))
            Pw=Pwr;

                  else
            Pw=0;

      end;
  outwind(i_wind,3)=Pw;

i_wind=i_wind+1;
hour=hour+1;

end
```

```
i_wind=1;

lole=0;
loee=0;
lf=0;
loeeeachtime=0;
duration=0;
out100(:,1)=out2(:,1)+out4(:,1)+out6(:,1)+out8(:,1)+out10(:,1)+out12(:,1)+out1
4(:,1)+out16(:,1)+out18(:,1)+out20(:,1)+out22(:,1);

while i_wind<8737
        if out100(i_wind,1)+outwind(i_wind,3)*2<out_load5(i_wind,1)*175/184
                lole=lole+1;
                %disp('Loss of load occur at ')
                %disp(i1_solar)
                duration=duration+1;

loee=loee+out_load5(i_wind,1)*175/184-out100(i_wind,1)-outwind(i_wind,3)*2
;

loeeeachtime=loeeeachtime+out_load5(i_wind,1)*175/184-out100(i_wind,1)-ou
twind(i_wind,3)*2;
        else
        end

        if out100(i_wind,1)+outwind(i_wind,3)*2>=out_load5(i_wind,1)*175/184
&& duration>0
               lf=lf+1;
                %disp('Duration of loss of load without solar energy')
               %disp(durationwithnosolar)
               duration=0;
               %disp('Loss of energy expection without solar energy')
               %disp(loeeeachtime)
               loeeeachtime=0;

      else
      end

        i_wind=i_wind+1;


end
sumlolp175=sumlolp175+lole;
sumloee175=sumloee175+loee;
```

```
sumlf175=sumlf175+lf;
```

PV generator output

```
clc;
latitude=21.6;
type='tropic';
A=0.002;
out_solar=zeros(8736,4);
out_solar1=zeros(364,1);
i1_solar=1;
i2_solar=1;
out_solar4=zeros(31,1);
out_solar5=zeros(28,1);
out_solar6=zeros(31,1);
out_solar7=zeros(30,1);
out_solar8=zeros(31,1);
out_solar9=zeros(30,1);
out_solar10=zeros(31,1);
out_solar11=zeros(31,1);
out_solar12=zeros(30,1);
out_solar13=zeros(31,1);
out_solar14=zeros(30,1);
out_solar15=zeros(30,1);
out_solar4(:,1)=randsrc(31,1,[1,2,3;0.29,0.42,0.29]);%1 yue
out_solar5(:,1)=randsrc(28,1,[1,2,3;0.28,0.44,0.28]);%2 yue
out_solar6(:,1)=randsrc(31,1,[1,2,3;0.26,0.45,0.29]);%3 yue
out_solar7(:,1)=randsrc(30,1,[1,2,3;0.2,0.47,0.33]);%4 yue
out_solar8(:,1)=randsrc(31,1,[1,2,3;0.23,0.51,0.26]);%5 yue
out_solar9(:,1)=randsrc(30,1,[1,2,3;0.2,0.57,0.23]);%6 yue
out_solar10(:,1)=randsrc(31,1,[1,2,3;0.23,0.58,0.19]);%7 yue
out_solar11(:,1)=randsrc(31,1,[1,2,3;0.26,0.55,0.19]);%8 yue
out_solar12(:,1)=randsrc(30,1,[1,2,3;0.27,0.53,0.2]);%9 yue
out_solar13(:,1)=randsrc(31,1,[1,2,3;0.23,0.48,0.29]);%10 yue
out_solar14(:,1)=randsrc(30,1,[1,2,3;0.23,0.47,0.3]);%11 yue
out_solar15(:,1)=randsrc(30,1,[1,2,3;0.26,0.45,0.29]);%12 yue
out_solar1(:,1)=[out_solar4(:,1);out_solar5(:,1);out_solar6(:,1);out_solar7(:,1);ou
t_solar8(:,1);out_solar9(:,1);out_solar10(:,1);out_solar11(:,1);out_solar12(:,1);ou
t_solar13(:,1);out_solar14(:,1);out_solar15(:,1)];
dn_solar=24;

%Conventional total generation
out100=zeros(8736,1);
out100(:,1)=out2(:,1)+out4(:,1)+out6(:,1)+out8(:,1)+out10(:,1)+out12(:,1)+out1
4(:,1)+out16(:,1)+out18(:,1)+out20(:,1)+out22(:,1);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
while dn_solar<8737 && i1_solar<8737
distance=1+0.033*cos(2*pi*dn_solar/8760);
declination=23.45*sin(2*pi*(284*24+dn_solar)/8760)*pi/180;
hour_angle=acos(-tan(latitude*pi/180)*tan(declination));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
A0=0.4237-0.00821*(6-A)^2;
A1=0.5055+0.00595*(6.5-A)^2;
K=0.2711+0.01858*(2.5-A)^2;
Isc0=7.69;%short-circuit current
Voc0=24.9;% manufacturer open-circuit voltage
Ta=5.2;%ambient temperature
NOCT=43;%Normal Operating Cell Temperature
nc=42;%number of cell
Pmax0=144;%manufacturer maximum power
number=5000000/144;
% ÆøºòÑ¡Ôñ
switch (type)
    case {'tropic'}
        r0=0.95;r1=0.98;rk=1.02;

    case {'midlatitude'}
        r0=1.00;r1=1.00;rk=1.01;

    case {'frigid zone'}
        r0=1.05;r1=1.02;rk=1.00;
end

a0=r0*A0;
a1=r1*A1;
k=rk*K;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
day=out_solar1(i2_solar,1);
switch(day)
    case {1}
        F=abs(normrnd(1,0.03));
    case {2}
        F=abs(normrnd(0.5,0.2));
    case {3}
        F=abs(normrnd(0.1,0.0003));
end

t=hour_angle;
t1=round((hour_angle*180/pi)/15);
```

```
gcbs_solar=0;
gcds_solar=0;
n_solar=1;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        for i = drange(0:1:12-t1-1)
        [out_solar(i1_solar,1)]= i1_solar-1;
        [out_solar(i1_solar,2)]= 0;

        i1_solar=i1_solar+1;
        n_solar=n_solar+1;
        end

        for i = drange(-t+0.01:0.2617:t)
        [out_solar(i1_solar,1)]=i1_solar-1;

tb=(a0+a1*exp(-k/(cos(pi*latitude/180)*cos(declination)*cos(i)+sin(pi*latitude
/180)*sin(declination))));

g0=1366.0*24*60*60*distance/pi*(cos(pi*latitude/180)*cos(declination)*cos(i)
+sin(pi*latitude/180)*sin(declination))/7200000;
        gcb=tb*g0*0.2617;
        gcbs_solar=gcbs_solar+gcb;

td=0.271-0.294*(a0+a1*exp(-k/(cos(pi*latitude/180)*cos(declination)*cos(i)+si
n(pi*latitude/180)*sin(declination))));

g0=1366.0*24*60*60*distance/pi*(cos(pi*latitude/180)*cos(declination)*cos(i)
+sin(pi*latitude/180)*sin(declination))/7200000;
        gcd=td*g0*0.2617;
        out_solar(i1_solar,2)=(gcb+gcd)*F;
        out_solar(i1_solar,3)=(gcb+gcd);
        Isc=Isc0*out_solar(i1_solar,2);
        Tc=Ta+out_solar(i1_solar,2)*(NOCT-20)/0.8;
        Voc=Voc0-0.0023*nc*(Tc-25);
        FF=Pmax0/(Isc0*Voc0);
        out_solar(i1_solar,4)=FF*Isc*Voc*number/1000000;
        gcds_solar=gcds_solar+gcd;

          i1_solar=i1_solar+1;
          n_solar=n_solar+1;
        end

                for i = drange(n_solar-1:1:23)
```

```
        [out_solar(i1_solar,1)]= i1_solar-1;
        [out_solar(i1_solar,2)]= 0;
        out_solar(i1_solar,4)=0;

        i1_solar=i1_solar+1;
                end

if dn_solar<745

        Ta=22.7;%Normal Operating Cell Temperature
elseif dn_solar>745 && dn_solar<1417

        Ta=22.8;%Normal Operating Cell Temperature
elseif dn_solar>1417 && dn_solar<2161

        Ta=23.6;%Normal Operating Cell Temperature
elseif dn_solar>2161 && dn_solar<2881

        Ta=24.3;%Normal Operating Cell Temperature
elseif dn_solar>2881 && dn_solar<3625

        Ta=25.3;%Normal Operating Cell Temperature
elseif dn_solar>3625 && dn_solar<4345

        Ta=26.3;%Normal Operating Cell Temperature
elseif dn_solar>4345 && dn_solar<5089

        Ta=26.9;%Normal Operating Cell Temperature
elseif dn_solar>5089 && dn_solar<5833

        Ta=27.4;%Normal Operating Cell Temperature
elseif dn_solar>5833 && dn_solar<6553

        Ta=27.2;%Normal Operating Cell Temperature
elseif dn_solar>6553 && dn_solar<7297

        Ta=26.4;%Normal Operating Cell Temperature
elseif dn_solar>7297 && dn_solar<8017

        Ta=25.1;%Normal Operating Cell Temperature
else

        Ta=23.4;%Normal Operating Cell Temperature
end
```

```
        i2_solar=i2_solar+1;
        dn_solar=dn_solar+24;
end
```

Incremental peak load carrying capability when 20MW PV(tropical)generator added

```
i10=1;
sumlolp10=0;
sumloee10=0;
sumlf10=0;
lole=0;
loee=0;
loeeeachtime=0;
lf=0;
duration=0;
while i10<8737
out100(:,1)=out4(:,1)+out6(:,1)+out8(:,1)+out10(:,1)+out12(:,1)+out14(:,1)+out
16(:,1)+out18(:,1)+out20(:,1)+out22(:,1);

      if out_solar(i10,4)*2+out100(i10,1)<out_load5(i10,1)
         lole=lole+1;
         duration=duration+1;
         loee=loee+out_load5(i10,1)-out100(i10,1)-out_solar(i10,4)*2;

loeeeachtime=loeeeachtime+out_load5(i10,1)-out100(i10,1)-out_solar(i10,4)*2;
      else
      end

%Duration time
    if out_solar(i10,4)*2+out100(i10,1)>=out_load5(i10,1) && duration>0
        lf=lf+1;
        %disp('Duration of loss of load without battery')
        %disp(durationwithnobattery)
        %disp('Loss of energy expection without battery')
        %disp(loeeeachtimenobattery)
        %disp('Duration of loss of load with battery')
        %disp(durationwithbattery)
        %disp('Loss of energy expection with battery')
        %disp(loeeeachtime)
        duration=0;
        loeeeachtime=0;
    else
    end
     i10=i10+1;
end
sumlolp10=sumlolp10+lole;
sumloee10=sumloee10+loee;
```

```
sumlf10=sumlf10+lf;
```

10MW PV(tropical) generator added to system when a 5MW hydro unit is removed from RBTS

```
i10=1;
sumlolp10=0;
sumloee10=0;
sumlf10=0;
lole=0;
loee=0;
loeeeachtime=0;
lf=0;
lf_nobattery=0;
durationwithbattery=0;
durationwithnobattery=0;
while i10<8737
out100(:,1)=out2(:,1)+out4(:,1)+out8(:,1)+out10(:,1)+out12(:,1)+out14(:,1)+out
16(:,1)+out18(:,1)+out20(:,1)+out22(:,1);

%battery charge
      if
out_charge(i10,1)+out_solar(i10,4)*2+out100(i10,1)-out_load5(i10,1)<=0.03 &&
out_solar(i10,4)*2*2+out100(i10,1)>out_load5(i10,1)
            out_charge(i10+1,1)=0.03;
      elseif
out_charge(i10,1)+out_solar(i10,4)*2+out100(i10,1)-out_load5(i10,1)>0.03 &&
out_charge(i10,1)+out_solar(i10,4)*2+out100(i10,1)-out_load5(i10,1)<=1 &&
out_solar(i10,4)*2+out100(i10,1)>out_load5(i10,1)

out_charge(i10+1,1)=out_charge(i10,1)+out_solar(i10,4)*2+out100(i10,1)-out_l
oad5(i10,1);
      elseif
out_charge(i10,1)+out_solar(i10,4)*2+out100(i10,1)-out_load5(i10,1)>1 &&
out_solar(i10,4)*2+out100(i10,1)>out_load5(i10,1)
                  out_charge(i10+1,1)=1;
      else
      end

%Duration time
     if out_solar(i10,4)*2+out100(i10,1)>out_load5(i10,1) &&
durationwithnobattery>0 && durationwithbattery==0
          lf_nobattery=lf_nobattery+1;
          %disp('Duration of loss of load without battery')
          %disp(durationwithnobattery)
          %disp('Loss of energy expection without battery')
```

```
        %disp(loeeeachtimenobattery)
        %disp('Duration of loss of load with battery')
        %disp(durationwithbattery)
        %disp('Loss of energy expection with battery')
        %disp(loeeeachtime)
        loeeeachtime=0;
        durationwithnobattery=0;
    elseif out_solar(i10,4)*2+out100(i10,1)>out_load5(i10,1) &&
durationwithnobattery>0 && durationwithbattery>0
        lf=lf+1;
        lf_nobattery=lf_nobattery+1;
        loeeeachtime=0;
        durationwithnobattery=0;
        durationwithbattery=0;
    else
    end

    %battery discharge
      if out_solar(i10,4)*2+out100(i10,1)<out_load5(i10,1) &&
0.03<=out_charge(i10,1)+out_solar(i10,4)*2+out100(i10,1)-out_load5(i10,1)
          durationwithnobattery=durationwithnobattery+1;

out_discharge(i10,1)=out_load5(i10,1)-out_solar(i10,4)*2-out100(i10,1);
          out_charge(i10+1,1)=out_charge(i10,1)-out_discharge(i10,1);
      elseif out_solar(i10,4)*2+out100(i10,1)<out_load5(i10,1) &&
out_charge(i10,1)+out_solar(i10,4)*2+out100(i10,1)-out_load5(i10,1)<0.03
          durationwithnobattery=durationwithnobattery+1;
          durationwithbattery=durationwithbattery+1;
          out_discharge(i10,1)=out_charge(i10,1)-0.03;
          out_charge(i10+1,1)=0.03;
          lole=lole+1;

loeeeachtime=loeeeachtime+out_load5(i10,1)-out100(i10,1)-out_solar(i10,4)*2-
out_discharge(i10,1);

loee=loee+out_load5(i10,1)-out100(i10,1)-out_solar(i10,4)*2-out_discharge(i10,
1);
      end
      i10=i10+1;
end
sumlolp10=sumlolp10+lole;
sumloee10=sumloee10+loee;
sumlf10=sumlf10+lf;
```