EVALUATING THE RELIABILITY CONTRIBUTION OF PHOTOVOLTAICS IN ELECTRIC POWER SYSTEMS

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ABSTRACT

The utilization of renewable energy sources in electric power systems has increased considerably in recent years due to global environmental concerns and the acceleration in energy costs associated with the use of conventional energy sources. Solar power is widely acknowledged as a cost-effective source of energy with financial support from government and private organizations. Due to the intermittent nature of the solar irradiation at system locations, solar power has a varied impact on generating system reliability when compared to conventional power sources. It is therefore, important to assess the impact of adding photovoltaic (PV) sources to an electric power system in terms of their reliability contribution to meeting energy demands.

Two test systems consisting of conventional and PV generation, and representative load model, are utilized in this thesis to examine the adequacy of the overall generation system and to determine the capacity value of PV generation. A probabilistic technique using analytical methods was employed and different studies were conducted taking into consideration peak load variations, installed PV capacity, geography and weather factors. PV generation produces most of its power during summertime, less in spring and fall, little in winter, and zero at night. Power output ranges from high to low as the geographic location moves from 0° to 50° latitude with lower power levels in cloudy areas. It is therefore important to develop methods that can incorporate the impacts of location and weather factors in evaluating the system adequacy and the capacity value of PV generation. The results presented in this thesis illustrate the ability to perform quantitative analyses on integrated system reliability and the capacity contribution of solar power located at different latitudes around the world.

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LIST OF ABBREVIATIONS

CC	Capacity Credit
CF	Capacity Factor
COPT	Capacity Outage Probability Table
DPLVC	Daily Peak Load Variation Curve
ELCC	Effective Load Carrying Capability
FOR	Forced Outage Rate
h/y	Hour per year
HL	Hierarchical Levels
HL-I	Hierarchical Level-I
HL-II	Hierarchical Level-II
HL-III	Hierarchical Level-III
H_o	Solar Irradiation outside the Atmosphere
H_T	Solar Insolation for specific Hour
H_{Tr}	Reference Solar Insolation
IC	Installed Capacity
IEEE-RTS	IEEE Reliability Test System
I_{Ref}	Reference Module Current
I_{scr}	Reference Short Circuit Current
I-V	Current-Voltage
kWh	Kilowatt-hours
LDC	Load Duration Curve
LLU	Loss of the Largest Unit
LOEE	Loss of Energy Expectation

LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
MCS	Monte Carlo Simulation
MPP	Maximum Power Point
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MW	Megawatt
MWh	Megawatt-hours
p.u.	Per Unit
PL	Peak Load
P_o	Power Output
P_r	Reference Module Power
PV	Photovoltaic
RBTS	Roy Billinton Test System
RM	Reserve Margin
SIPS	Small Isolated Power System
V_{ocr}	Reference Open Circuit Voltage
V_{Ref}	Reference Module Voltage

CHAPTER 1

INTRODUCTION

1.1 Power System Reliability

Electrical energy is vital in meeting the day to day needs of modern society and ensuring the future development of mankind. The basic function of an electric power system is to supply the consumer load requirement at an acceptable cost. The production of electric energy must be continuous and be able to satisfy the consumption demand at all times. It is therefore necessary to plan generation capacity with adequate reserve to meet the load demand. It is also important to create ways to evaluate power system reliability in order to minimize non-continuity in service and interruptions in the electric supply. Reliability studies and the development of reliability models and tools are important activities in the design and operation of reliable power systems. Reliability is considered to be a key element in power system operation and planning. The term 'power system reliability' can be defined as a measure of the ability of an electric power system to provide acceptable electricity supply [1, 2].

Power system reliability assessment is an integral element in determining the facilities required in a power system to satisfy the load requirement in a reasonably continuous manner. Power system reliability evaluation is typically divided into the two segments of system adequacy and system security, as shown in Figure 1.1[2]. System adequacy can be defined as the ability of the existing or planned system facilities to meet the load demand. Overall system adequacy includes the ability of the transmission and distribution systems to deliver the generated energy from the generation plants to the different types of customer loads connected to the system. System security is related to the ability of the power system to react to unexpected disturbances that occur in the electric power system [2]. System security assessment is important to avoid outage situations that can lead to blackout scenarios.

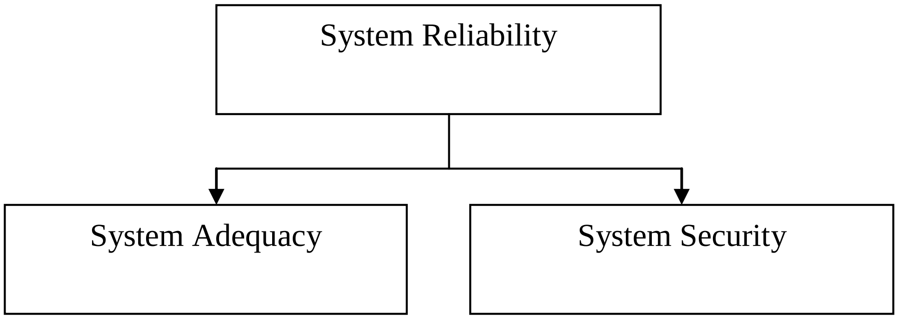

Figure 1.1: Subdivision of power system reliability

An electric power system can be very large with a complex network. In these cases, reliability evaluation of the entire power system becomes very complicated. Hence, electric power system reliability studies are usually divided into three hierarchical levels (HL) as shown in Figure 1.2: (1) generation, (2) transmission, and (3) distribution systems [3, 4]. The system generation reliability or HL-I assessment considers the ability of the total system generation to satisfy the total system load. It is evaluated by creating a model of the total system capacity and convolving it with the system load model. Composite system reliability or HL-II assessment includes the ability of the system generation capacity to satisfy load point energy demands considering the transmission line constraints. The third hierarchical level (HL-III) includes all three functional segments, i.e. generation, transmission and distribution. The results from HL-II studies can be utilized as inputs for distribution system adequacy studies.

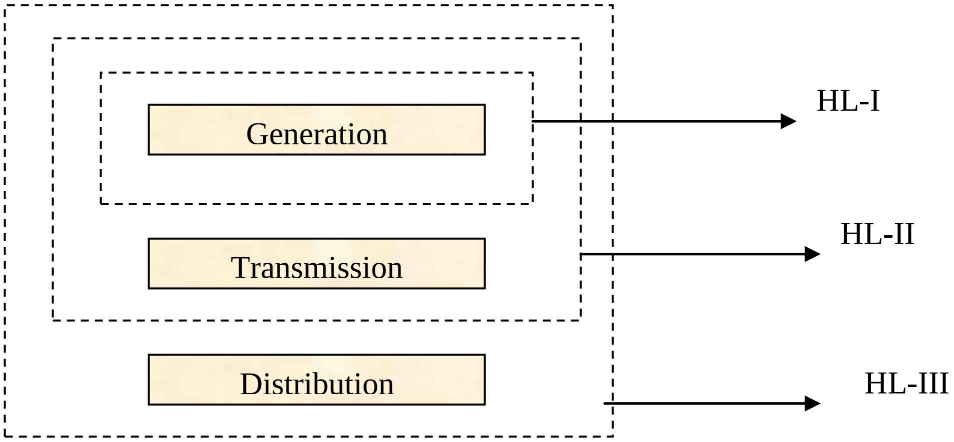

Figure 1.2: Hierarchical levels of power system reliability evaluation

The work described in this thesis is focused on the adequacy evaluation of generation system which include solar energy and therefore is conducted at HL-I.

1.2 Power Systems Including Solar Energy

Pollution of the environment and climate change are big challenges facing humanity. Electric power generation from conventional generating sources is recognized as a major contributor to carbon emissions. The amount of electricity generated by conventional resources has increased considerably with the increasing demand for electrical power. The world is currently facing environmental damages caused by increasing energy consumption from high polluting energy sources, such as oil and coal. Renewable energy sources are currently receiving considerable attention to reduce the usage of conventional energy generation [5, 6]. Renewable sources provide an environmentally friendly option and local energy resources as well. Photovoltaic (PV) and wind sources are considered to be among the most promising environmentally friendly electric energy generation sources. Many researchers have studied different aspects of wind and PV applications in electric power generation. This project is focused on reliability assessment of PV application in an electric system grid.

There is global support for solar energy, and many governments around the world have implemented energy policies to support its growth. Different factors such as no noise, no moving parts, zero carbon dioxide emission, locally available energy resource and ease of operation and maintenance make PV a practical energy source. PV technology has developed rapidly over the years leading to increases in PV efficiency and declines in PV prices. The system price line in Figure 1.3 shows the decrease in average PV price from the year 1990 to 2020 in the U.S [7]. The market penetration line in the same figure shows the increase in installed PV capacity.

PV is used in many different applications in electric power generation, such as in the power system grid, in small isolated power systems, buildings, transportation, standalone devices and solar roadway signals. The application of PV in a small isolated electric power system is studied in this thesis.

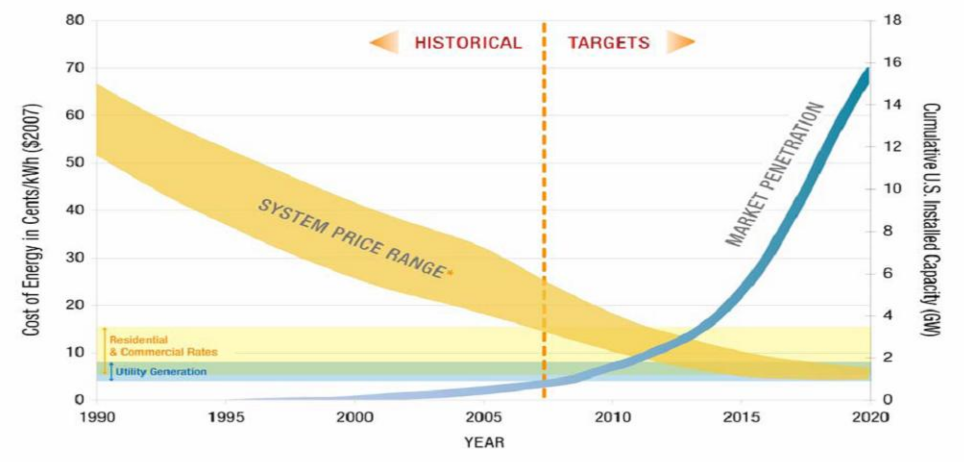

Figure 1.3: PV U.S production and cost (Source: U.S Department of Energy. Solar Energy Technology Program)

1.3 Reliability Evaluation in Power System Planning

The main objective of power system planning is to determine the appropriate design and system facilities required over a planning horizon to meet the growth in system load with acceptable level of reliability and minimum investment and operating costs. Long-term reliability studies are routinely performed as part of system planning to determine appropriate system capacity to meet the system load, build suitable transmission systems, determine proper load management policies, and efficiently schedule maintenance.

Renewable energy sources, such as wind and PV sources, were not normally considered in conventional system planning. As the application of PV generation in electric power system networks increases, it becomes important to evaluate the impact of adding PV generation to the electric power system. The ratio of the installed PV capacity in an electric system to the overall system capacity is termed as the PV penetration ratio. Large PV penetration involves significant capacity investment in the overall system, and should therefore be carefully considered during planning. The proper mix of conventional capacity will depend on the amount of renewable generation, such as PV sources that will be connected to the system.

Conventional generation sources, such as hydro, thermal and nuclear can produce steady power outputs up to their rated values. The output of a renewable source, such as wind and PV, vary widely depending on the available wind or sunlight. It is therefore difficult to assess the capacity value of these sources in system planning. The evaluation of the capacity value of PV generation is considered in this thesis.

1.4 Problem Definition

Population and industrial growth have lead to increasing demands for electricity. This has resulted in increased burning of fossil fuels and green house gas emissions into the atmosphere. This issue has lead energy policy makers and researchers in the electric energy area to investigate the cost and benefit of using renewable energy such as, PV generation to decrease the impact on the environment. The practical application of photovoltaic technology is a relatively new and is gradually expanding in small isolated system as well as large grid connected systems. The variability of this source however adds complexity to modeling the output power of PV. References [8-10] focus on the modeling of PV power output. These models are different in terms of their simplicity. Complex methods are not readily applied in system planning for real systems. The development of relatively simple methods will greatly benefit system planning in order to apply these methods in actual systems.

PV sources have a wide range of application, ranging from small devices to large power systems. In power system applications, PV sources are used in small isolated power system as well as in large grid-connected systems. Power system applications of PV energy can have environmental, energy saving, reliability, and economic benefits. There is a considerable amount of research done in the cost analysis and potential environmental benefits of using PV in a power system. References [11, 12] examine the economic contribution of PV in an electrical power system. Reference [13] shows that at the current price, the economical analysis of connecting PV to the power system grid in an electric power system is cost-effective with government subsidy. Other study [14] found that 1 kW of PV generation can prevent between 700 g to 2300 kg of CO_2 emission annually depending on the type of conventional fuel being offset. Similarly, the annual

SO_2 offset ranges from 4g/kW to 16 kg/kW of PV capacity. There is however relatively little work done on the reliability evaluation of power systems including PV generation.

Although a PV energy system provides clean energy, the power output cannot be easily controlled and varies depending on the solar irradiance throughout the day. It is, therefore, important to evaluate the performance and reliability of incorporating PV energy in the power system. It is also necessary to develop suitable models and techniques to conduct reliability evaluation of PV integrated power systems.

Both analytical [15-17] and simulation [3, 4] methods have been used in the past to evaluate the reliability of PV integrated power systems. Simulation methods can incorporate many system complexities and chronology in the evaluation. These methods however require large amounts of data and are often very complex. Analytical methods are relatively simple and require less computation. These methods can be further developed to create techniques that provide reasonable accuracy and can be readily used in practical application.

Researchers have studied both large and small isolated power systems. The power system group at the University of Saskatchewan is a major contributor to research in the area of PV system reliability. A wide range of research has been conducted on the reliability contribution of solar energy in small isolated power systems. References [11, 18, 19] present studies that show that there are considerable adequacy benefits associated with using solar energy in an electric power system. Solar energy is considered as an alternative source to meet the load energy demand in small isolated power systems in [20]. The published papers consider both day and night-time periods in evaluating of the reliability contribution of a solar source in a power system. PV systems are designed to operate during the daytime. Determining the reliability contribution of a PV source in the daytime and in different seasons are necessary since the output power of solar cell has considerable coincidence with the electric demand in the daytime [21]. It is important to develop appropriate reliability models to easily evaluate the daytime reliability contribution of PV. The amount of sunlight at any geographical location highly depends on the latitude and on cloud cover. There is a lack of research on the impact of these factors on system reliability. It is therefore important to evaluate the reliability contribution of PV considering these factors. The work presented in this thesis is focused on evaluating the reliability contribution of PV in a power system to address the problems noted in this section.

1.5 Research Objective

The benefits and impacts of utilizing PV energy sources to meet energy demand requirements in an electric power system are evaluated in this project. As noted earlier, the work presented in this thesis is concentrated on HL-I adequacy assessment. This work is focused on analyzing and determining the contribution of a PV system to the overall system reliability. A major objective of the research is to develop appropriate models and methods for solar energy systems that can be utilized to evaluate the reliability of a power generating system containing PV. Another major objective is to investigate the effects of various key factors and elements associated with PV energy generation in terms of their impact on the overall system reliability. The evaluation of capacity credit of PV sources, and the impact of various system parameters on the capacity credit are also important objectives of this research.

PV sources are commonly used in Small Isolated Power Systems (SIPS). The application of PV in large power systems is also receiving considerable attention. The studies consider both small isolated and large power systems in the evaluation. A test SIPS-1 and the Roy Billinton Test System (RBTS) [22] are used as test systems in the studies presented in this thesis. The impact of different factors such as the system peak load and the installed PV capacity on the overall system reliability are analyzed. One of goals of this research is to also investigate the benefits associated with installing different amounts of PV in a power system.

The amount of solar irradiation on the earth's surface is affected by the latitude of the site, and the amount of cloud cover. These factors are considered in evaluating the system reliability in this work. One of the objectives is to assess the impact of geographical latitude and cloud cover on the capacity credit of PV sources. A determination of the capacity value of PV is important in system planning. The capacity output of a PV source, however, varies throughout the day. Different seasons and the time of the day have significant impacts on the power output of a solar cell and therefore the impacts of these factors on system reliability have been investigated. Different factors that influence the contribution of PV are incorporated in the developed model and several case studies are presented to illustrate the reliability contribution of adding PV to an electric power system.

1.6 Thesis Outline

This thesis consists of five chapters, and the main content of each chapter is described as follows:

- Chapter 1 presents the basic reliability concepts of electric power systems and a description of the power system functional zones and hierarchical levels. A brief background on reliability evaluation in power system planning is provided in this chapter. It also describes the problems, the main objective, and the thesis outline.
- Chapter 2 briefly describes the basic technique for determining the risk indices of an electric power system. The analytical and simulation approaches for system adequacy evaluation are introduced in this chapter together with details of the two test systems and load models.
- Chapter 3 presents the basic model of PV energy sources. The WATGEN and WATSUN programs [23, 24] utilized in this chapter to generate hourly solar irradiation data for a large number of years are described. Actual and simulated hourly solar irradiation data is compared in this chapter. The results of two different output power PV models are compared to compare the presented models. The developed models are used in this chapter to examine system adequacy evaluation including solar energy.
- Chapter 4 demonstrates the effect of various factors on system adequacy indices. Different studies involving cloud coverage, different latitudes, different seasons and times of day are discussed in detail to evaluate the overall system reliability. The adequacy evaluation study in this chapter is useful to system planners in making appropriate decisions in generation capacity investment considering PV sources. The results obtained from this work provide valuable input regarding appropriate models.

- Chapter 5 presents the evaluation of the capacity value of PV generation. Effective load carrying capability, capacity credit and capacity factor are used to determine the capacity value of PV sources considering the impact of geographical factors.
- Chapter 6 concludes the thesis.

CHAPTER 2

GENERATING SYSTEM ADEQUACY ASSESSMENT

2.1 Introduction

An appropriate reliability evaluation technique is required in planning an electric power system to ensure a continuous power supply in the future. Reliability evaluation is essential to ensure that customers receive adequate and secure energy supply at reasonable costs. One objective in reliability evaluation is to develop suitable measures to assess the continuity of power supply. The purpose of adequacy assessment at HL-I is to assess the ability of the total generation capacity to meet the total system load demand and the transmission lines are not taken into consideration in an HL-I study. The entire system generation is connected to the total system load demand in an HL-I reliability model, as shown in Figure 2.1.

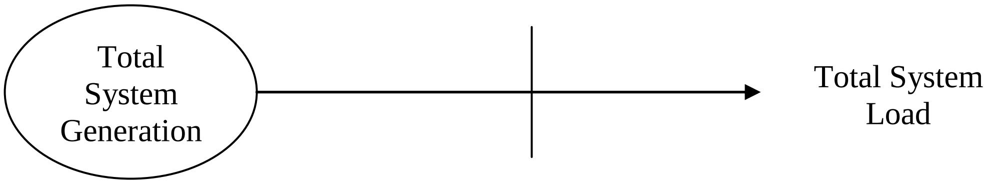

Figure 2.1: Generation adequacy evaluation model

A wide range of reliability evaluation techniques are used in generation capacity planning [3] and a large number of papers have been presented or published on these techniques [15-17]. In the past, HL-I reliability studies were done using deterministic techniques [25, 26]. These techniques are still used in some small isolated power systems and also in some large power systems. Probabilistic methods are, however, applied in most modern large power systems. The HL-I evaluation techniques are utilized to quantify the capacity level required to provide an acceptable level of adequacy. These two basic approaches are described in the following sections.

2.2 Deterministic Techniques

Deterministic techniques have been applied in power system planning over many years [27], and have been used to determine the system reserve margin or capacity in a generating system to meet the load demand. The most common deterministic criteria used in capacity planning are as follows:

1. Capacity Reserve Margin

Reserve margin (RM) is defined as the amount of generating capacity in excess of the system peak load (PL), and is required to account for generating unit failures and increases in customer demand. The reserve margin is expressed as a percentage of the system PL or the total installed capacity (IC) as shown in Equation 2.1. A fixed percentage of RM is used as the criterion for capacity requirement in this method.

$$RM = \frac{IC - PL}{IC} \times 100\% \tag{2.1}$$

2. Loss of the Largest Unit (LLU) or (N-1)

The LLU or N-1 is a widely used deterministic criterion [3]. This criterion states there must be sufficient reserve margin in the system such that the system load will not be curtailed if any single generating unit in the system fails. The capacity reserve margin is at least equal to the largest unit in this method.

3. Loss of the Largest Unit and Capacity Reserve Margin

This method is a combination of the previous two methods, in which the capacity reserve margin should be equal to or greater than the sum of the largest unit and a fixed percentage of the system PL or the IC.

The deterministic approach can be used to easily evaluate the total capacity required in the overall power system, but is not capable of accounting for the random nature of power system behavior [28]. The three previously noted techniques do not define the true risk in the power system. The application of these techniques to generation planning in complex power systems is therefore limited. Most electric power companies tend to use probabilistic techniques in capacity planning. Table 2.1 illustrates the results of a survey from 1964-1977 of the criteria used in capacity reserve planning [29].

Table 2.1: Criteria used in reserve capacity planning

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

* With supplementary checks for probabilistic index LOLE

Table 2.1 shows that electric power companies have gradually shifted from deterministic to probabilistic criteria. In 1987, most utilities turned to probabilistic techniques, with only one utility using a deterministic criterion with supplementary checks for probabilistic index.

2.3 Probabilistic Techniques

As electric power systems have become larger and more complex, probabilistic techniques have become more important in the analysis and evaluation of power system reliability. Probabilistic technique can respond to the stochastic nature of power systems and provide appropriate risk indices in adequacy evaluation. The need for the application of probabilistic methods for evaluating the risk indices were recognized [3, 4, 28] in order to respond to the random nature of system behavior. Probabilistic approaches have been utilized by most Canadian electric companies for system risk evaluation at the HL-I level [30].

The HL-I reliability risk indices estimate the ability of a particular generation configuration to supply the load demand. These indices respond to various factors, such as the number and capacity of generating units, unit failures, load levels, and load shapes. The unavailability (U) of a generating unit [1, 3] is the basic element in building a probabilistic generation model, and is defined as the probability that a unit undergoes a random failure and is not available to serve the load. This is conventionally known as the forced outage rate (FOR). This is an important parameter in building the generation model [1, 3]for HL-I evaluation. The availability (A) is the complement of the unavailability, or A=1-U. A generating unit may be available or unavailable at any point in time due to various operating conditions as shown in Figure 2.2 [31].

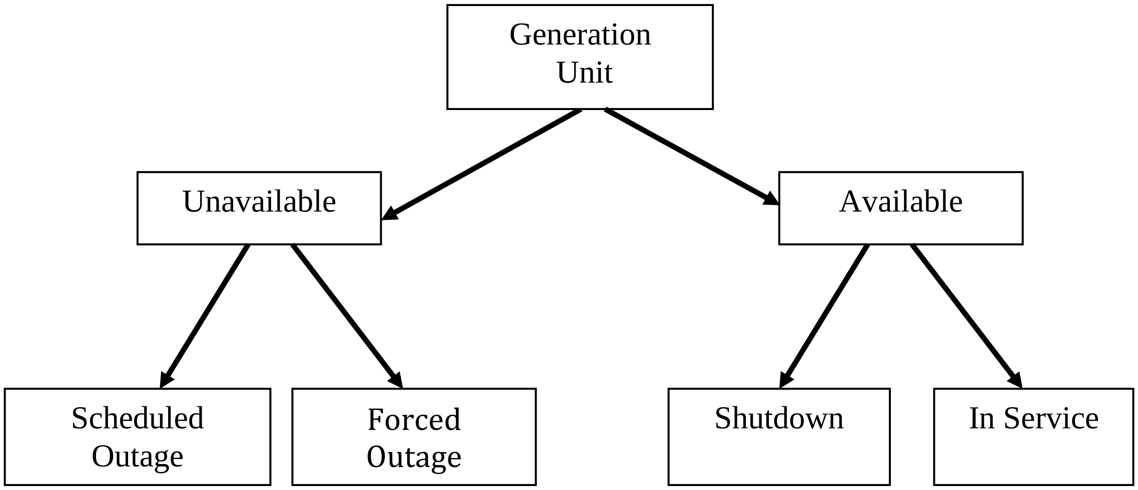

Figure 2.2: Generating unit states

The development of a generation model in a reliability evaluation technique requires generation unit data, such as the FOR or mean time to failure (MTTF) and the mean time to repair (MTTR).

Probabilistic techniques can be broadly categorized under the following two approaches 1) the analytical approach and 2) the simulation approach [3, 4]. The analytical method estimates the system risk level using mathematical calculations. This technique requires less computation time than the simulation approaches and can provide accurate reliability indices. Adequacy evaluation results from the application of these two techniques are compared in this chapter.

2.4 Analytical Techniques

These techniques determine the system risk using a mathematical solution. This approach can provide accurate system indices with a simple method in a short time. The wide range of analytical approaches used in HL-I and HL-II studies are illustrated [15-17, 32].

The main requirement in HL-I adequacy evaluation is to develop a generation model and a load model for the entire power system, and then convolve the two models to create the system risk model as shown in Figure 2.3.

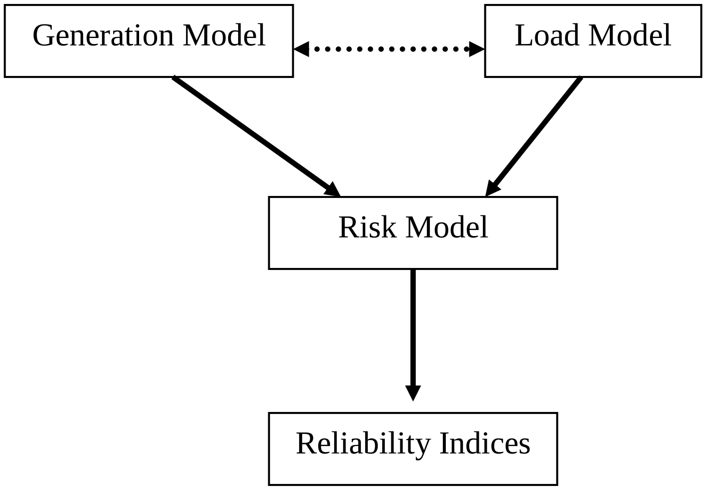

Figure 2.3: Elements of generation reliability evaluation

2.4.1 Generation and Load Model

The generation model in most analytical techniques is generally created with a series of states, each of which consist of a capacity level and its corresponding probability. This formation is known as a capacity outage probability table (COPT) [3]. Building a COPT is an important procedure in generating capacity reliability evaluation.

Each generating unit in a power system can be represented by two or more operating states. A two-state model of a single generating unit is shown in Figure 2.4, in which the unit can reside in either the up (operating) state or the down (outage) state.

The component failure rate (λ) and the repair rate (μ) are the transition rates between the two states. The FOR or unavailability (U) and availability (A) can be calculated using Equations 2.2 and 2.3.

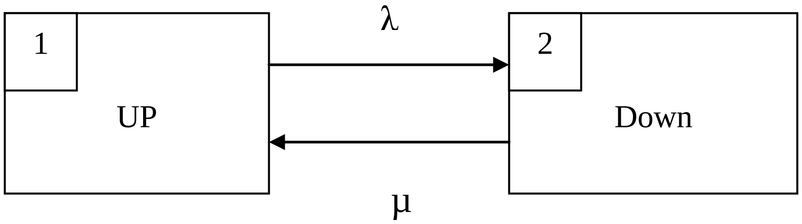

Figure 2.4: The two states of a single component

$$A = \frac{\mu}{\mu+\lambda} = \frac{m}{m+r} = \frac{\sum[UpTime]}{\sum[UpTime + DownTime]} \tag{2.2}$$

$$U = \frac{\lambda}{\mu+\lambda} = \frac{r}{m+r} = \frac{\sum[DownTime]}{\sum[UpTime + DownTime]} \tag{2.3}$$

Where:

m = Mean time to failure = MTTF = $\frac{1}{\mu}$

r = Mean time to repair = MTTR = $\frac{1}{\lambda}$

Several methods have been proposed for constructing a capacity model [3, 33, 34]. The COPT is normally constructed using a recursive technique [3]. The generating units in the recursive algorithm are added sequentially to the table. Equation 2.4 can be used to develop the COPT if the generating units have two states.

$$P(X) = (1-U)P'(X) + (U)P'(X-C) \tag{2.4}$$

Where:

X = A capacity state in the COPT (in kW or MW).

C = The capacity rating of the added unit (in kW and MW).

P'(X) and P(X) are the cumulative probability of the X capacity outage state before and after the C unit is added.

Initially, P'(X) = 1.0 for X ≤ 0 and P'(X) = 0 otherwise.

U = Force outage rate of the added unit.

Equation 2.5 is a more general recursive algorithm that can incorporate multi-state units.

$$P(X) = \sum_{i=1}^{n} p_i P'(X-C_i) \tag{2.5}$$

Where:

n = Number of states.

p_i = Probability of existence of the unit state i.

The load model incorporates the variation in system load level with time in a specified period. The basic period utilized in power system planning is a calendar year. Different load models can be used in analytical methods depending on the type of evaluation required. The load data collected over the period of one year can be sorted from the highest to the lowest value to create an annual load model. If the load data consist of daily peak load values, the load model obtained is known as the Daily Peak Load Variation Curve (DPLVC). If the load data used are hourly values, the load model obtained is known as the Load Duration Curve (LDC). Both the DPLVC and LDC can be utilized in adequacy evaluation using analytical techniques.

2.4.2 Probabilistic Risk Indices

The capacity outage probability table described in the previous section is combined with the load model to evaluate the risk indices. The most widely used indices for generation capacity planning at the present time are the loss of load expectation (LOLE) and the loss of energy expectation (LOEE) [29]. A loss of load will occur whenever the system load exceeds the total generating capacity in service. The probability that the total load demand will not be met is known as the Loss of Load Probability (LOLP). The expected number of days or hours in a year that the system generation cannot meet the load demand is the LOLE. The units of the LOLE are in days per year (d/y) or hours per year (h/y). This is the most widely used probabilistic method in generating system reliability evaluation. The LOLE does not provide any indication of the magnitude of load curtailment in the system. The LOEE is the expected energy curtailed in a year and provides information on the magnitude of energy curtailment.

Figure 2.5 shows the combination of the COPT with the LDC in order to evaluate the LOLE and LOEE indices. This figure also shows the installed capacity, the reserve capacity, the different capacity levels of the generation model and the load model. It can be seen in this figure that a capacity outage in excess of the reserve will cause load curtailment at some point in time. The capacity outage O_k results in the inability to supply the load for a time interval t_k. The system loss of load expectation is given by Equation 2.6.

$$LOLE = \sum_{k=1}^{n} p_k \times t_k = P_k \times (t_k - t_{k-1}) \tag{2.6}$$

Where:

n : The number of capacity outage states in the COPT.

p_k : Individual probability of capacity outage O_k.

t_k : Duration of outage if the loss of load occurs due to outage O_k.

P_k : Cumulative probability of capacity outage O_k.

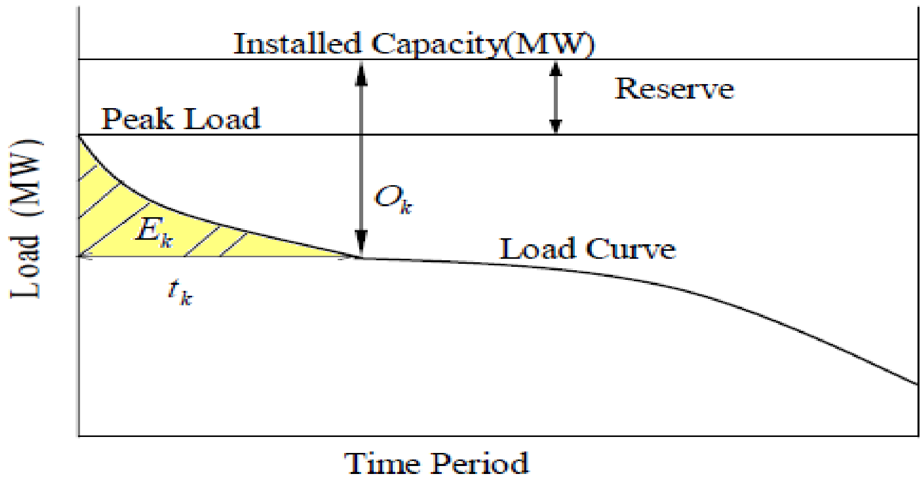

Figure 2.5: Load model and risk indices

The area under the LDC represents the total energy demand. The shaded area (E_k) in Figure 2.5 represents the unsupplied energy due to outage O_k. The LOEE can be calculated using Equation 2.7.

$$LOEE = \sum_{k=1}^{n} p_k \times E_k \tag{2.7}$$

2.5 Simulation Techniques

The analytical method described in the previous section adopts a mathematical model for the adequacy evaluation. Simulation techniques provide an alternative method to evaluate the probabilistic indices by simulating the random behavior of generation systems and the actual process [35]. These techniques can easily incorporate many of the various complexities in a large power system. Simulation techniques can also provide distributions of the various risk indices. The sequential and non-sequential approaches are the two basic Monte Carlo simulation (MCS) techniques utilized in power system reliability. The SIPS+ [36] program is utilized to estimate the reliability indices of small systems containing PV source using the sequential MCS approach.

The SIPS+ program was developed at the University of Saskatchewan in order to use probabilistic techniques to study reliability and cost indices on small power systems utilizing renewable energy. In this program, the generation model is combined with the annual chronological hourly load. In each hour, the total generation capacity is compared with the total load demand to evaluate the LOLE and LOEE. The simulation is run for a large number of years to obtain acceptable accuracy. Convergence criteria are used to stop the simulation program and to determine the maximum and minimum number of simulations. The overall system generation reliability evaluation steps in SIPS+ are represented in Figure 2.6 and are described in detail in [36].

A brief comparison of the adequacy indices at HL-1 using analytical and simulation is conducted in Section 2.7.

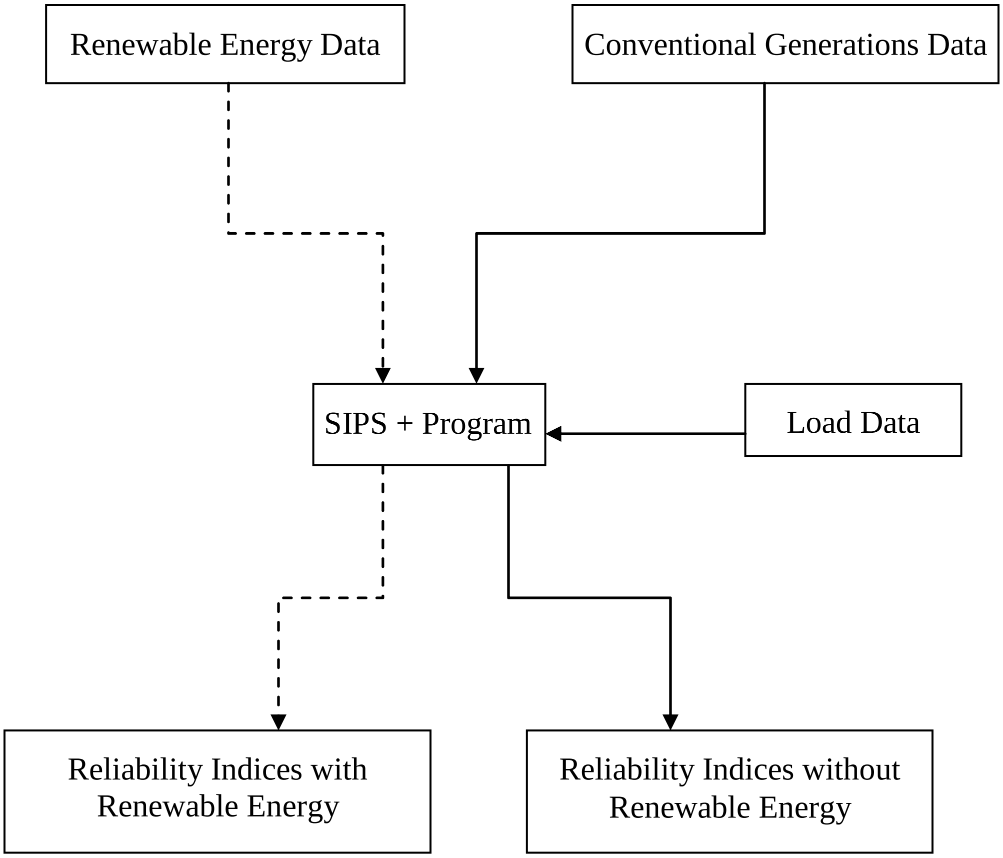

Figure 2.6: SIPS+ [36] program steps

2.6 Test Systems

A SIPS and the RBTS [22] are used in this work. These systems differ in size and configuration. A SIPS is usually located in a remote area or in island communities with typically low load demand. This system in fact may or may not have transmission lines and is not connected with any other electric power system. The test system used in this case has one 70 kW and two 40kW generation units with a total system capacity of 150 kW. Each generating unit has a FOR of 5%. The peak load is 80 kW. This system is designated as SIPS-1. This system meets the deterministic loss of the largest unit or N-1 criterion [37]. A 1995 survey of SIPS in Canadian utilities is shown in Table 2.2 [37].

Table 2.2: SIPS in Canadian utilities

Utility	Number of SIPS	Total Installed Capacity (kW)	Largest System (kW)	Smallest System (kW)
Newfoundland Hydro	30	46,775	18,750	90
Hydro Quebec	21	56,000	11,200	550
Ontario Hydro	23	20,226	2,350	170
Manitoba Hydro	12	18,445	4,085	350
Saskatchewan Power	1	132	132	132
Alberta Power Ltd.	27	35,295	16,880	40
BC Hydro	9	35,550	9,420	1,850
NWT Power Crop.	47	188,000	52,560	70
Yukon Electrical	7	8,855	5,050	245

The RBTS has been utilized for over twenty years by researchers conducting reliability assessment and other probabilistic applications in electric power systems. This system was developed at the University of Saskatchewan for learning purposes and research, and is a large system compared to SIPS-1. It contains eleven generation units, seven buses and nine transmission lines as shown in Figure 2.7. The total installed generation capacity is 240 MW, and the system peak load is 185 MW.

The annual chronological hourly load profile of the IEEE-RTS [38] is used in both test systems. The Appendix contains the details of the two test systems.

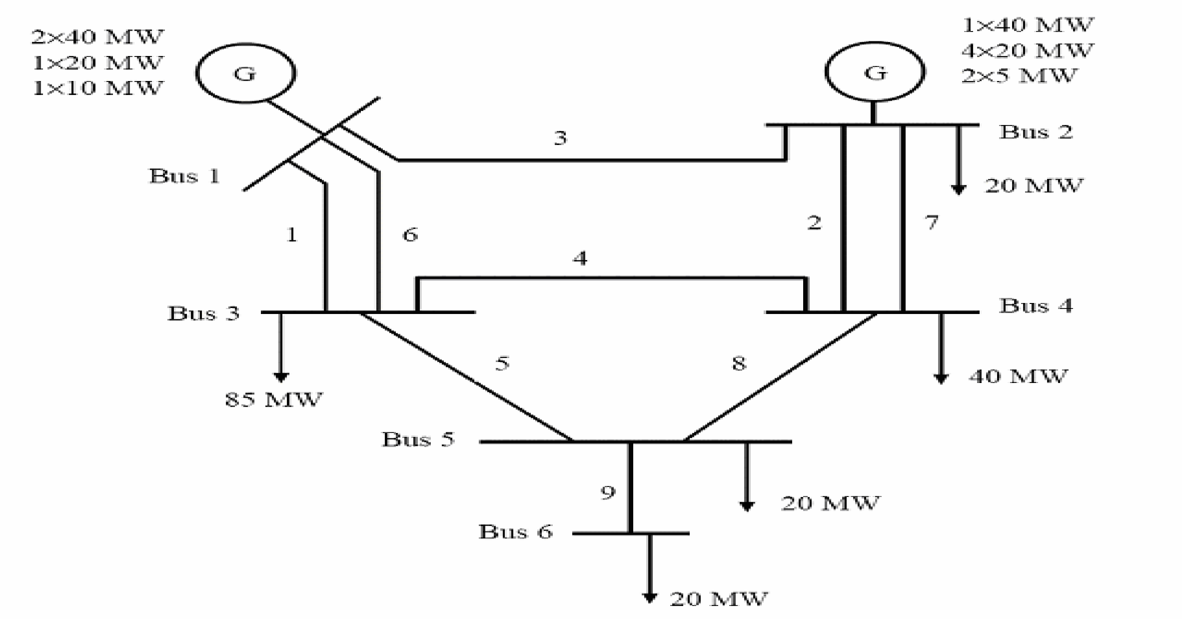

Figure 2.7: Roy Billinton test system [22]

2.7 The HL-I Annual System Indices Obtained using Analytical and Simulation Techniques

An electric power generating system is considered to be successful as long as there is sufficient generation capacity to supply the system load. A generating capacity adequacy evaluation of the test SIPS-1 and the RBTS were conducted using both the analytical and the simulation techniques. The annual system LOLE and LOEE were used to compare the results obtained from the two techniques.

The first study was applied to the test SIPS-1. The total installed generation capacity of SIPS-1 is 150kW, and the system peak load is 80 kW. The LOLE and LOEE results obtained using the analytical approach and the MCS technique using different simulation runs are shown in Table 2.3. A similar study was also done for the RBTS.

The total installed generation capacity of the RBTS is 240 MW, and the system peak load is 185 MW. The LOLE and LOEE of RBTS are shown in Table 2.3.

The LOLE and LOEE results obtained from the analytical approach and the sequential MCS technique using different simulation runs are shown in Table 2.3. It can be seen that there are fluctuations in the LOLE and LOEE values obtained for SIPS-1 with an increase in the simulation time due to the small size of the test system. The results obtained for the RBTS gradually converge with increase in the number of simulations. The accuracy in the results is achieved considering different factors as described in [36]. This table illustrates that the adequacy evaluation of SIPS-1 and the RBTS obtained using a suitable number of simulations are relatively close to the results obtained utilizing the analytical technique. A major disadvantage of the MCS method is the requirement of considerable computing time to obtain reasonable results. The analytical technique requires considerably less computation time. The two test systems utilized in this thesis are not complex systems, and therefore it was decided to use the analytical approach described earlier in this chapter to conduct the studies required to meet the research objective in Section 1.5.

Table 2.3: The HL-1 annual system indices for SIPS-1 and RBTS

SIPS-1				RBTS		
No. of Simulations	LOLE (h/y)	LOEE (kWh/y)		No. of Simulations	LOLE (h/y)	LOEE (MWh/y)
242	33.79	528.09		579	1.33	14.75
500	32.93	498.33		1051	1.26	12.64
1028	32.99	509.36		1512	1.22	11.90
1500	32.94	502.40		2215	1.15	10.76
3000	32.41	489.88		3014	1.11	10.18
6000	31.67	474.64		5388	1.07	10.04
10000	31.58	470.42		7752	1.03	9.58
30000	31.85	477.42		30000	1.02	9.19
Analytical	32.26	483.46		Analytical	1.09	9.86

2.8 Summary

The function of an HL-I system reliability study is to quantitatively determine the system generation capability to satisfy the total system demand with acceptable system risk. The models used to represent the generation system, the load model and the calculation of the reliability indices are introduced in this chapter. Both deterministic and probabilistic techniques are employed by electric power utilities to assess generating system reliability. Probabilistic techniques, however, are required to incorporate random events in the assessment.

The LOLE and LOEE are the most extensively used risk indices. These indices can be evaluated by combining the generation and load models. Quantitative adequacy evaluation can be conducted by analytical or simulation approaches. These two approaches are introduced in this chapter. The MCS approach requires considerably more solution time compared to the analytical technique. MCS is however, practical when the system contains complex models or operating constraints.

Two test systems known as the RBTS and SIPS-1 are employed in this research. The RBTS is an educational test system. The SIPS is a relatively small system compared to the RBTS. Both test systems use the same hourly load model designated as the IEEE-RTS hourly load model.

This chapter briefly illustrates the annual indices of LOLE and LOEE calculated using analytical and simulation techniques. The analytical technique is a simpler method than simulation for evaluating basic generating system reliability, and is used in the remainder of this research. The analytical results for SIPS-1 and RBTS obtained in this chapter are used as reference in the various studies introduced in Chapter 4 and 5.

CHAPTER 3

SYSTEM MODEL AND EVALUATION METHOD

3.1 Introduction

The utilization of conventional capacity has increased with the increase in demand for electrical power, as stated earlier. These sources are, however, one of the major contributors to increasing air pollution. Renewable sources, such as PV can therefore contribute to electric power generating systems due to their advantages in reducing carbon dioxide, and air pollution.

The contribution of solar energy to an electric power system is different from that obtained from conventional generating sources since solar energy is not always available on demand. The power output of a photovoltaic cell is highly variable and uncertain, and it cannot be controlled in the same way as conventional power generation. It is therefore important for power system planners to evaluate the reliability contribution of using PV energy.

Three steps are required to estimate the system adequacy of a PV integrated power system, as shown in Figure 3.1: 1) modeling the solar irradiation data for the desired sites, 2) modeling the output power models for the PV sources and 3) calculating the system reliability indices obtained by combining the system load with the generation model. This chapter discusses modeling the hourly solar irradiation, the output power of PV units and the adequacy effects of adding PV energy sources to the SIPS-1.

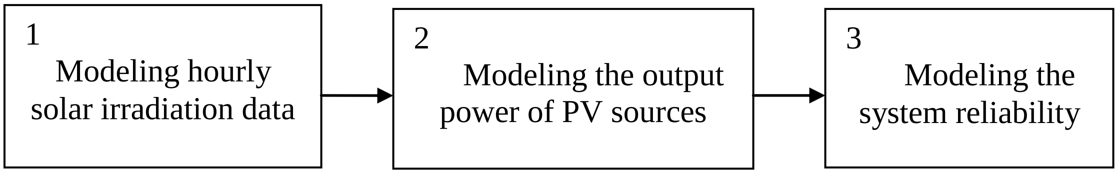

Figure 3.1: The adequacy evaluation steps of a power system including solar energy

3.2 Photovoltaic System

The PV module is a solid sheet of material, known as a solar cell that converts solar irradiation into electric energy. The word photovoltaic comes from two parts: “photo” comes from the Greek word for light, and “Volta” comes from the electricity pioneer Alessandro Volta. These two words explain the task of PV device to convert light to electricity, as Edmund Becquerel discovered in 1839 [39]. A PV system located at a site usually consists of a number of solar arrays each composed of a number of solar modules arranged in a desired configuration with appropriate series and parallel connections. Each solar module is made up of a number of solar cells as shown in Figure 3.2 [40].

Figure 3.3 [41] demonstrates the physical operation of a solar cell. A PV device is made from semiconductor materials, such as silicon. When solar irradiation falls on the solar cell, electrons become excited and move from one layer to another. These electrons will form a DC electric current if an electrical circuit is connected to the P and N sides, and therefore a DC to AC inverter is required to run AC devices.

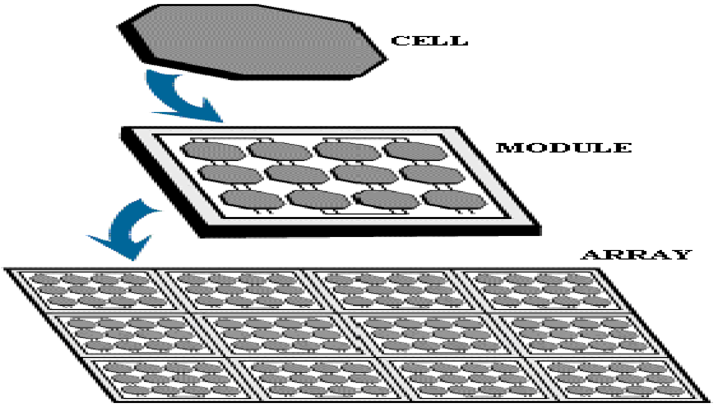

Figure 3.2: Solar cell model [40]

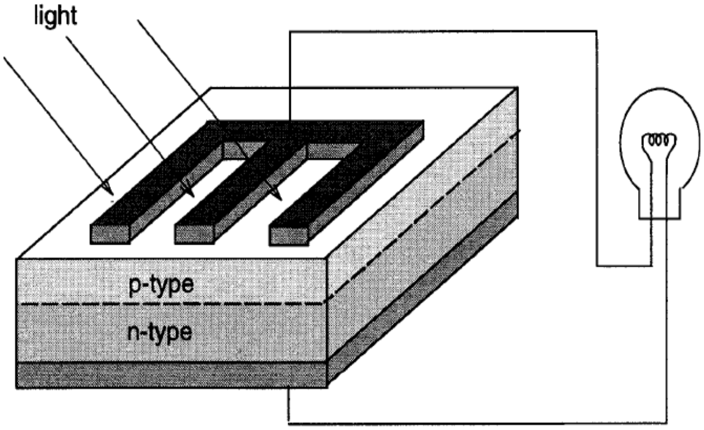

Figure 3.3: PV operation principles [41]

3.2.1 Modeling Solar Irradiation Data

The amount of output power of a PV device is based on the amount of solar irradiation that strikes the solar cell. This irradiation is produced by the sun, and is in wave form [42]. The mean value of solar irradiation that arrives in the upper level of earth's atmosphere in a particular area is known as the solar constant and is 1367 (W/m^2) [43]. This amount inside the earth's atmosphere is however reduced by such factors as weather variables, season-time, daytime, latitude, solar cell temperature and direct and diffuse solar irradiation. The term diffuse irradiation means the irradiation is spread by cloud cover, water vapour, snow and anything else in the earth or atmosphere, while with direct irradiation the irradiation is not blocked by any obstructions. Recorded solar irradiation data at specific sites are required in order to compute the total output power of a solar cell and detailed atmospheric records are not available in many locations around the world. When actual data are unavailable at a certain location, generation of synthetic data can be used to simulate the hourly solar irradiation data for a large number of years. The WATGEN [23] software developed by the WATSUN simulation laboratory at the University of Waterloo [44, 45] uses a degree-day estimation approach [45] to simulate hourly solar irradiation data from monthly average weather values. This program is based on numerical techniques.

The WATGEN program has been utilized to generate hourly solar irradiation data [36]. The required data are the monthly average values of the wind speed, the ambient temperature and the solar irradiation on a horizontal surface [36]. These data are used by the program to generate hourly solar irradiation data for a large number of sample years in a very short time. This program can realize and successfully recognize direct, diffused and reflected irradiation [46]. The WATGEN program can be described as a two-step process as shown in Figure 3.4. The first step involves generating daily solar irradiation values from the monthly average values. The second step uses the daily values to generate the hourly solar irradiation for a number of years.

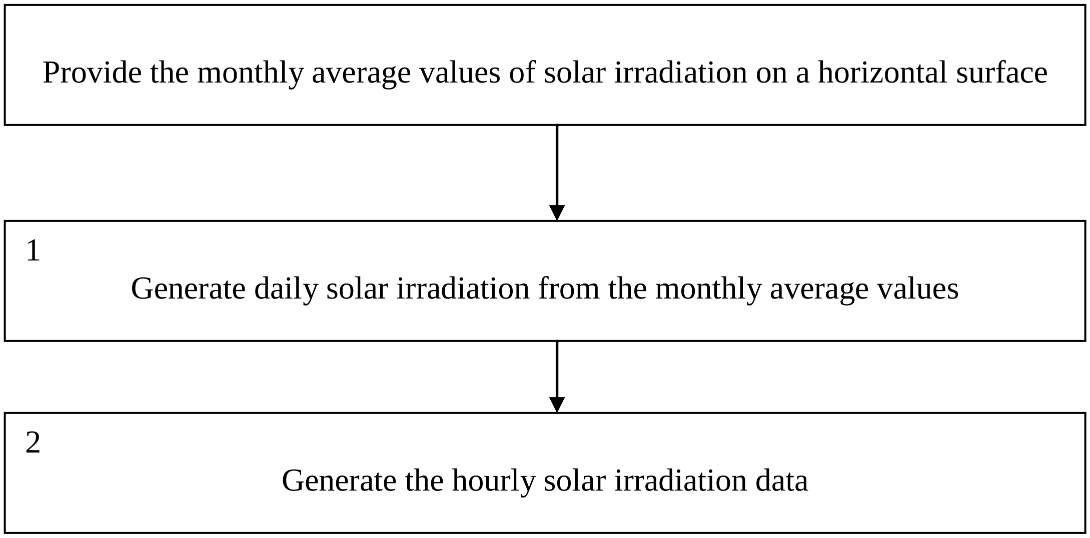

Figure 3.4: Estimating hourly solar irradiation using the WATGEN program

The model used in the WATGEN program for predicting hourly solar irradiation is based on the latitude of the desired site and the monthly average weather data. The modeling process uses a stochastic probability transformation of the clearance index (K_t) to obtain a Gaussian random variable. Subsequently, the hourly solar irradiation is calculated using the new variable in an ARMA (1, 0) model [44, 45]. The K_t index is determined in each step by taking the ratio of global (observed) solar irradiation to solar irradiation outside the atmosphere as shown in Equation (3.1) [47].

$$K_t = \frac{H_t}{H_o} \tag{3.1}$$

Where:

H_t : the global solar irradiation.

H_o : the solar irradiation outside the atmosphere.

Five-years of hourly solar radiation historical data in Solar Village in Saudi Arabia located at 24.9° N, 46.4° E [48] were compared with 15 years of hourly solar radiation values obtained from the WATGEN program as shown in Figure 3.5. The monthly average data used in the WATGEN program is presented in the Appendix. Figure 3.5 presents the observed and simulated solar irradiation values versus the probability of occurrence for Solar Village. The probability of zero solar irradiation is 0.46 and is not shown in the figure. The accuracy of the software simulations of hourly solar irradiation is illustrated in Figure 3.5.

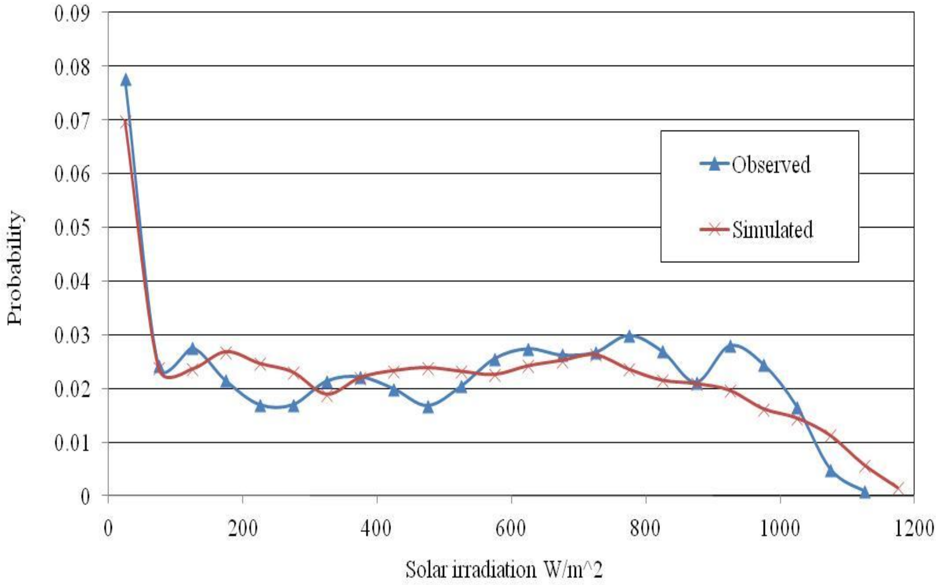

Figure 3.5: Observed [48] and simulated solar irradiation distributions for Solar Village site when night-time is not considered

The output of the simulation program provides a reasonable replication of the actual historical data [48], and therefore the WATGEN program was used in this thesis to generate the hourly solar irradiation for a large number of years.

The monthly average weather data utilized in this thesis is provided by NASA as this organization developed a dataset for global solar irradiation and meteorological data. These datasets are formulated specifically for the needs of the solar and renewable energy system design researchers. The Surface metrology and Solar Energy (SSE) website includes over 200 satellite-derived meteorology and solar energy parameters averaged over 22 years from July 1, 1983 to June 30, 2005. This website provides averaged daily and monthly measurement for 1195 ground sites around the world [49]. Reference [49] includes the parameter definitions used in this website. The latitude and longitude of a specific location are required to specify the desired data tables. Monthly global solar irradiation, monthly average weather data such as wind speed and temperature were obtained using this website.

3.2.2 Modeling the Output Power of a Photovoltaic System

A solar panel is a PV system which uses multiple solar cell layers to convert the sun's irradiation to electricity. The amount of PV power relies on the weather conditions, the array site and other factors as noted earlier. Throughout history, numerous models have been applied to estimate the output power of PV devices. Two prediction models of energy production by solar cells are presented in this section to examine the accuracy and ease of use of these models.

The first model designated as Model-I is a detailed computational model that takes into account the operating point of the solar cell. The output power of a PV device can be determined utilizing the current-voltage (I-V) characteristic as shown in Figure 3.6. The short circuit current (I_{sc}) on this figure can be defined as the maximum current that the solar cell can supply and where it occurs. The open circuit voltage (V_{oc}) can be defined as the maximum voltage that exists between solar cell terminals, and is obtained when there is no load connected. The maximum power (P_{max}) in Figure 3.6 occurs at the intersection points of the maximum current and maximum voltage. All the data needed are available from the solar cell manufacturer. A BP Solar, BP 4175T, monocrystalline 175W [50] array was simulated in this work. The electrical characteristics of a BP 4175T array are presented in the Appendix.

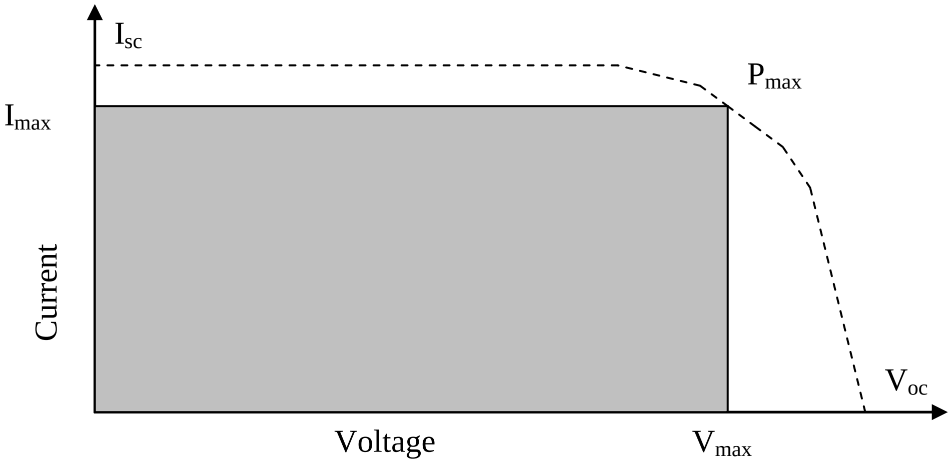

Figure 3.6: I-V characteristics of solar cell device

The output power (P_o) of the solar cell is initially estimated using Equation 3.2, where V_{Ref} and I_{Ref} are defined as the reference voltage and current for the PV module. The parameters A, H_{Tr} and H_T are the panel area, reference solar insolation, and solar insolation for a specific hour, respectively [24]. The P_o calculated in Equation 3.2 is utilized to determine the solar array temperature using a thermo-dynamic model [24].

$$P_o = \frac{V_{Ref} \times I_{Ref}}{H_{Tr} \times A} \times H_T \tag{3.2}$$

The power output of a solar panel can be estimated from the I-V curve. This curve is built by the voltage and current of a specific cell. The I-V characteristic data are used in the WATSUN program to estimate the PV output power [51, 52]. The program evaluates the maximum power using Equation 3.3. The overall concept of this program is executed in two steps as shown in Figure 3.7.

$$P_{\max} = \frac{V_{oc} \times I_{sc}}{V_{ocr} \times I_{scr}} \times P_r \tag{3.3}$$

Where:

V_{ocr} : Reference open circuit voltage.

I_{scr} : Reference short circuit current.

P_r : Reference module power.

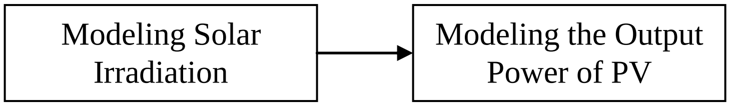

Figure 3.7: Evaluation steps of WATSUN

The second model designated as Model-II is a simple analytical model which depends on solar cell efficiency and solar cell irradiation. The efficiency of a solar cell varies with the solar irradiation, and can be evaluated using Equations 3.4 and 3.5 [53]. The power output model from a solar cell can be estimated by multiplying the solar irradiation obtained from the WATGEN program by the efficiency using Equations 3.6, 3.7 and 3.8 [53] as shown in Figure 3.8. The power output states for the PV solar cell and the associated probabilities of Model-II are presented in the next section.

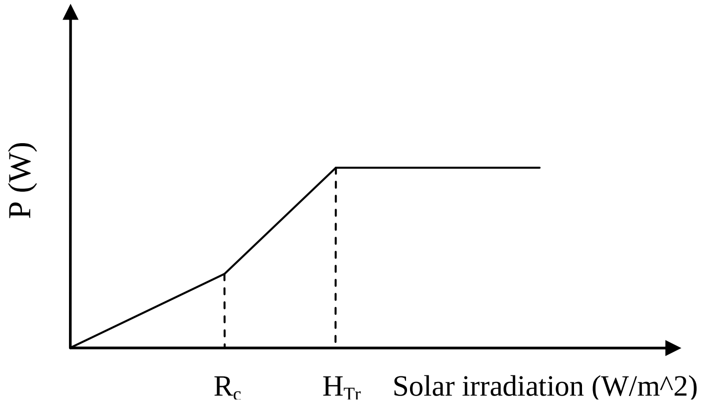

Figure 3.8: Power output of PV source

$$\eta = \frac{\eta_c}{R_c} \times H_T \qquad 0 \le H_T < R_c \tag{3.4}$$

$$\eta = \eta_c \qquad R_c \le H_T \tag{3.5}$$

$$P = P_{sn} \times \frac{{H_T}^2}{H_{Tr} \times R_c} \qquad 0 \le H_{Tr} < R_c \tag{3.6}$$

$$P = P_{sn} \times \frac{H_T}{H_{Tr}} \qquad R_c \le H_{Tr} < H_{Tr} \tag{3.7}$$

$$P = P_{sn} \qquad H_T \ge H_{Tr} \tag{3.8}$$

Where:

P : the PV output power (W).

H_T : hourly solar irradiation (W/m^2).

H_{Tr} : solar irradiation in a standard environment set as 1000 (W/m^2).

R_c : a certain irradiation point set as 150 (W/m^2).

P_{sn} : equivalent rated capacity of PV (W)

η : Efficiency of PV module.

η_c : rated module efficiency.

3.3 Model Comparison

The two PV output power models described in section 3.2.2 are compared in this section. The test system used in this study is SIPS-1 which consists of one 70 kW and two 40 kW diesel generating. The FOR [3] of the units is 5%. The basic physical system model used in this study is shown in Figure 3.9. The annual chronological hourly load profile of the IEEE-RTS [38] was used in this analysis with a peak load of 80 kW. The system LOLE and LOEE without PV support are 32.26 h/y and 483.46 kWh/y respectively.

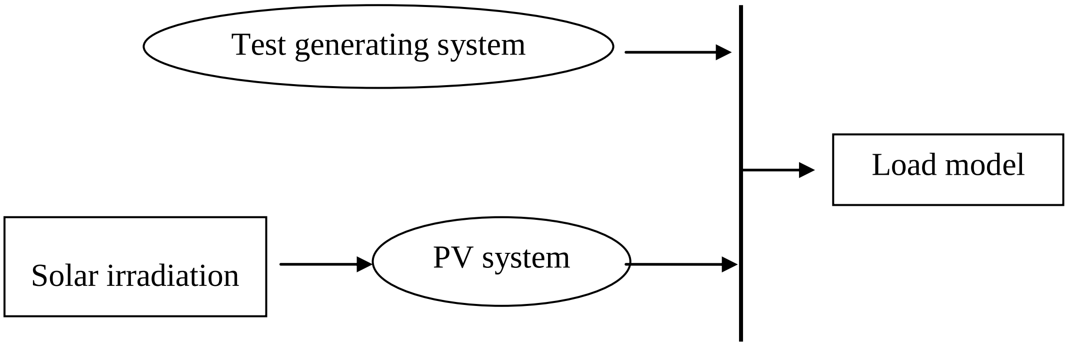

Figure 3.9: System reliability evaluation model incorporating PV generation

The adequacy effect of adding 15 kW of PV capacity to SIPS-1 was analyzed using PV data for Swift Current, Saskatchewan, Canada, situated at 50.3° N latitude. The PV capacity is 10% of the conventional generating capacity. The monthly average weather data for Swift Current are presented in the Appendix. The hourly solar irradiation data were first simulated using the WATGEN program. The output of this program is the input data for Model-I and Model-II described in Section 3.2.2 which are used to obtain the PV output power. The power output of a PV array is zero during the night.

The hourly solar irradiation, simulated using the WATGEN program, and the solar array parameters, required to define Model-I, are used in the WATSUN-PV to obtain the hourly output power of the PV unit. The output of the WATSUN-PV program and the generating units in SIPS-1 were combined with the hourly load model to calculate the LOLE and the LOEE using the SIPS+ program [36] as noted in Chapter 2. The SIPS+ software uses a sequential MCS approach. The SIPS+ includes the WATGEN and WATSUN-PV model and calculates the HL-I reliability indices incorporating the conventional generation and PV generation. The numerical results are shown in Table 3.1.

The approach described in Model-II was used to create a power output probability model for the 15 kW PV unit. This model was obtained by first simulating the hourly solar irradiation for a large number of samples. The probability p_{soi} for a given level of solar irradiation was calculated using Equation 3.9. A step size of 50 W/m^2 was used in this analysis.

$$p_{soi} = \frac{N_i}{N * 8760} \tag{3.9}$$

Where N is the number of simulation years, and N_i is the number of occurrences of solar irradiation in the range (Solar Irradiation$_x$, Solar Irradiation$_{x+1}$).

The power output of the 15 kW PV source was evaluated using Equations (3.4-3.8). The resulting probabilistic PV generation model consists of twenty two power output levels with their associated probabilities, as shown in Table 3.2 and Figure 3.10. The power output of the PV device depicted in Figure 3.10 is in per unit (p.u.), and was created using annual data for the particular location. In later studies, the hourly solar irradiation data for daytime and seasonal periods were utilized to build the power output states of PV units at selected sites using the same procedure described above. Table 3.3 shows the generation model developed for the three conventional units in SIPS-1. The SIPS-1 generation model in Table 3.3 was convolved with the PV generation model in Table 3.2 obtained using Model-II to create the overall system generation model. The system generation model thus obtained was combined with the hourly load model to obtain the LOLE and LOEE using the analytical approach described in Chapter 2. The results of this analysis are also shown in Table 3.1.

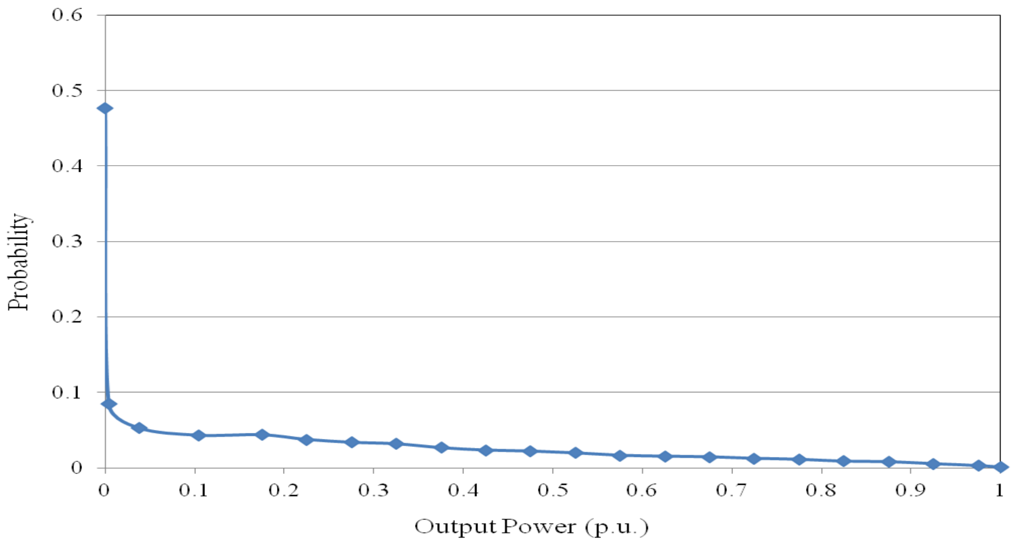

Figure 3.10: The annual PV generation model at Swift Current

Table 3.1 shows the improvement in system reliability due to adding 15 kW of PV power. The adequacy indices obtained using SIPS+ and the analytical techniques are similar. Model-II is utilized in all the following studies in this thesis to obtain PV output power states due to its simplicity compared to Model-I.

Table 3.1: The HL-1 annual system adequacy indices with the addition of 15 kW of PV power generation

	Without PV	Model-I using MCS	Model-II using analytical method
LOLE (h/y)	32.26	30.20	29.34
LOEE (kWh/y)	483.46	418.99	420.46

Table 3.2: The PV COPT model for Swift Current

States	Capacity In (p.u.)	Probability
1	0	0.47749
2	0.004	0.08486
3	0.038	0.05306
4	0.104	0.04347
5	0.175	0.0439
6	0.225	0.03785
7	0.275	0.03413
8	0.325	0.03212
9	0.375	0.02699
10	0.425	0.02379
11	0.475	0.02247
12	0.525	0.02014
13	0.575	0.01692
14	0.625	0.01568
15	0.675	0.01486
16	0.725	0.01285
17	0.775	0.01158
18	0.825	0.00909
19	0.875	0.00842
20	0.925	0.00578
21	0.975	0.00324
22	1	0.00121

Table 3.3: SIPS-1 model

States	Capacity In (kW)	Probability
1	0	0.000125
2	40	0.004750
3	70	0.002375
4	80	0.045125
5	110	0.090250
6	150	0.857375

3.4 Summary

The output power of a PV source cannot be easily controlled or predicted due to the number of random weather variables and the fact that the amount of solar irradiation reaching a solar array depends on many factors. A comparison of observed and the simulated hourly solar irradiation data is presented in this chapter. The hourly solar irradiation levels generated by the WATGEN [23] program replicates the actual data, and WATGEN is used in the following studies. This program is a practical tool for studying most locations around the world as only monthly average data and latitude are required.

Model-I estimates the output power of a PV source using the relationship between I-V and is used in WATSUN-PV. This model uses a MCS approach to evaluate the system reliability indices. Model-II evaluates the output power of PV using the relationship between solar irradiation and the output of a PV device as shown and explained in Figure 3.8. An analytical approach using a multi-state PV power model is utilized in Model-II presented in this chapter. Models I and II respectively are used in the described simulation and analytical studies to obtain the system adequacy indices. The results are relatively similar; Model-II applied in the analytical approach is a relatively simple method, and is used in the studies described in the followings chapters of this thesis.

Chapter 4

THE SYSTEM RELIABILITY CONTRIBUTIONS OF PV POWER GENERATION CONSIDERING VARIOUS FACTORS

4.1 Introduction

Solar power is being increasingly utilized in electric power systems. This source has however a different effect on system reliability than conventional power sources due to the intermittent nature of the atmospheric conditions at the system location and the solar array location. The solar irradiation varies throughout the day and seasons, and is influenced by cloud cover. These factors play an important role in the PV output power and therefore it is important to consider the impact of these factors in the reliability contribution of PV devices in meeting energy demand.

The basic generating system adequacy model for an electric power system, including solar energy, is shown in Figure 4.1. The output power of a PV unit is represented by a multi-state probabilistic model as in the case of a wind turbine generator (WTG) [54-56]. The analytical method described in Chapters 2 and 3 is used to perform the adequacy analysis using data from different locations around the world.

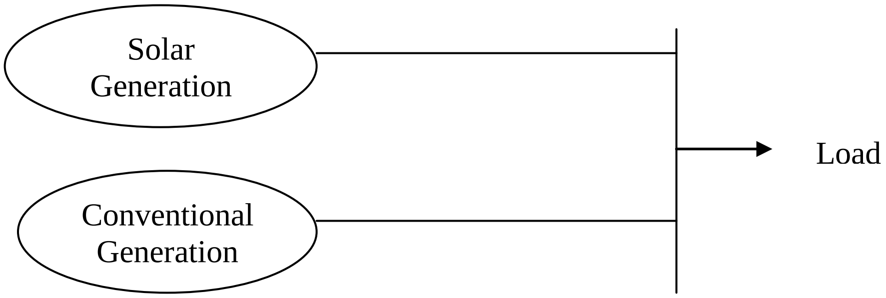

Figure 4.1: The basic generating system model

This chapter discusses the application of the developed model in a small power system including a PV source. The LOLE and LOEE indices are evaluated considering the following factors: (i) system peak load variation, (ii) installed capacity of PV, (iii) daytime contribution, (iv) seasonality effects, (v) effects of latitude, and (vi) cloud cover. The analyses discussed in this chapter are conducted at HL-I using the RBTS and SIPS-1.

4.2 Effects of Peak load Variation and PV Installed Capacity on System Adequacy

The SIPS-1 test system described in Section 3.3 was used to conduct two basic studies. The first study examines the effect of peak load variation on the system adequacy. The second study analyzes the reliability contribution of adding additional PV generation to the test system. The annual system load is utilized in both studies, and the system peak load is varied from 80kW to 118 kW. The system LOLE and LOEE at a peak load of 80 kW are 32.26 h/y and 483.46kWh/y respectively, before adding any PV capacity.

It is assumed that a PV park consisting of a number of PV arrays are connected to the SIPS-1 in both studies. Solar irradiation data from Solar Village, Saudi Arabia situated at 24.91^{o}N latitude are used. The required monthly solar irradiation and weather data are provided in the Appendix. The system LOLE was computed for different cases in which the test system was expanded utilizing different installed PV capacities, ranging from 10% to 20% of the total test system conventional generating capacity. The per unit PV COPT model used to represent different installed PV capacities is shown in Figure 4.2. The probability of zero output is 0.46, and is not shown in this figure.

Figure 4.3 shows that the LOLE increases as the peak load increases. Figure 4.3 also shows how adding more PV generation to SIPS-1 improves the LOLE. It can be seen from Figure 4.3 that the system LOLE was 118 h/y before adding PV at a peak load of 104 kW. The system LOLE decreases by approximately 21%, 27% and 31% by adding approximately 15 kW, 24 kW, and 31 kW of PV generation, respectively. The system reliability increases with further installed PV capacity. The incremental reliability benefits, however, decrease, after certain a point no further reliability benefit can be obtained by further increasing installed PV capacity.

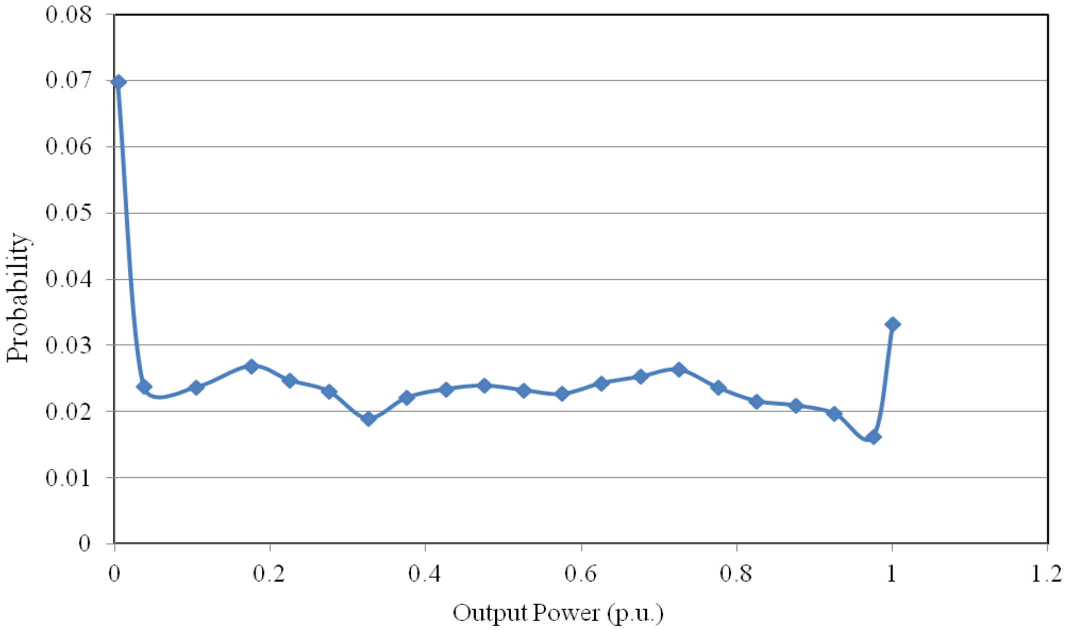

Figure 4.2: The annual PV COPT model at Solar Village

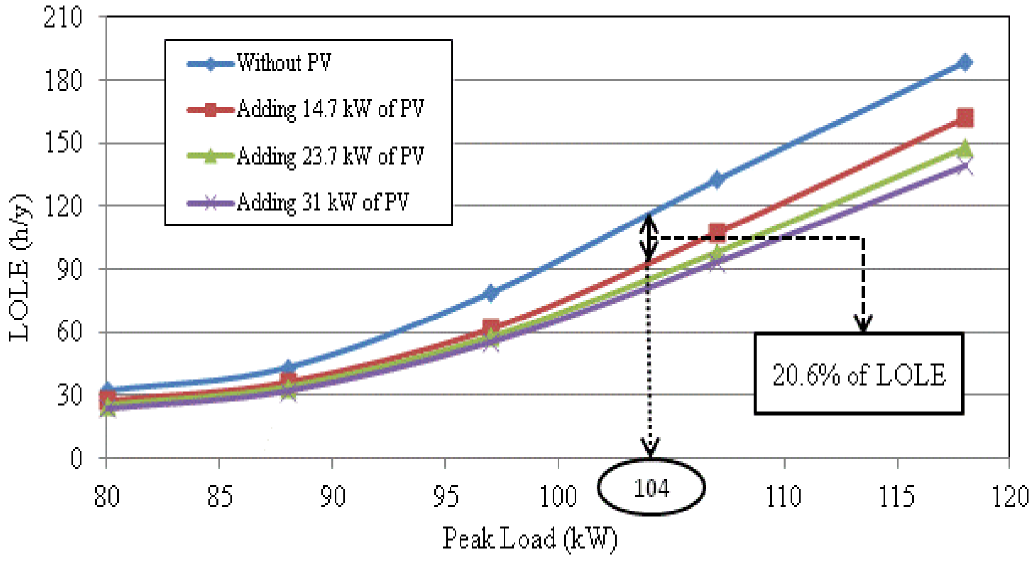

Figure 4.3: Variation in risk level with system peak load at Solar Village for different PV installations

4.3 Seasonality Effects on System Adequacy

A preliminary study of the mean seasonal variation in solar irradiation (MJ/m^2) at Solar Village indicated that seasons have direct impacts on the amount of solar irradiation as shown in Figure 4.4. It is clear that maximum seasonal solar irradiation occurs in the summer followed by spring and fall, and the minimum solar irradiation occurs in the winter. The PV power output models were evaluated for each season, and the seasonal impacts on system reliability were studied using SIPS-1. This section investigates the reliability contribution of PV generation located in a solar park at Solar Village.

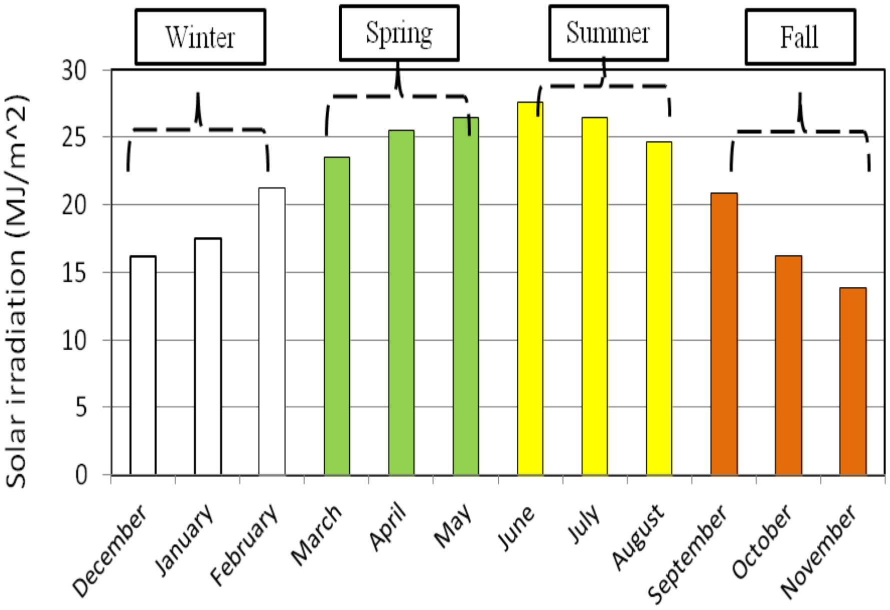

Figure 4.4: Monthly averaged solar irradiation at Solar Village

The following four steps were used to examine the seasonal impacts on the system reliability:

1) The system risk level before adding PV was evaluated for each season using the seasonal hourly load models. The system LOLE indices in winter, spring, summer and fall without adding PV generation are 9.28, 7.27, 7.92 and 7.78 h/season, respectively, for an annual peak load of 80 kW. The annual LOLE index is obtained by summing the respective seasonal LOLE indices.
2) The PV COPT models for each season are shown in Figure 4.5. The probability of zero output for winter, spring, summer and fall are 0.5, 0.44, 0.42 and 0.49, respectively.
3) Thirty one kW of PV was added to SIPS-1. The LOLE profile after adding 31 kW of PV for each season is shown in Figure 4.6 for an annual peak load of 80 kW.

Figure 4.6 shows that the summer period provided the largest reliability contribution from the added PV generation at Solar Village.

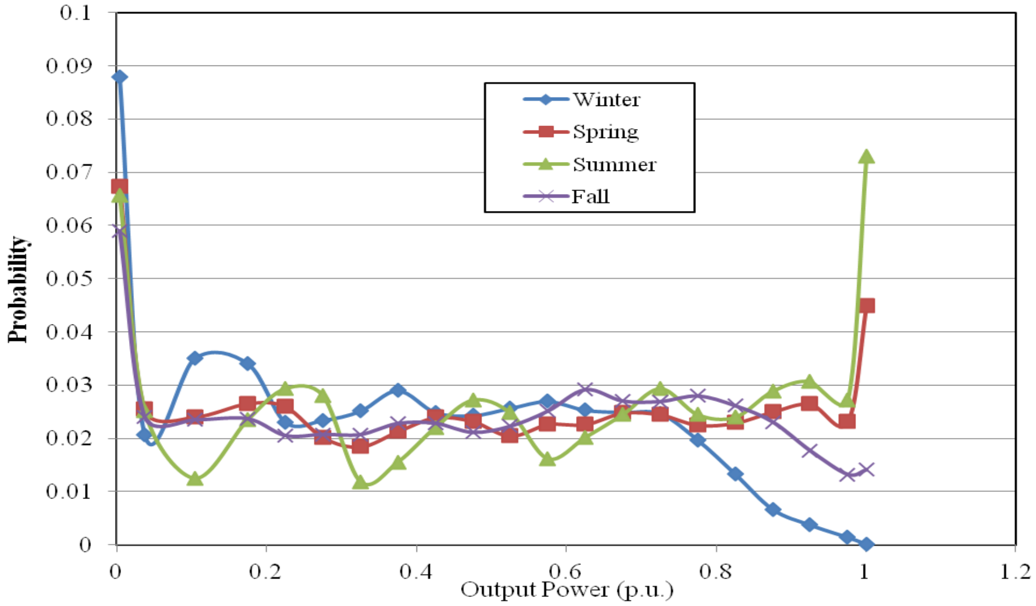

Figure 4.5: The PV COPT models at Solar Village for the four seasons

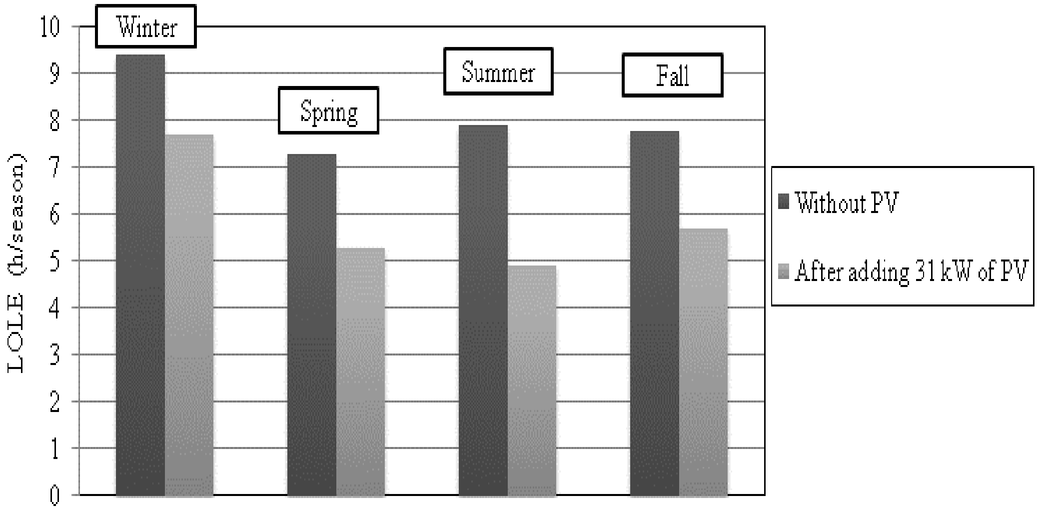

Figure 4.6: System risk at Solar Village for the four seasons

4.4 Daytime Contribution to System Reliability

The spectral distribution of solar irradiation is effected by the time of day, and is correlated with the hourly load model in the daytime. There are significant differences in the annual distribution of the solar irradiation between the daytime and the whole day, including day and nighttime, as shown in Figure 4.7. The analysis of the reliability contribution of PV in the daytime is described in this section.

The SIPS-1 and the annual load model described in Section 3.3 were used in this study. This system is considered to be located in the middle of Saudi Arabia at Solar Village.

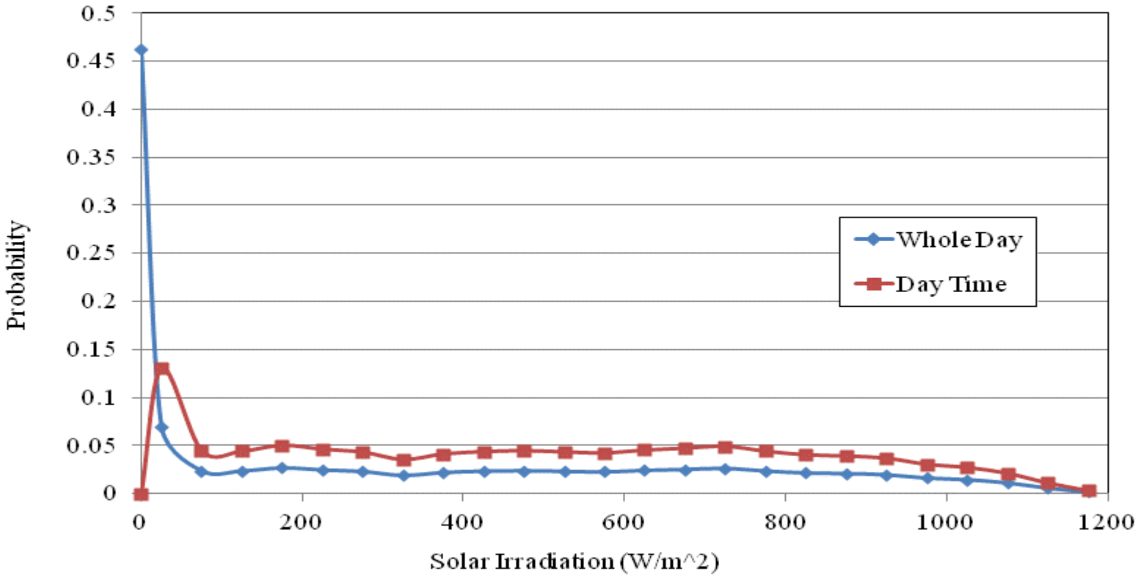

Figure 4.7: The annual distribution of the solar irradiation at Solar Village

The steps to evaluate the daytime impacts on the adequacy evaluation are as follow:

1) The annual risk level for the test system before adding PV was determined. The system LOLE is 32.26 h/y for annual peak load of 80 kW.
2) Thirty one kW of PV capacity was added to SIPS-1 to evaluate the new LOLE.
3) The PV COPT models are then calculated and shown in Figure 4.8. The probability of annual zero solar irradiation is approximately 0.46 when the nighttime is included, but is not shown in Figure 4.8.

The results obtained from this analysis are illustrated in Figure 4.9. There is a reliability benefit from adding renewable PV energy to SIPS-1 shown by a reduction in the LOLE, as shown in this figure. This study demonstrates that there is a significant impact on system reliability during the daytime.

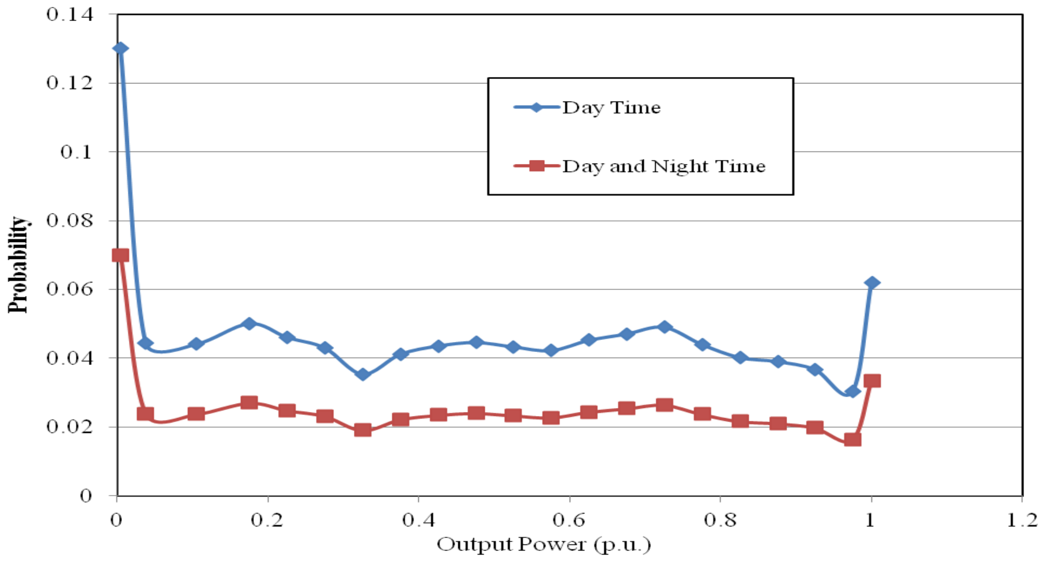

Figure 4.8: The PV COPT models at Solar Village for an annual model considering whole day and daytime periods

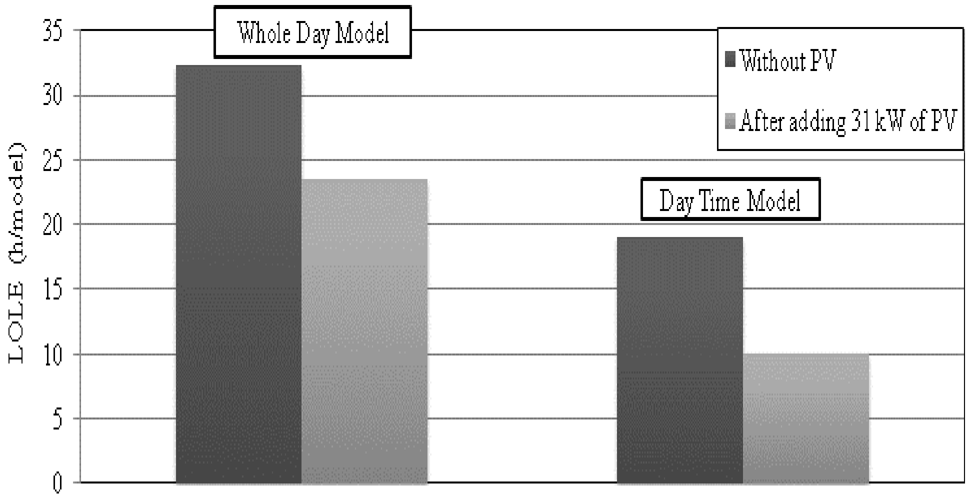

Figure 4.9: System risk at Solar Village for the two Models

4.5 Effects of Latitude on System Reliability

Solar irradiation is reduced due to absorption, scattering, and reflection in the earth’s atmosphere as stated earlier. This amount differs from one geographical region to another. A preliminary study of the mean seasonal variation of solar irradiation (MJ/m^2) for three different locations provided valuable insight on the impact of latitude on the solar irradiation. Figure 4.10 shows that the monthly solar irradiation at Singapore city, located in Singapore, which is close to the equator, is approximately constant for most of the year. This figure also shows that the variation in seasonal solar irradiation increases with the angle of latitude. The solar irradiation at Swift Current located at 50^0 N and Taipei located at 25^{0}N vary considerably throughout the year. Taipei has the highest amount of solar irradiation in summertime while Swift Current is lower as shown in Figure 4.10. It is, therefore, important to evaluate the impact of latitude on the reliability contribution of PV considering both annual and seasonal models.

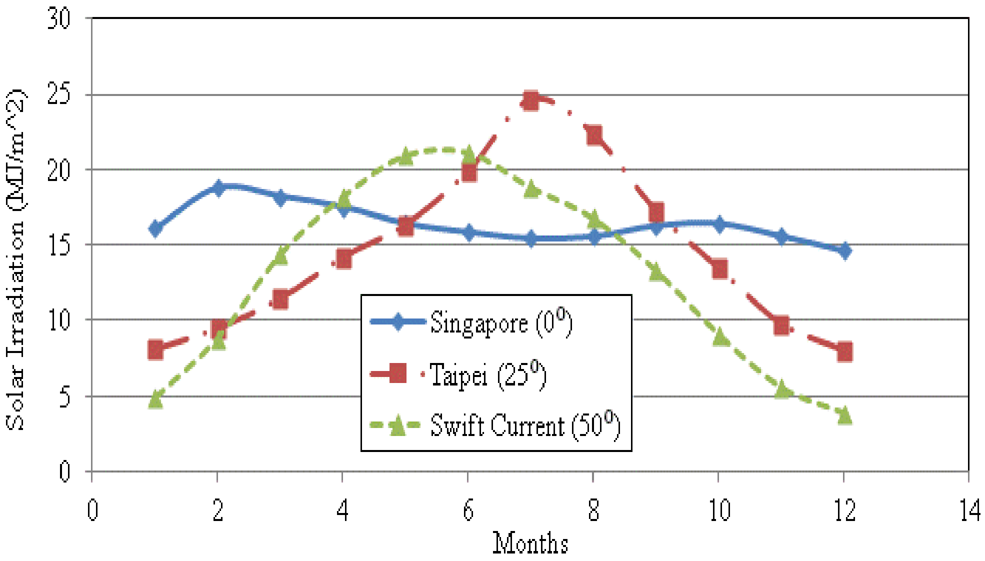

Figure 4.10: Monthly averaged solar irradiation at the three latitudes

The RBTS was used as the test system in this study. The details of the RBTS generation system including the FOR of each unit are given in the Appendix. The total generation capacity is 240 MW, and the system peak load is 185 MW.

4.5.1 Impact of Latitude Using an Annual Model

The annual hourly load model was used in the first study. The LOLE and LOEE without adding PV for the test system are 1.09 h/y and 9.86 MWh/y respectively for a peak load of 185 MW. Solar irradiation models were determined for latitudes of 0°, 25° and 50° roughly corresponding to Singapore city located in Singapore, Taipei located in Taiwan and Swift Current located in Canada, respectively. The monthly solar irradiation and weather data for these cities required to evaluate the PV output power are shown in the Appendix. The annual PV COPT models for these locations are shown in Figure 4.11. A comparison of the reliability contributions of PV at the three different locations was conducted using the LOEE index. Figure 4.12 shows that the LOEE decreases with the addition of 48MW of PV for all locations, but not to the same degree. It can be seen that the equator area has the highest PV contribution and that the PV reliability contribution generally declines as the distance from the equator increases. This is not always true, due to the impact of cloud cover, as discussed later in Section 4.6.

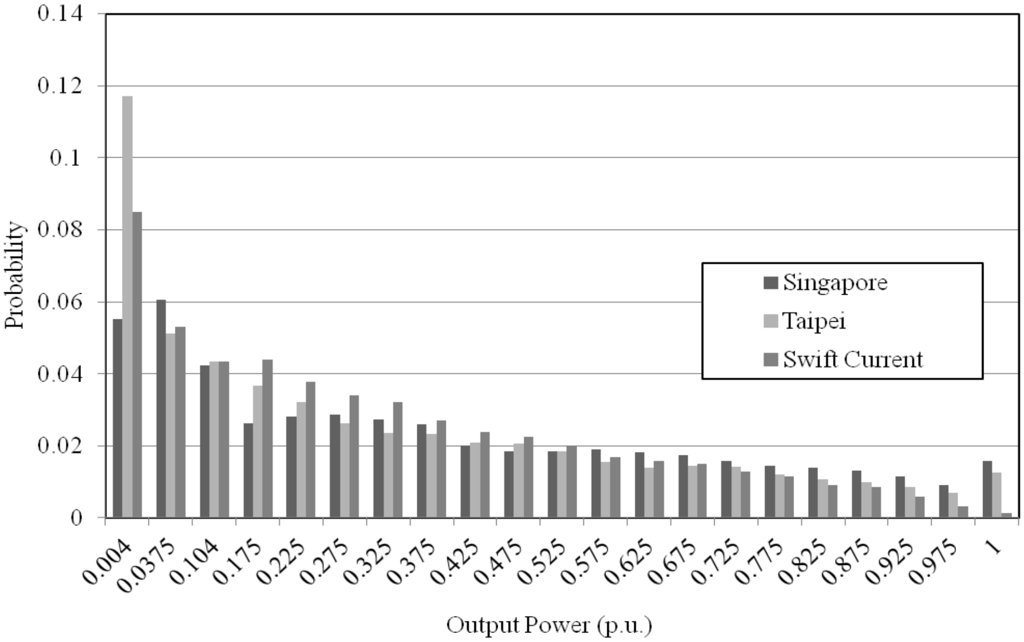

Figure 4.11: The annual distribution of the PV output power at the three different locations (Zero output power probability, not shown, is approximately 0.5)

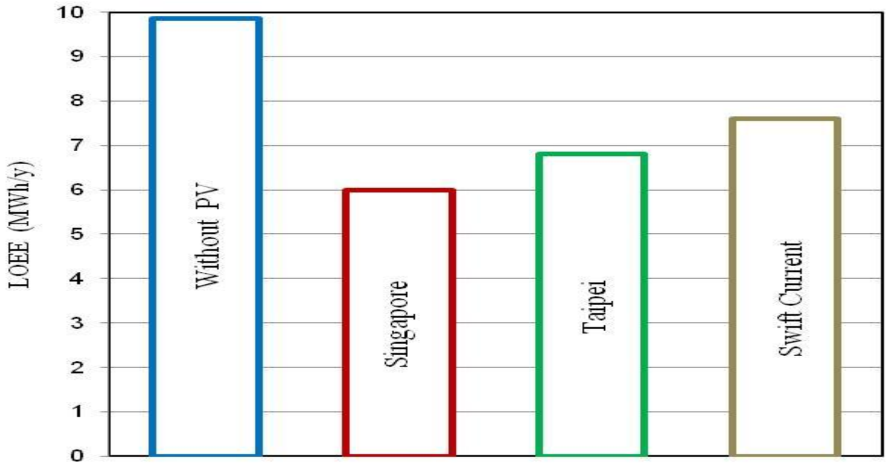

Figure 4.12: System risk at the three different locations

4.5.2 Impact of Latitude Using a Seasonal Model

An extension of the latitude impact on system reliability study was conducted for the same locations to evaluate the system reliability considering the winter and summer models for each location. The winter and summer PV COPT models for these locations are shown in Figures 4.13 and 4.14, respectively. The probabilities of zero output in winter for Singapore, Taipei and Swift Current are approximately 0.5, 0.51 and 0.62, respectively. The probabilities of zero output in summer for Singapore, Taipei and Swift Current are approximately 0.5, 0.42 and 0.35, respectively. The LOEE without PV for the winter and summer periods are 5.92 and 1.44 MWh/season, respectively. Forty eight MW of PV generation was added to the RBTS.

Figure 4.15 shows that the Swift Current location has the highest reliability contribution in summertime and has the lowest contribution in the winter. This is due to the fact that the daytime is long in summertime in Swift Current. This study demonstrates that the seasonal contributions to system reliability are important factors.

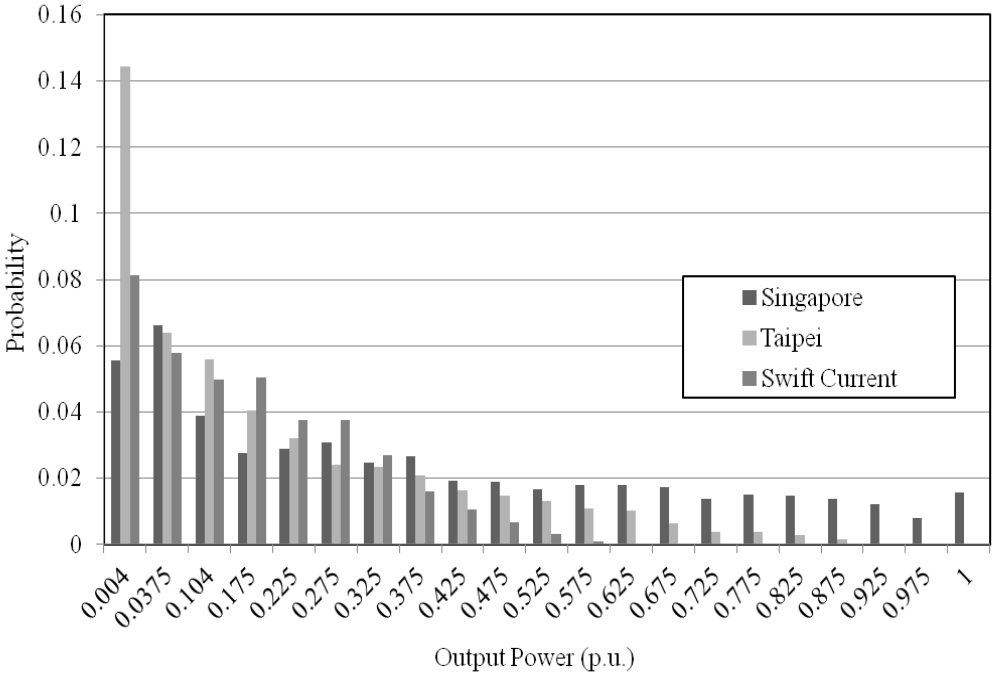

Figure 4.13: The winter PV COPT models for Singapore, Taipei and Swift Current.

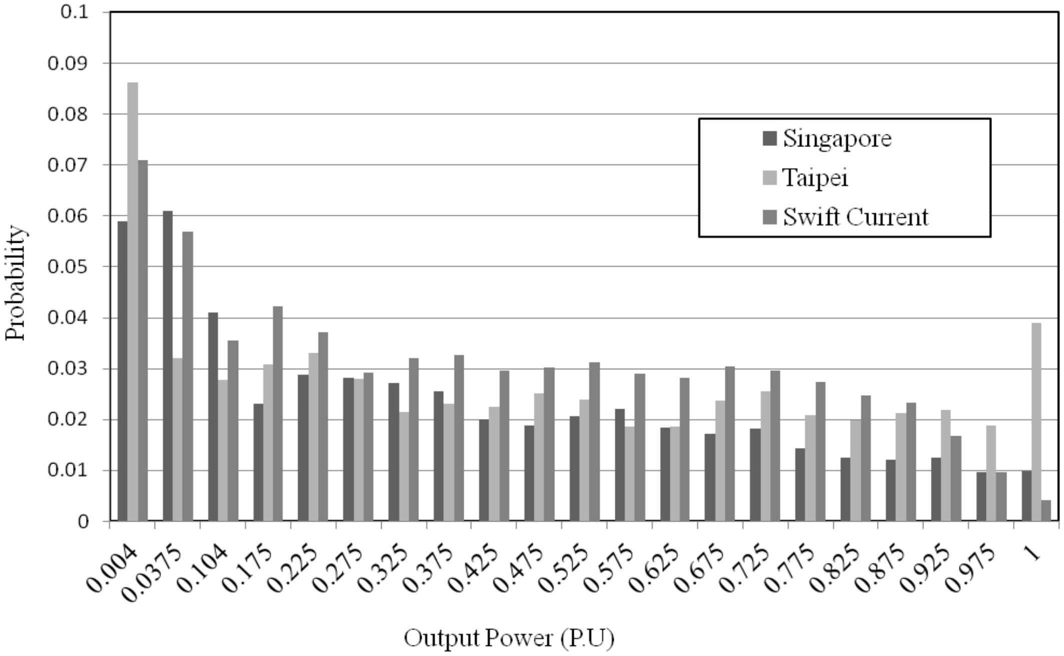

Figure 4.14: The summer PV COPT models for Singapore, Taipei and Swift Current

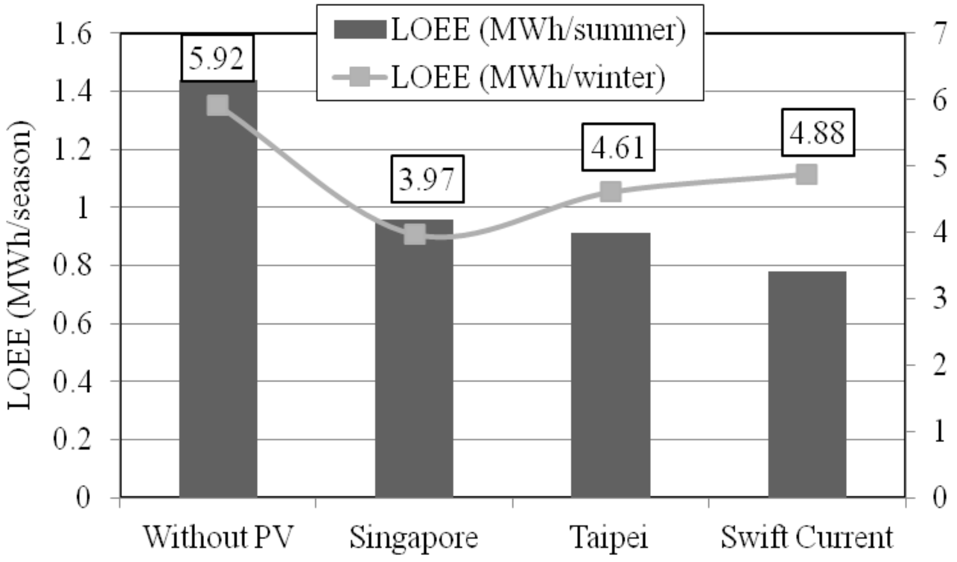

Figure 4.15: System risk at the three different locations using winter and summer data

4.6 Cloud Cover Contributions to System Reliability

The randomness of cloud cover is a significant factor, which can significantly affect the effectiveness of solar irradiation. Most researchers recognize cloud cover as an important factor affecting solar energy [57, 58]. Studying the effect of cloud cover on system reliability is therefore considered in this research. Two different sites, both located at approximately 25º latitude, corresponding to Solar Village and Taipei were used in this study. The two locations, however, have quite different cloud cover. The annual average daylight cloud cover at Taipei and Solar Village are 69.2 % and 28.7 %, respectively [49].

The RBTS was used in this study. The annual PV COPT models are shown in Figure 4.16. The probabilities of zero output for these models are approximately 0.46 at both locations. The system LOEE without added PV capacity is 9.86 MWh/y for a peak load of 185 MW. Forty eight MW of PV capacity was added to the RBTS. Table 4.1

shows the effect of cloud cover on the reliability contribution of solar energy at the two locations.

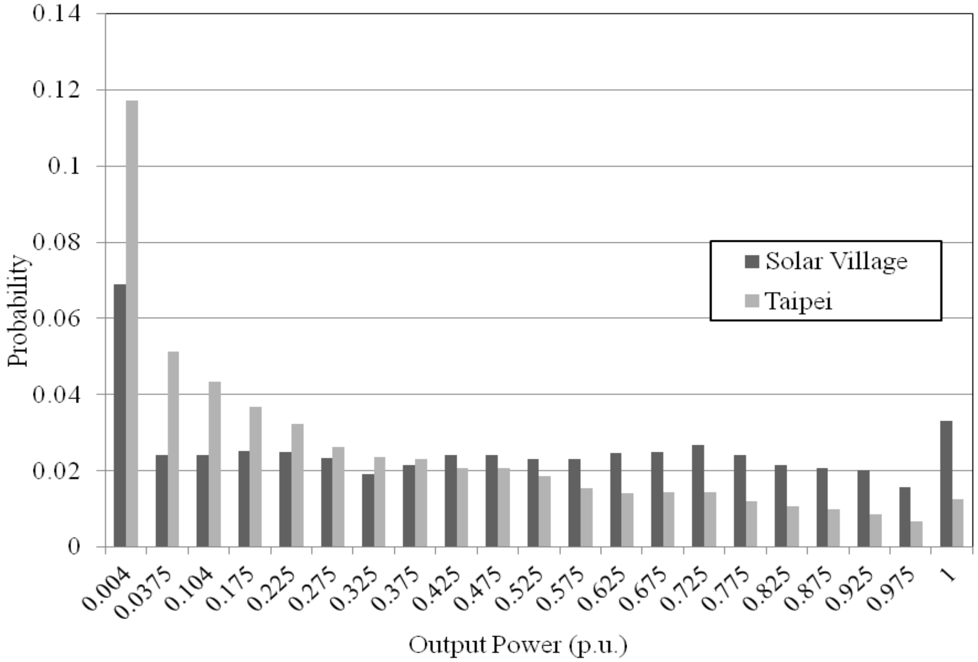

Figure 4.16: The annual PV COPT models at Solar Village and Taipei

Table 4.1: The adequacy effect of cloud cover

LOEE (MWh/y) Without PV	LOEE (MWh/y) with the addition of 48 MW of PV capacity at Taipei	LOEE (MWh/y) with the addition of 48 MW of PV capacity at Solar Village
9.86	6.82	5.81

4.7 Summary

This chapter presents the details of the adequacy analyses conducted on the two test systems in order to examine the reliability implications of adding PV generation. The assessment was conducted by comparing the LOLE and LOEE reliability indices for the test systems with and without PV integration.

Different factors, such as the effects of system peak load, the installed PV capacity, seasonality contributions, daytime effects, latitude and cloud cover, are discussed in this chapter. The results presented in this chapter illustrate how these factors affect the PV COPT models and the resulting system reliability. These models are applied to the RBTS and SIPS-1 to quantify the reliability contribution of PV.

The results obtained in this chapter illustrate that the system reliability is improved by increasing the amount of installed PV, however this increase in reliability is relatively small compared to that associated with conventional generation. The improvement in the system reliability is expressed in terms of reduction in the LOLE and LOEE. The reliability improvement decreases with increases in system peak load.

The results also demonstrate that knowledge of the solar power distribution at different times and in different locations are essential to obtain an overall picture of the system reliability. The analyses indicate that reliability contributions of PV capacity differ from season to season and are highly dependent on the PV site location. The studies also indicate that cloud cover can strongly impact the system adequacy benefits of PV capacity.

Chapter 5

SOLAR ENERGY CAPACITY VALUE ASSESSMENT

5.1 Introduction

Peak electrical load levels have gradually increased with population growth and it is essential to plan the addition of new generating capacity to meet this demand at an acceptable level of system reliability. System planners have a variety of generation sources that can be called upon to supply the system load and one of them is solar energy. The installation and integration of large scale PV generating facilities are growing rapidly around the world. Accurate estimates of the capacity value of PV generation are therefore critical for planning purpose.

Capacity credit is a measure of the load carrying contribution that solar energy can make in an electric power system. A number of techniques have been considered to calculate the capacity credit of power system generating sources [59, 60]. These methods are diverse in terms of simplicity and data requirements, and the most comprehensive techniques utilize basic reliability indices such as LOLE and LOEE [61]. The capacity contribution can be expressed in terms of physical capacity (kW, MW) or the fractional capacity (%). Effective load carrying capability, capacity credit and capacity factor are utilized in this research to estimate the physical capacity value and the fractional capacity contribution of adding PV generation to an electric power system.

This chapter presents the concepts and technical processes of calculating the capacity value of adding PV generation in terms of the effective load carrying capability (ELCC), capacity credit (CC) and capacity factor (CF). These contribution indices are evaluated considering different factors such as the effects of latitude, installed PV capacity, seasonality effects and cloud cover.

5.2 Effective Load Carrying Capability

The ELCC is the oldest basic approach to calculate the capacity contribution of new generation [62]. It can be considered as the total amount by which the system peak load can increase when new generation is added to the system, while maintaining the system reliability criterion [62].

The ELCC is a useful index for evaluating the PV capacity value as it is easy to understand and provides a physical contribution measure due to the additional capacity. The concept of determining the increase in system load due to adding new generation while maintaining a constant specified risk level is illustrated in Figure 5.1 [62]. The specified risk index used in this study is the LOLE. The ELCC depends on a number of factors such as the size of the existing and added generating units, the unit FOR, the peak load and the system risk criterion.

Figure 5.1 shows the annual system risk versus the annual system peak load before and after adding new generation. In this figure, the original power system generation risk level is represented by the solid curve and the system risk profile after adding the new generation is shown by the dotted curve. The ELCC is estimated from the graph using the system capacity reliability criterion designated as R^* in Figure 5.1. The North American Electricity Reliability Corporation (NERC) recommended capacity adequacy criterion is 0.1 d/y [63]. In the following studies, the risk level R^* is the LOLE of the system before adding new generation.

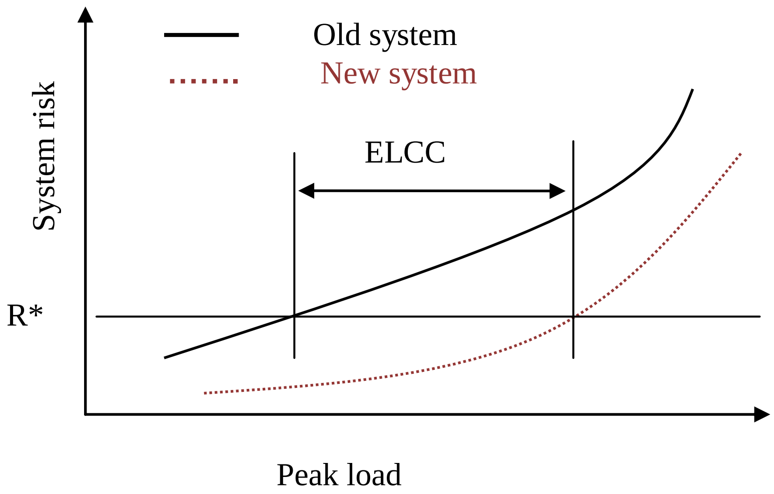

Figure 5.1: Evaluation of ELCC

5.3 Capacity Credit

Capacity credit (CC) is an important parameter in capacity value evaluation and has been applied extensively to assess the capacity contribution of wind power generation. In a general sense, CC is a measure of the contribution of a power generating source to meeting the load carrying capability of the system at a specified risk level [64-66]. The CC of a PV generating unit in this research is obtained using Equation 5.1.

$$CC\ (\%) = \frac{ELCC}{C_A} \times 100 \tag{5.1}$$

C_A is the rated capacity of the added generating unit.

The procedure used to determine the capacity credit of a PV installation involves the following five steps:

1. Define the system risk level before adding the PV generation to the power system.

2. Add the PV capacity to the system reliability model.
3. Increase the system peak load and calculate the system reliability.
4. Evaluate the ELCC.
5. Use Equation 5.1 to calculate the CC.

5.4 Capacity Factor

The CF is a useful index to assess the capacity value of PV generation [67]. It is defined as the ratio of the expect output power over a designated period of time expressed as a percentage of the rated capacity, as shown in Equation 5.2. The rated installed capacity of a solar park is the combined maximum power of each solar cell. The CF is considered as a quantity factor that measures the capacity value of a PV energy source and is a key index used to assess the productivity of energy generation [68]. This factor does not have any relationship to the load model and is not related to PV penetration. The expected annual capacity can be obtained using Equation 5.3.

$$\text{CF (\%)} = \frac{EC}{RC} \times 100 \tag{5.2}$$

$$\text{EC} = \sum_{i=1}^{n} P_i \times PO_i \tag{5.3}$$

Where:

EC : expected capacity.

RC : rated capacity.

P_i : probability in state i.

PO_i : power output in state i.

i : number of states.

5.5 Effects of Geographic Factors on the Capacity Value of PV Generation

The impact on the PV capacity credit of the various geographical factors, such as, the season, time of day, latitude and cloud cover are evaluated and presented this section.

5.5.1 Seasonality Effects on Capacity Credit

This section investigates the capacity value of PV generation associated with a single location solar park. The seasonal 22-state PV COPT model for Solar Village given in Figure 4.5 was added to SIPS-1. The LOLE was used in this study for capacity credit evaluation. In order to examine the seasonal impact on the PV capacity credit, the following four steps are required to determine the ELCC for each season:

1) Steps 1 and 2 utilized in Section 4.3 were applied.

2) The 22-state model for 14.7, 23.7 and 31 kW of PV generation were added to SIPS-1 to evaluate the HL-I indices as a function of the peak load.

3) The annual peak load was increased and the new system risk levels were evaluated for each season.

4) The amount of load that can be carried by the additional PV was determined by calculating the difference between the two risk profile system with and without the PV addition at the risk level obtained in step 1 for each season. Figure 5.2 shows the ELCC associated with adding 31 kW of PV to SIPS-1 in the summertime. The ELCC for each season was calculated in the same way.

Equation 5.1 was applied to evaluate the capacity credit for different PV installations for each season. Installed PV capacity levels of 14.7, 23.7 and 31kW corresponding to approximately 10%, 15% and 20% respectively of the conventional capacity were considered. Figure 5.3 shows the PV capacity credit at Solar Village for the four different seasons.

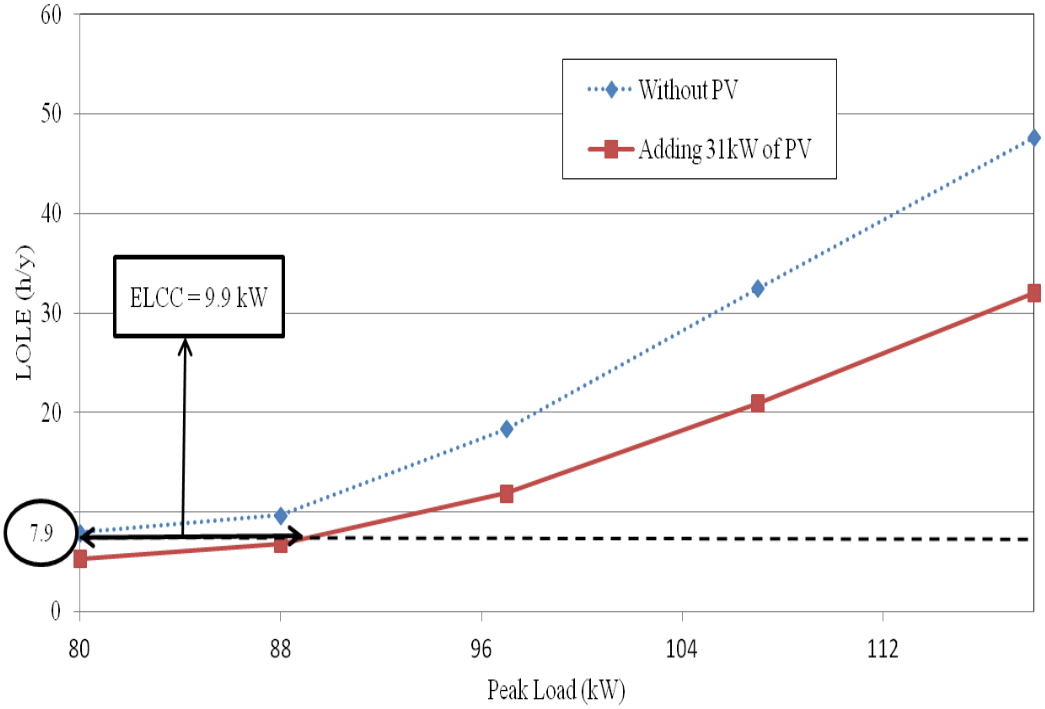

Figure 5.2: Variation in risk with system peak load at Solar Village for the summer period

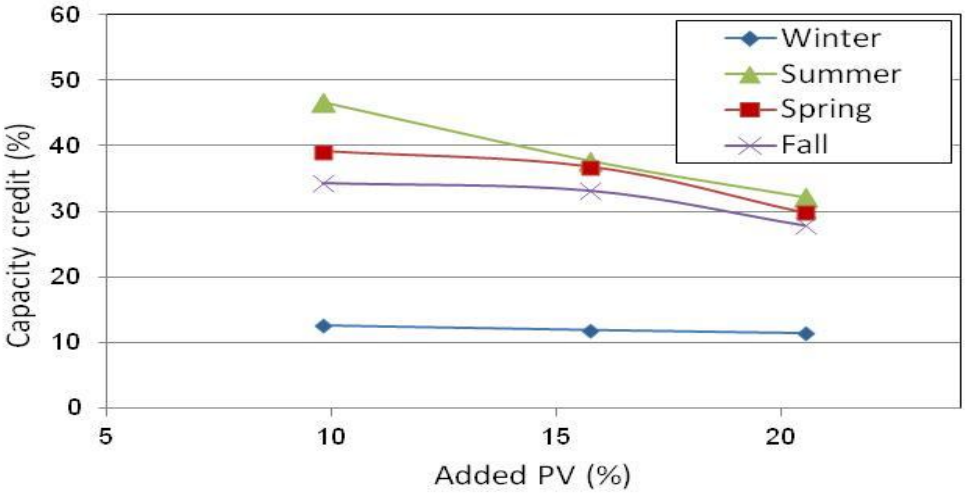

Figure 5.3: Capacity Credit for different seasons at Solar Village

An analysis of this study resulted in several important observations:

- The results clearly illustrate that the summer period provides the largest PV capacity contribution at Solar Village.
- There is improvement in the power system reliability by adding more PV capacity to the test system, as shown in Figure 5.2. The relative reliability contribution as measured by capacity credit, however, decreases as more PV capacity is added, as shown in Figure 5.3. These results are obtained by adding more PV capacity to the SIPS-1 while maintaining the system reliability level. Previous conducted studies [19, 36] agree with the observation that no further reliability improvement can be obtained by increasing the installed PV capacity.

5.5.2 Daytime Effects on the PV Capacity Credit

This study is an extension of the work presented in Section 4.4 to investigate the capacity credit using the annual and daytime models. The SIPS-1 and the annual and daytime hourly load models described in Section 4.2 were utilized in this study. The PV generation system is located at Solar Village. The steps to evaluate the PV capacity credit in which each model is individually combined with the test system are described as following:

1) Steps 1 and 2 utilized in Section 4.4 were used.

2) The annual PV COPT models for 14.7, 23.7 and 31 kW of PV capacity were added to SIPS-1 to determine the LOLE for peak loads of 80, 88, 97, 107 and 118 kW.

3) The ELCC was evaluated for each model. The maximum allowable peak load at a risk level of 32.26 h/y in SIPS-1 with a PV addition of 31 kW is 88.1kW. The ELCC in this case is 8.1 kW, as shown in Figure 5.4.

4) The capacity credit values were determined using Equation 4.1, for the 14.7, 23.7 and 31 kW PV capacity additions.

5) The steps from 1 to 4 were repeated considering the daytime model only.

The results obtained from the above steps are illustrated in Figure 5.5. The following conclusions were obtained from the analyzed results:

- The benefit of adding renewable energy to the system in the form of PV capacity expressed by reducing LOLE, is clearly shown in Figure 5.4.
- The PV capacity credit decreases with increased installed PV capacity.
- This study illustrates that the PV capacity credit considering only daytime periods is almost twice the PV capacity value considering the annual model as shown in Figure 5.5.

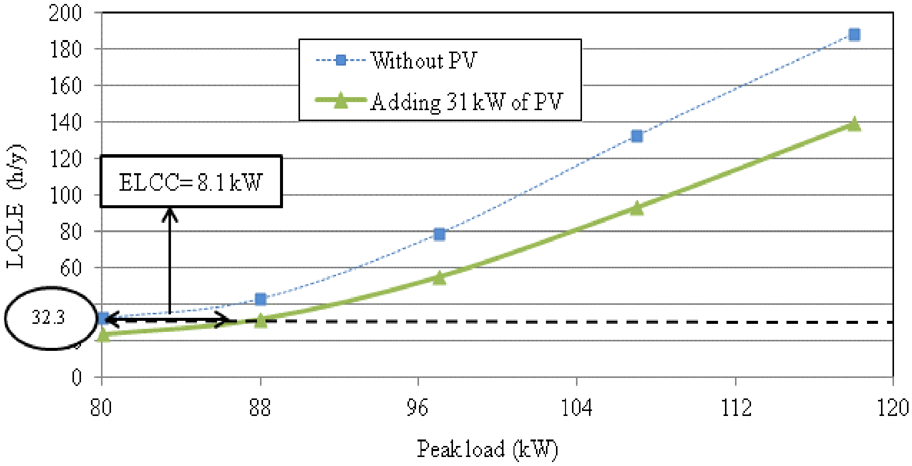

Figure 5.4: Variation in risk with system peak load at Solar Village using an annual model

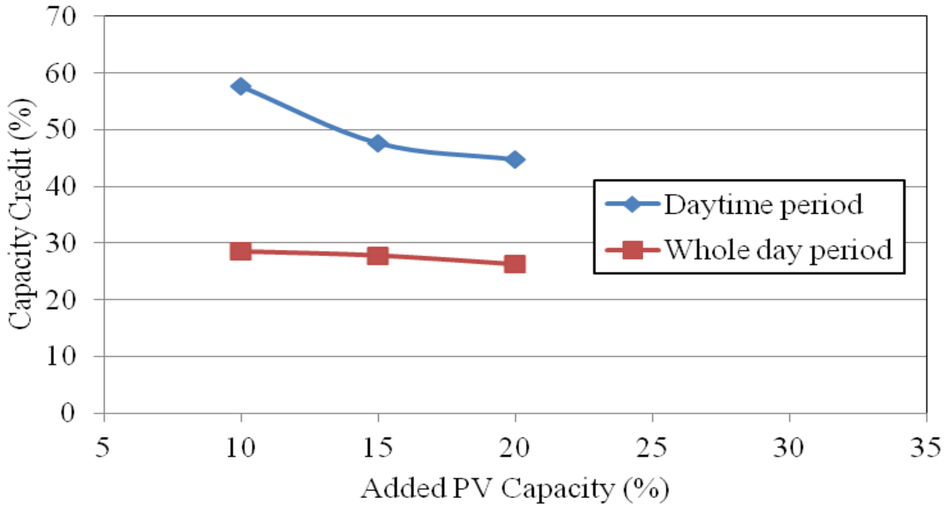

Figure 5.5: The PV Capacity Credit at Solar Village

5.5.3 Latitude Effects on Capacity Credit and Capacity Factor

The capacity credit and the capacity factor of PV for different latitudes are an extension of the study presented in Section 4.5. The annual PV COPT models for Singapore, Taipei and Swift Current are individually added to the RBTS to determine the LOLE. The LOLE without PV capacity is 1.09 h/y for a peak load of 185 MW. The LOLE with the added PV capacity was evaluated for peak loads of 185, 190, 195, 200 MW. The ELCC for each location then was evaluated at a risk level of 1.09h/y in the RBTS with the addition of 24, 36 and 48 MW of PV capacity. The CC was determined for each addition.

The analysis demonstrates that the PV Capacity Credit decreases with added generation at all three locations. Figure 5.6 shows that the capacity credit of the PV unit installed at Singapore is significantly higher than that for a similar installation at Taipei and Swift Current.

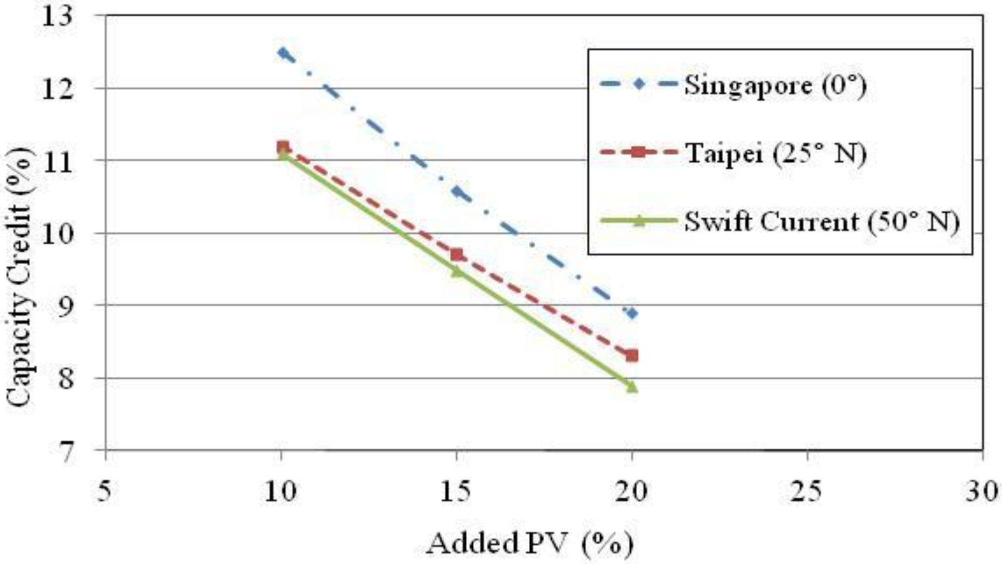

Figure 5.6: Capacity Credit at the three different locations

This work was extended to evaluate the impact of latitude on capacity factor. The expected output power and the rated capacity are required to estimate the capacity factor using Equation 5.2. The expected capacity obtained from the annual distribution of the PV output power shown in Figure 4.11 was determined using Equation 5.3 for the 24, 36 and 48 MW PV capacity additions.

The results presented in Figure 5.7 demonstrate that the capacity factor varies significantly with the changes in geographic location. The yearly capacity factor at Singapore is considerably higher than that at Taipei or Swift Current since Singapore is located on the equator. Overall system information including conventional generation and hourly load data are not included in the capacity factor analysis and the calculated index is simply a measure of PV installation performance.

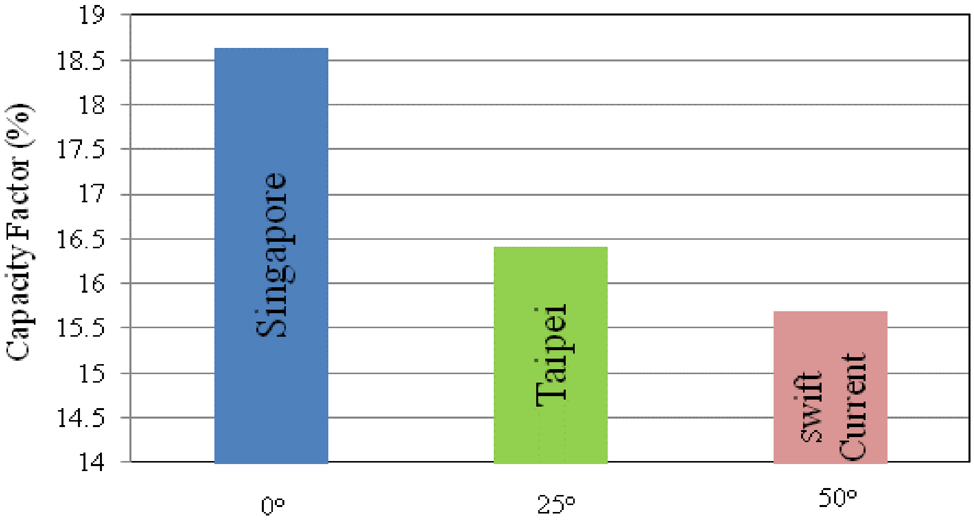

Figure 5.7: Capacity Factor for different latitudes

5.5.4 Cloud Cover Effects on Capacity Credit

The system generation and load models applied in Section 4.5.1 were used to evaluate the impact of cloud cover on PV capacity credit. The procedure for estimating the PV capacity value illustrated in Section 5.5.2 was used in this study considering weather data at the two locations. These locations are located at the same latitude, but have different amounts of cloud cover as indicated in Section 4.6. Forty eight MW of PV capacity was added to the RBTS. Table 5.1 shows that the degree of cloud cover has a big impact on the PV capacity credit.

Table 5.1: Cloud cover effect on the capacity credit of a PV unit

Added PV capacity MW	Capacity Credit (%) at Taipei	Capacity Credit (%) at Solar Village
20	8.3	11.7

5.6 Summary

The addition of large amounts of PV generation is accelerating throughout the world due to the decreasing cost of solar cells and the financial incentives provided by some organizations. Economic benefit of solar energy technology in an electric power system however depends on the capacity value of PV generation. This chapter presents three different techniques to estimate the capacity value of PV generation designated as effective load carrying capability, capacity credit and capacity factor.

The probabilistic method for evaluating the generation adequacy is applied to estimate the ELCC and CC of PV generation and these two quantities provide a physical measure of the capacity value of PV for different PV installed capacities. The amount of actual energy produced by a solar energy system in a specific period relative to the maximum power output of the solar system is the CF of the PV unit. The ELCC and CC identifies the capability of this source to carry additional peak load at a given risk level

The impact of daytime, season time, latitude and cloud cover on the capacity value of a PV power source is illustrated in this chapter. The analysis indicates that the CC of a PV power source decrease as more PV capacity is added to the system. The study illustrates that the biggest seasonal contribution to PV power output occurs during the summer season and that PV site location and cloud cover plays an important role in the amount of capacity credit of a PV power generation facility.

Chapter 6

SUMMARY AND CONCLUSIONS

Many developed countries support electric utilities in their use of environmental energy sources such as solar and wind power due to the gradual increase of CO_2 production. Due to this encouragement, the application of these two energy sources has grown rapidly. Solar energy was the focus in this research. Solar energy is variable and intermittent by nature and therefore evaluating and assessing the reliability contribution of solar power and the capacity value of PV generation are an important requirement in generating capacity planning. The fundamental objective of this research was to evaluate the reliability contribution and the capacity value of PV sources considering various important factors. The reliability indices used in this thesis assess generation system adequacy at HL-I.

Chapter 1 presents a brief introduction to power system reliability evaluation including the general concepts of adequacy and the three hierarchical levels of a power system. Chapter 2 explains different technical methods to determine the system generation reliability. These methods can be categorized as deterministic and probabilistic techniques and both approaches are briefly discussed in this chapter. Probabilistic techniques were used in this research work. The basic indices used in the simulation and analytical approaches are presented in Chapter 2. Both methods apply the same basic concept, which combines the generation model and the load model to estimate the system reliability indices. The SIPS+ program [36] was used to determine the basic reliability indices of the test systems using the sequential MCS method.

The annual reliability indices for two test systems, the RBTS and SIPS-1, obtained using both sequential MCS and analytical techniques are compared in Chapter 2. The basic reliability indices from the simulation and analytical approaches are fairly similar when using an appropriate number of simulations. The sequential MCS approach requires considerable simulated samples to obtain an accurate result and consumes more computing time when compared to the analytical method. The analytical technique utilizes relatively simple numerical calculations and it was therefore used in the detailed studies in this thesis.

Chapter 3 presents the adequacy evaluation process for a power system including PV energy. These steps are divided into the three levels of modeling solar irradiation, determining the output power of a PV source and calculating the system risk.

A significant amount of historical hourly solar irradiation data at desired locations is required to develop an appropriate solar irradiation model for a particular area. Recorded hourly solar irradiation data are, however, often unavailable for many sites around the world. The hourly solar irradiation probability distributions obtained using the WATGEN simulation [23] program and the actual data at Solar Village located at 24.91° N, 46.41° E [48] in Saudi Arabia are compared in Chapter 3. The output analysis of the simulation program provides a reasonable comparison to the actual historical data, and the WATGEN program was therefore used in this project to generate hourly solar irradiation values for desired locations. This program requires only monthly averages of weather and solar irradiation data. The overall procedure of the WATGEN program [23] is introduced in Chapter 3.

Model-I and Model-II are presented in Chapter 3 to calculate the generated power from a solar cell. Model-I uses a thermodynamic model [24] based on the I-V characteristic of the solar arrays provided by the manufacturer, and the relationship between I and V is a non-linear curve. The WATSUN-PV [24] program was utilized to generate the hourly output power of a solar cell in Model-I. The output results of the WATSU-PV program were used as inputs to the SIPS+ [36] program to obtain the HL-I reliability indices in Model-I. Model-II depends on hourly solar irradiation and solar cell efficiency, and was used in the analytical approach to obtain the LOLE and LOEE.

Model-I and II were compared to evaluate the reliability contribution of adding approximately 15 kW of PV capacity to SIPS-1. This study was conducted using PV data for Swift Current located at 50.3° N latitude. The results of this study indicate the improvement in system reliability when 15 kW of PV energy is added to SIPS-1. The LOLE and LOEE obtained using SIPS+ and the analytical approaches are reasonably similar. The numerical calculation procedure in Model-II is much simpler, and was therefore used in this research.

The simplified analytical model was used to investigate the reliability contribution and the capacity value of a PV source considering peak load variation, installed PV capacity, geography and weather factors. Solar power depends on daytime, the season of the year, the location of the solar cell panels and cloud cover. All these factors were considered to calculate the reliability contribution, CC, ELCC, and CF and discussed in Chapters 4 and 5.

The effect of using different installed PV capacity when the peak load was varied was analyzed using SIPS-1. This study was assumed to be located at Solar Village. The results demonstrate that the peak load has a significant impact on the LOLE. The analysis shows that there is improvement in system reliability by adding PV generation to the SIPS-1, however further increases in PV capacity show deceases in system incremental reliability benefit as the CC benefit declines.

The global solar irradiation changes from season to season. The output power of PV for different seasons was examined using SIPS-1 to evaluate the reliability contribution and capacity value of PV at a specified area. In this study, the PV capacity is assumed to be located at Solar Village. The results confirm that the summer period provides the greatest reliability contribution and capacity credit. This study was extended to examine the reliability contribution and capacity credit of PV in daytime since the pattern of hourly load data curve over a day is correlated with the hourly solar irradiation. The results indicate that the CC obtained from analyzing daytime data is almost double the CC considering the whole day model.

It is known that areas near the equator receive the largest amount of solar irradiation. Estimating the reliability contribution, CC and CF of PV units for different latitudes were performed using annual, summer and winter models. The RBTS was used in this study. Three different latitudes of 0º, 25º and 50º corresponding to Singapore City located in Singapore, Taipei located in Taiwan and Swift Current located in Canada, respectively, were considered. The results from the annual and winter models show that when solar panels are located close to the equator, there are more benefits in terms of system reliability and capacity value of PV generation. The reliability benefit and capacity values decrease as the geographic locations move from 0º to 50º using the annual and winter models. With the summer model, the reliability contribution and capacity credit of PV generation however increase as the geographic locations move from 0º to 50º.

Studies were conducted to evaluate the impact of cloud cover. The PV capacity was assumed to be located at Taipei and Solar Village. The analysis indicates that installing solar panels at Solar Village has a greater effect on the system reliability and CC than at Taipei as Solar Village has much lower amount of cloud cover. The results from the conducted studies quantitatively show that cloud cover has a significant impact on reliability contribution and CC of PV.

This thesis presents a procedure that can be used to integrate solar power in generating capacity reliability evaluation. The results of the studies conducted in this research illustrate the sensitivity of the calculated reliability indices to some of the important factors that should be incorporated in the reliability analysis of PV integrated electric power generating systems.

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APPENDIX

The generating unit data for the RBTS system is shown in Table A.1.

Table A.1: RBTS data

Unit Type	No. of Units	Rated Power (MW)	Failure Rate (occ/yr)	Repair Time (occ/yr)	Failure Prob.
Hydro	1	40	3	60	0.02
Thermal	1	10	4	45	0.02
Thermal	1	20	5	45	0.025
Hydro	2	5	2	45	0.01
Thermal	2	40	6	45	0.02
Hydro	4	20	2.4	55	0.015

The generating unit data for the small test system, SIPS-1 is shown in Table A.2.

Table A.2: SIPS-1 data

Unit No.	Rating (KW)	Failure Rate (occ/yr)	Repair Time (occ/yr)	Failure Prob.
1	70	950	50	0.05
2	40	950	50	0.05
3	40	950	50	0.05

The hourly load data in per unit of the peak load for the IEEE-RTS is shown in Figure A.1. This load profile is used for both the test systems, the RBTS and SIPS-1.

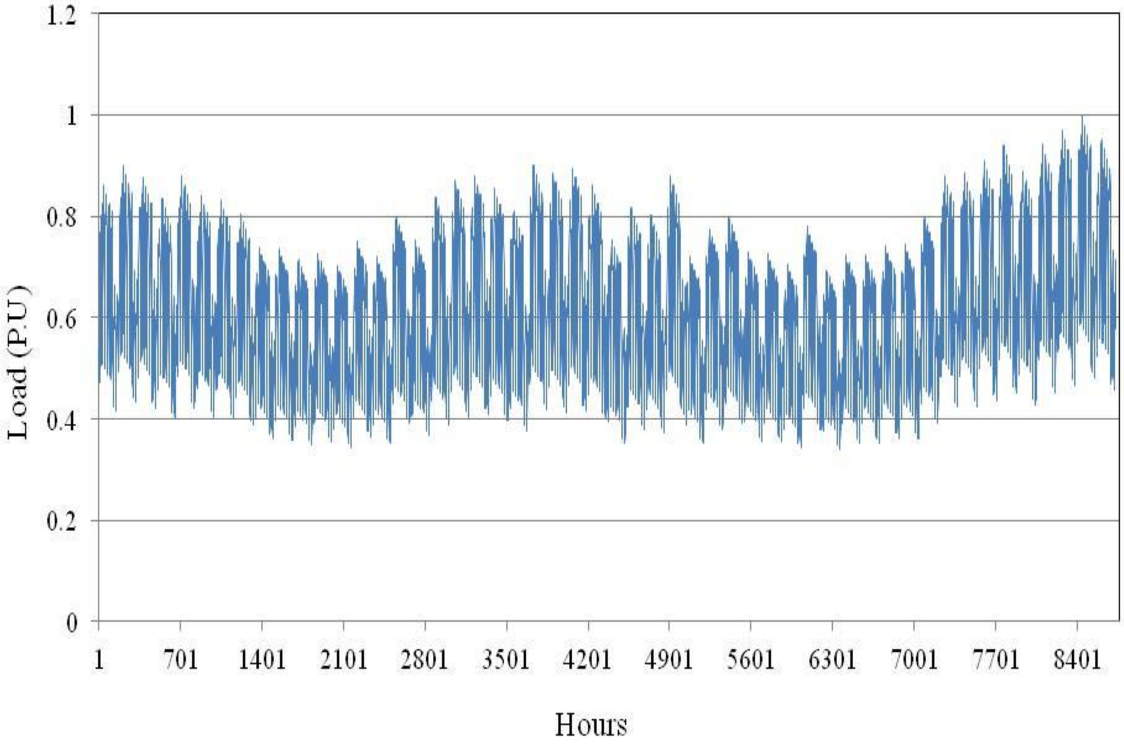

Figure A.1: Hourly load data in p.u.

The monthly average weather data for Solar Village is shown in Table A.3.

Table A.3: Monthly average weather data at Solar Village

Months	Wind speed (km/h)	Temperature (C)	Solar Irradiation (MJ/m^2)
January	15.59	12.81	16.20
February	17.53	19.4	17.50
March	17.46	20.2	21.28
April	17.98	25.5	24.74
May	15.97	32.2	25.10
June	17.89	35.03	26.25
July	17.94	34.89	27.59
August	15.66	35.49	26.58
September	14.07	33.09	24.95
October	12.87	27.01	21.18
November	14.04	21.55	16.19
December	13.65	15.96	14.6

The monthly average weather data for Taipei is shown in Table A.4.

Table A.4: Monthly average weather data at Taipei

Months	Wind speed (km/h)	Temperature (C)	Solar Irradiation (MJ/m^2)
January	23.04	17.6	8.14
February	21.96	17.7	9.47
March	19.08	19.4	11.45
April	16.56	22.1	14.18
May	14.76	25.1	16.34
June	15.48	27.1	19.87
July	14.04	28.5	24.62
August	14.4	28.3	22.32
September	17.64	26.8	17.24
October	21.6	24.5	13.46
November	23.4	22	9.79
December	22.68	19.2	8.03

The monthly average weather data for Singapore is shown in Table A.5.

Table A.5: Monthly average weather data at Singapore

Months	Wind speed (km/h)	Temperature (C)	Solar Irradiation (MJ/m^2)
January	12.24	25.1	16.13
February	10.8	25.4	18.79
March	8.64	25.8	18.23
April	5.76	26.2	17.53
May	6.84	26.1	16.45
June	9.72	25.8	15.88
July	10.08	25.4	15.48
August	10.8	25.5	15.59
September	8.28	25.6	16.31
October	6.48	25.9	16.45
November	8.28	25.8	15.62
December	11.88	25.3	14.65

The monthly average weather data for Swift Current is shown in Table A.6.

Table A.6: Monthly average weather data at Swift Current

Months	Wind speed (km/h)	Temperature (C)	Solar Irradiation (MJ/m^2)
January	24	-13	4.90
February	23	-9.6	8.86
March	22	-4	14.4
April	22	4.3	18.22
May	22	10.8	20.95
June	21	15.6	21.13
July	18	18.3	18.83
August	18	17.6	16.78
September	20	11.4	13.32
October	22	5.5	9.10
November	22	-4	5.58
December	24	-10.8	3.89

The electrical characteristic of a BP 4175T array are shown in Table A.7.

Table A.7: Parameters defining the current-voltage relationship of A BP 175B

Description	Value	Unit
Number of series group in parallel	1	
Number of series group in series	1	
Area per module	1.25	m^2
Collector slope	60	deg
Collector azimuth	0	deg
Reference array operating temperature	25	^{o} C
Reference radiation level	1000	W/m^2
Reference MPP voltage	35.4	V
Reference MPP current	4.94	A
Reference open circuit voltage	43.6	V
Reference short circuit current	5.45	A
Array resistance	0.06	Ω
Wind speed correction factor	1	
Alpha	0.0025	
Beta	0.5	
Gamma	0.0029	
Solar cell absorbance	0.9	
Front panel emissive	0.95	
Front panel transmittance	0.95	
Back panel emissive	0.9	
Back panel transmittance	0.9	