2012

Reactive power considerations in reliability analysis of solar photovoltaic systems

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REACTIVE POWER CONSIDERATIONS IN RELIABILITY ANALYSIS OF SOLAR PHOTOVOLTAIC SYSTEMS

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Electrical Engineering

in

Department of Electrical and Computer Engineering

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August 2012

Dedicated to my beloved parents

Smt. Rambha and Sri. Nivritti Gaikwad

ACKNOWLEDGEMENTS

Firstly thanks to the almighty, who is the very cause of existence. I would like to offer my deepest gratitude to my major professor Dr. Shahab Mehraeen, for giving this extraordinary research opportunity. His knowledge, guidance, timely support and encouragement were vital in completion of this work.

I also would like to thank Dr. Ernest Mendrela and Mr. Michael McAnelly for serving on my committee and their valuable inputs.

I am also thankful to my friends, colleagues, Electrical Engineer Department and everyone from Louisiana State University, who made this learning experience very enjoyable.

Lastly, I thank to my loving parents, who supported my dreams, who were with me during all the highs and lows.

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NOMENCLATURE

LOLE: Loss of Load Expectation

LOLF: Loss of Load Frequency

LOLD: Loss of Load Duration

EENS: Expected Energy Not Supplied

MTTR: Mean Time to Repair

MTTF: Mean Timer to Failure

PV: Photovoltaic

GTI: Grid-tied-inverter

ENS: Energy not supplied

ABSTRACT

Reliability is one of the key aspects of power system operation and therefore reliability analysis techniques are well developed. However reliability analysis conventionally takes into account active power and limited attention has been given to reactive power. Reactive power is very essential in maintaining voltage stability of power systems. The voltage constraint at network can restricts active power delivery to the loads and could result in forced load curtailment. This research investigates the effect of reactive power shortage on reliability of power systems with significant penetration of PV cells. The reactive power issues become more significant in distributed generation using renewable energy sources such as photovoltaic (PV) Cells, which operate mostly at unity power factor. The IEEE 14-Bus system is utilized to perform this study. Twenty four state PV generation model was developed based on 24-hour solar radiation trend. Reliability indices are calculated analytically and verified through simulation without considering reactive power shortage. Next, a measure of Expected Energy Not Supplied (EENS) on account of reactive power shortage and voltage violation in network is calculated. Monte Carlo simulation was performed in MATLAB environment, where simulation results are compared with the case without taking into account reactive power and voltage violation. This research suggests that placement of the PV in the network can greatly reduce active and reactive power shortage during the contingencies. The reactive power is studied here from design and planning perspectives for reliable and stable power system operation when high penetrations of PV energy sources are present.

CHAPTER 1
INTRODUCTION

1.1 Introduction

The foremost important aspect of electrical utility is to deliver economical, reliable, and quality power to its customers. The electrical energy has only seen increasing demand over the centuries and still continues to grow. The failure of power has significant socio-economic impact on utility and its customers. While great emphasis is given to reliability of supply, which runs businesses and essential services such as hospitals and communications networks, failure in power system is random, sometimes outside of the controls. The electrical power network is very complex; a failure may result in loss of power to a large number of customers or sometimes catastrophic events such as blackouts. The effect of failure may not just be limited to revenue loss to utility and supply interruption to customers but can indirectly affect the society and the nation. The Electricity Consumers Resource Council (ELCON) report [1] about August 14, 2003 blackout reports power failure to 50 million people and failure cost between $7 Billion -$10 Billion. Therefore reliable power system operation and design is very important.

Reliability analysis techniques are well developed [3,4] and are applied to the conventional power system. The reliability analysis techniques have been conventionally developed for synchronous generators. Later on, with the use of renewable natural resources such as wind and solar photovoltaic, the conventional reliability techniques were modified to take into account time varying nature of those generation sources [5,6]. This thesis presents reliability aspects of time varying and intermittent nature of the renewable energy sources. Though the emphasis is on the solar photovoltaic cells, the introduced methods and approach can be applied to other intermittent energy sources. Intermittent renewables also impose serious stability and reliability

issues to the power system. One major issue is reactive power shortage and network voltage violations during contingency situations, as solar PVs are not sources of reactive power. This research investigates various aspects of reactive power shortage on reliability in a power system with solar PV generation. New measures of reliability are calculated to measure effect of reactive power and network voltage violation on system reliability.

1.2 Research Objective

This research focuses on reliability evaluation of power system with distributed renewable generation. The system under study comprises of solar photovoltaic cells and conventional synchronous generators. The reliability analysis of renewables such as solar PVs have its peculiarity of intermittent nature. Also, commercially available solar PVs are connected through GTI (Grid-Tied-Inverters,) which are designed to operate at unity power factor. Hence, they do not supply reactive power, which is essential to maintain network voltages. A MATLAB program is developed and random Monte Carlo simulation was performed to examine the effects of solar PV penetration on system reliability.

1.3 Background and Literature Review

Reliability evaluation techniques are well developed and various papers ,articles and books are published on this topic. Also, some commercially available computer programs has been developed for this purpose. Analytical and probabilistic techniques are in use for many decades. The development of reliability evaluation technique was associated with the aerospace industry and military applications [2]. It was subsequently followed by applications in nuclear industry and electric power systems where system failure has large social and economic impacts. The first large group of papers on probabilistic methods were published in 1947[3]. The Markov chain

method was used in reference [3] but that needs lots of computer storage and cause approximation error. Advances in reliability evaluation using Monte Carlo sequential simulation has become popular in later decades[4]. The reliability analysis of intermittent sources of power has been evaluated in [5, 6]. Limited importance has been given to reactive power aspects [7, 8] of reliability analysis. This research investigates the effect of reactive power shortage caused by solar PV on system's reliability.

1.4 Definition of Power System Reliability

In general term "reliability" is defined as [2] probability of device or system performing its purpose adequately for the intended operating period of time. Power system reliability is defined as ability of electrical power system to supply the system load with reasonable continuity and quality of supply. The definition of reliability is very vast and covers all aspects of supplying reliable power to consumers. Major subdivisions of power system reliability are 'system adequacy' and 'system security' as shown in Fig.1.1. The term adequacy relates to the existence of sufficient facilities within the system to satisfy the consumers' load demand and system operational constraints. This includes the facilities required to generate sufficient energy and the associated transmission and distribution facilities to supply energy to the consumers. Thus, adequacy majorly deals with static conditions and not the dynamic and transients of power system. Security is associated with system dynamics and disturbances in the system. Security is therefore related to the response of the system to perturbations it is subjected to. This research is focused on the adequacy assessment domain.

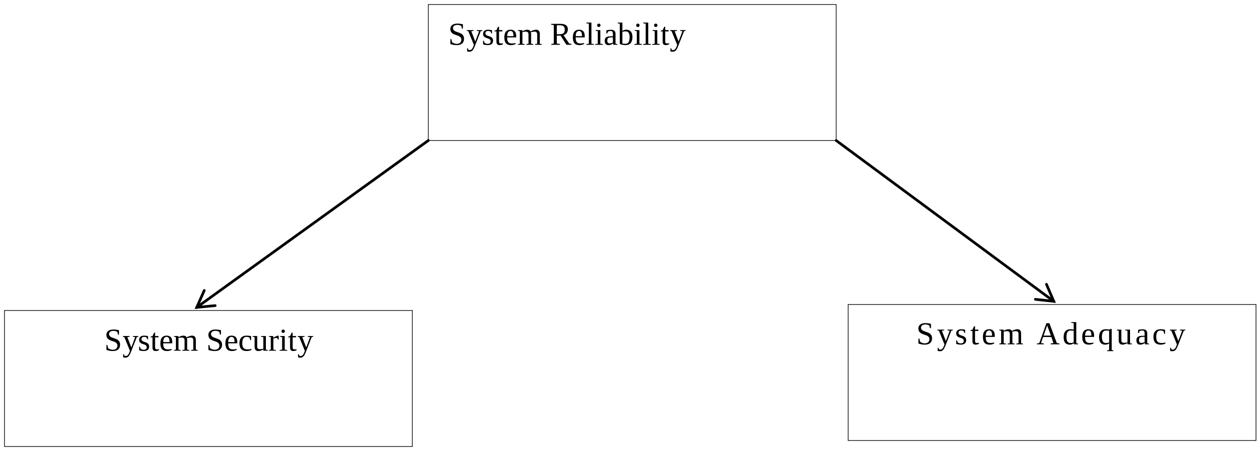

Fig.1.1 Subdivisions of power system reliability

1.5 Reliability Indices

Electrical power system is broadly divided into three parts: generation, transmission and distribution system. Different reliability indices have been defined [4] to measure performance of these systems. This research is focused on generation system hence we introduce the adequacy assessment indices here. The basic indices in generation system adequacy assessment are Loss of Load Expectation (LOLE), Loss of load Frequency (LOLF), Loss of Energy Expectation (LOEE) and Loss of load Duration (LOLD).Conceptually, these indices can be described by the following mathematical expressions. The first index is the loss of load expectation (LOLE) which is defined as, LOLE (days/yr or hrs/yr)

$$LOLE = \sum_{i \in S} p_i T \tag{1.1}$$

where p_i is the probability of system state i, S is the set of all system states associated with loss of load, and T is the given period (usually one year). The LOLE is the average number of days or hours in a given period T in which the daily peak load or hourly load is expected to exceed

the available generating capacity. Then the Loss of energy expectation, LOEE (MWh/yr) is defined as,

$$LOEE = \sum_{i \in S} 8760 C_i \, p_i \tag{1.2}$$

where p_i and S are as defined above and C_i is the loss of load for system state i. LOEE is the excepted energy not supplied by the generating system because load exceeds generation. The LOEE takes into account severity of deficiencies and number of incidents and their durations; hence, the impact of energy shortage and its likelihood is evaluated. This index is similar to Expected Energy Not Supplied in composite system reliability assessment. Expressions (1.1) and (1.2) mentioned above are general expressions of reliability indices using probabilistic approach. Obtaining these indices using analytical and simulation approaches is illustrated later in chapter 2.

CHAPTER 2
RELIABILITY EVALUATION- ANALYTICAL TECHNIQUE

2.1 Introduction

As discussed in the chapter 1, various techniques such as deterministic and probabilistic approaches are used for reliability evaluation of power system. Deterministic techniques are not suitable for large power systems as it becomes more complicated with more number of components. This research will use probabilistic techniques for reliability evaluation. Probabilistic methods can make use of analytical techniques or sequential simulation such as Monte Carlo simulation. Reliability of modified IEEE-14 Bus system [13] is evaluated analytically and through simulation and results are compared. Analytical techniques make use of capacity outage table for a generation system explained in subsequent sections. Recursive algorithm is used to build capacity outage model.

2.2 Generation system model

2.2.1 Generating unit unavailability

The basic generating parameter used in static capacity evaluation is the probability of finding the unit on forced outage [3]. This probability is nothing but the unavailability of the generator in the system on account of failure or planned maintenance. Historically, in power system applications this is known as forced outage rate (FOR) as

Unavailability (FOR)=U= $\frac{\lambda}{\lambda+\mu}=\frac{r}{m+r}$

$$= \frac{\sum[down\ time]}{\sum[down\ time]+\sum[\ up\ time]} \tag{2.1}$$

Availability (A)= $\frac{\mu}{\lambda+\mu}=\frac{m}{m+r}$

$$=\frac{\sum[up\ time]}{\sum[down\ time]+\sum[\ up\ time]} \tag{2.2}$$

where λ = expected failure rate

μ =expected repair rate

m =mean time to failure

r =mean time to repair

Definitions:

Mean-time-to-failure (MTTF): MTTF is described as the time to failure counted from the moment the component begins to operate to the moment it fails. Figure.2.1 shows typical time to failure and time to repair cycle of a component.

Mean-time-to-Repair (MTTR): MTTR is the time counted from the moment the component fails to the moment it is returned back to an operable condition.

Failure rate: The failure rate is the reciprocal of the mean time to failure and is defined as,

$$\lambda=\frac{number\ of\ failures\ of\ a\ component\ in\ the\ given\ period\ of\ time}{total\ period\ of\ time\ the\ component\ was\ operating}$$

Repair rate: The repair rate μ is the reciprocal of mean time to repair and is defined as,

$$\mu=\frac{number\ of\ repairs\ of\ a\ component\ in\ the\ given\ period\ of\ time}{total\ period\ of\ time\ the\ component\ was\ repaired}$$

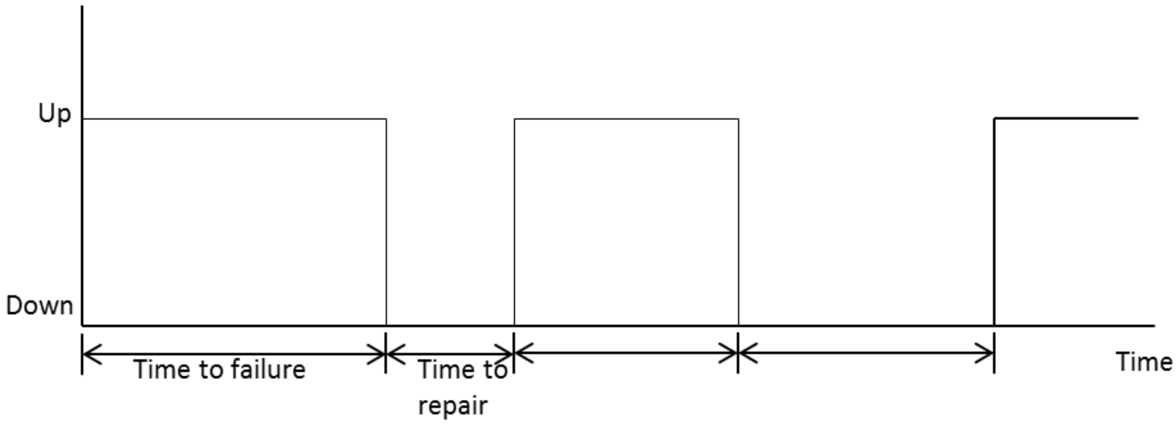

Fig.2.1 Typical ON and OFF cycle of a component

Then, availability and unavailability can be written as,

Unavailability (FOR)=U= $\frac{\lambda}{\lambda+\mu}$

Availability (A)= $\frac{\mu}{\lambda+\mu}$

The concept of availability and unavailability illustrated in equation 2.1 and 2.2 are associated with the simple two-state model shown in Fig.2.2.

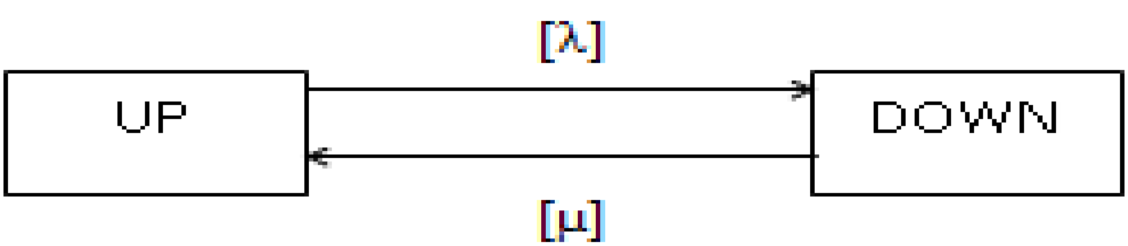

Fig.2.2 Two-state model for conventional generator

2.2.2 Capacity outage probability tables

As the name suggests, capacity outage probability table is a simple array of capacity levels and the associated probabilities of existence. If all units in the system are identical in capacity, binomial distribution can be used to obtain the capacity outage table [3]. Generators can be multi states; besides up and down, generators can have de-rated states which are between up and down. In this particular evaluation we are just considering two-state generator model. Units are added together using probability concepts to form capacity outage table [3]. These concepts can be explained by a simple numerical example. Consider a system consisting of two 50-MW generating units each with forced outage rate of 0.02. The two generators can exist in two states either in service with probability of 1-0.02=0.98 or out of service with probability 0.02. These two units can be combined to give capacity outage probability table shown in table 2.1

Table 2.1 Capacity outage probability table

Capacity out of service	Probability	Cumulative Probability
0 MW	(0.98)*(0.98)=0.9604	0.9604
50 MW	(0.02)*(0.98)=0.0392	0.9996
100 MW	(0.02)*(0.02)=0.0004	0.0004
		....
		1.0000

2.3 Calculation of reliability Indices

2.3.1 Loss of load expectation (LOLE)

A loss of load is the condition when the generating capacity in the system is exceeded by load level. The individual daily peak loads can be used in conjunction with the capacity outage table to obtain the expected number of days in which load will exceed available capacity. The index in this case is designated as the loss of load expectation (LOLE) in days/period. If hourly load is used, then the LOLE will be in hours/period. The LOLE can be presented as

$$LOLE = \sum_{i=1}^{n} P_i(C_i - L_i) \quad \text{days/period} \qquad (2.3)$$

where C_i =available capacity on day i, L_i =forecast peak load on day i, and P_i =probability of loss of load on day i , which can be obtained directly from the capacity outage probability table. This procedure is illustrated using 100 MW generation system shown in table 2.1.The data for a period of 365 days is shown in table 2.2.Using equation 2.3 ,LOLE can be calculated as

LOLE=12P(100-57)+83P(100-52)+ 107P(100-46)+ 116P(100-41)+ 47P(100-34)

=12(0.0396)+83 (0.0396)+ 107 (0.0004)+ 116 (0.0004)+ 47 (0.0004)

=4.2134 days/year

Table 2.2 Load data used to evaluate LOLE

Daily peak load (MW)	57	52	46	41	34
No. of occurrences	12	83	107	116	47

The same LOLE index can also be obtained using the daily peak load variation curve. Figure.2.3 shows typical system load-capacity relationship curve. The load model is shown as continuous curve for a period of 365 days. Figure.2.3 shows that any outage less than the reserve will not contribute to any loss of load. Any outage more than the reserve will result in a period of time during which loss of load will occur.

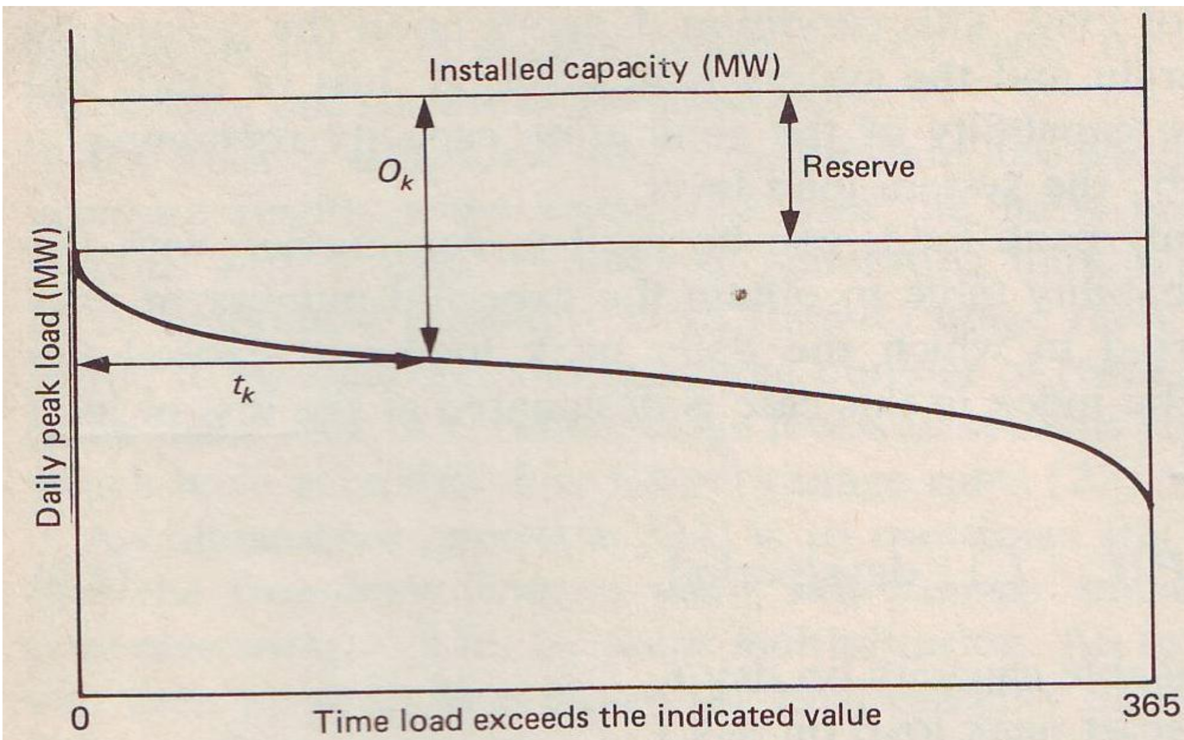

Fig.2.3 Relationship between load, capacity, and reserve

Expressed mathematically, the contribution to the system LOLE made by capacity outage O_k is $p_k t_k$ time units where p_k is the individual probability of capacity outage O_k, O_k is the magnitude of the kth outage in system capacity outage table, and t_k is the number of time units the outage of magnitude O_k results in a loss of load.

The total LOLE for the study interval is

$$LOLE = \sum_{k=1}^{n} p_k t_k \tag{2.4}$$

where n is the number of total capacity outages in outage probability table such as Table 2.1

2.3.2 Expected energy not supplied (EENS)

Expected energy not supplied is an index which calculates the actual MWh of load curtailment because of total system outages which result in loss of load. The basic expected energy curtailed can also be used to determine the expected energy produced by each unit. This approach is illustrated by following example.

Consider the load duration curve (LDC) shown in Fig. 2.4, the load duration curve is obtained for the period of 100 hours and generating unit capacity outage data shown in Table 2.3. The total energy required in this period is 4575 MWh i.e area under the LDC in Fig.2.4. If there were no units in the system the expected energy not supplied, EENS, would be 4575 MWh. If the systems have two generators with generation data shown in Table 2.2, the EENS can be calculated as shown in Table 2.4.

Table 2.3 Generation data

Capacity in service (MW)	Probability
0 MW	0.05
25 MW	0.30
75 MW	0.65

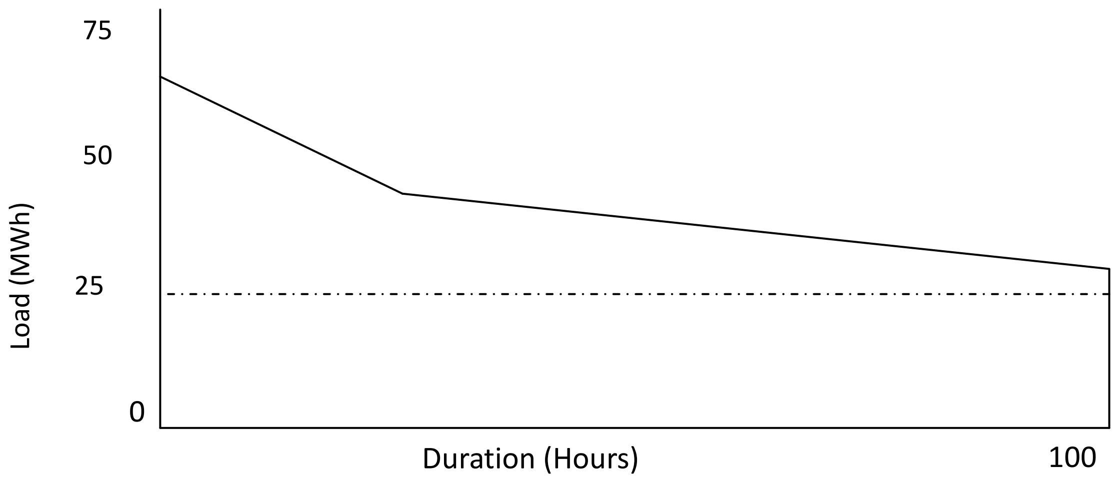

Fig.2.4 Load duration curve

Where, column four in table 2.4 is energy curtailment associated with that particular outage state, e.g. when full capacity i.e. 75 MW is in service no load is curtailed. Whereas, it can be observed that when 25 MW is in service 2075 MWh load is curtailed, this is nothing but the area above 25 MW line in Fig.2.4.

Table 2.4 Expected energy not supplied

Capacity out of service (MW)	Capacity in service (MW)	Probability (P_i)	Energy Curtailed (MWh) (E_i)	Expectation(MWh) ($P_i * E_i$)
0	75	0.65	-	-
50	25	0.30	2075	622.5
75	0	0.05	4575	228.75
			EENS	851.25 MWh

The expected energy not supplied, is the expectation of energy curtailment, which is the product of probability of that particular outage state in column three and energy curtailed in column four. The basic requirement for calculating EENS is to develop a sequential capacity outage probability table for the generating system.

2.4 System Modeling

The IEEE 14 bus system [13] is used for the evaluation of reliability by analytical and simulation approaches. The system consists of two synchronous generators each of 150 MW placed at bus 1 and bus 9 and three solar PVs placed across the buses in system. The IEEE Reliability Test system [11] load data, with a peak load of 285 as shown in Fig. 2.5 is used for analysis and simulation.

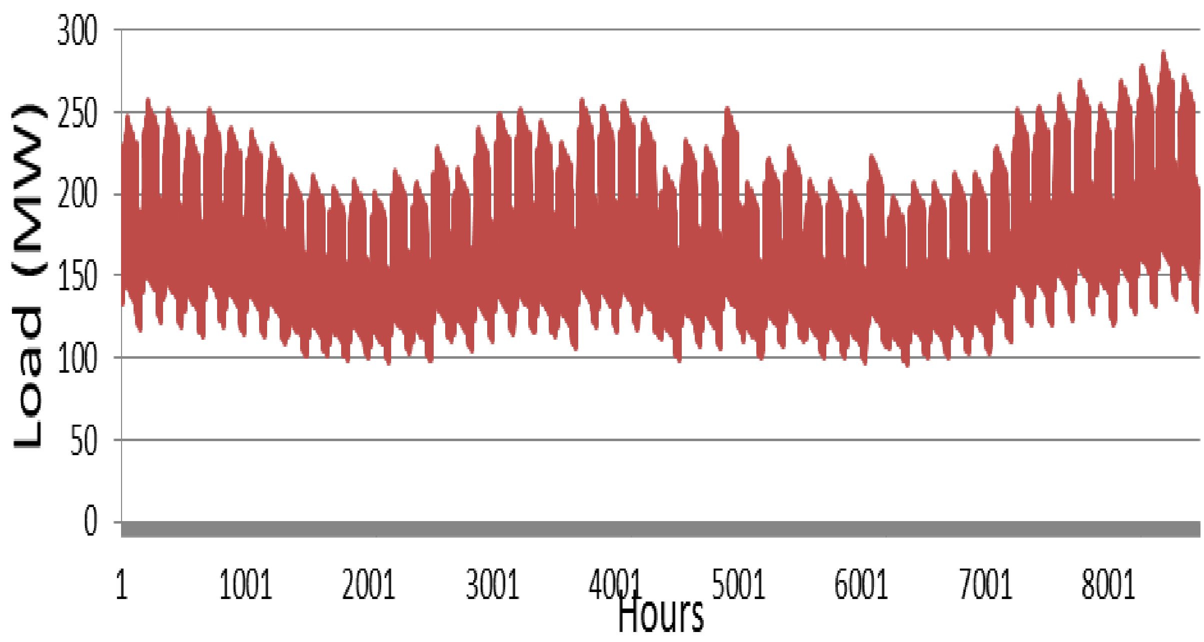

Fig. 2.5 IEEE hourly load data

2.4.1 Modeling of Synchronous Generators

As explained in section 2.2.1, the conventional generators are modeled as two-state models as shown in Fig.2.2. Generator forced outage rate (FOR) is calculated from failure rate λ and repair rate μ, which are determined form historical failure data of generators.

2.4.2 Modeling of Solar Photovoltaic Generators

The solar PV generation is intermittent and time-varying in nature, and the instantaneous power generation is dependent of solar irradiance at the instant. Therefore a two state model (up or down) similar to synchronous generators is not adequate for generation state representation of solar PVs. Studies [12] show that average hourly solar generation follows normal distribution as shown in Fig.2.6. Based on the normal distribution a 24-stage generation model as shown in Fig 2.7 is developed for solar PV. Each hour of the day corresponds to certain PV power output.

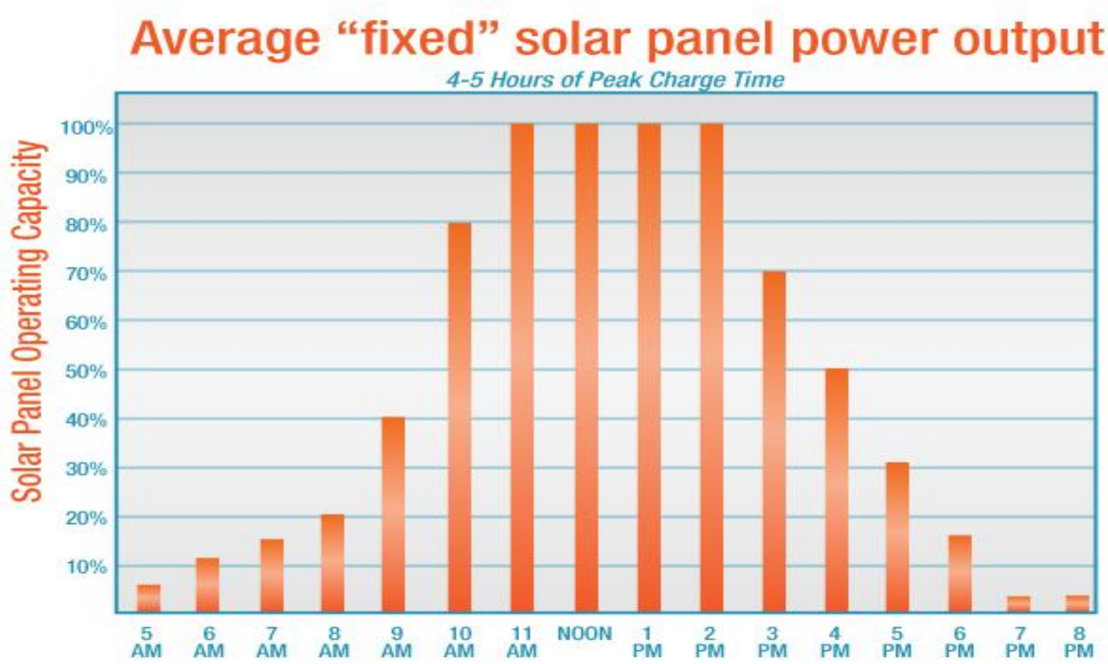

Fig. 2.6 Hourly solar radiation and PV power output

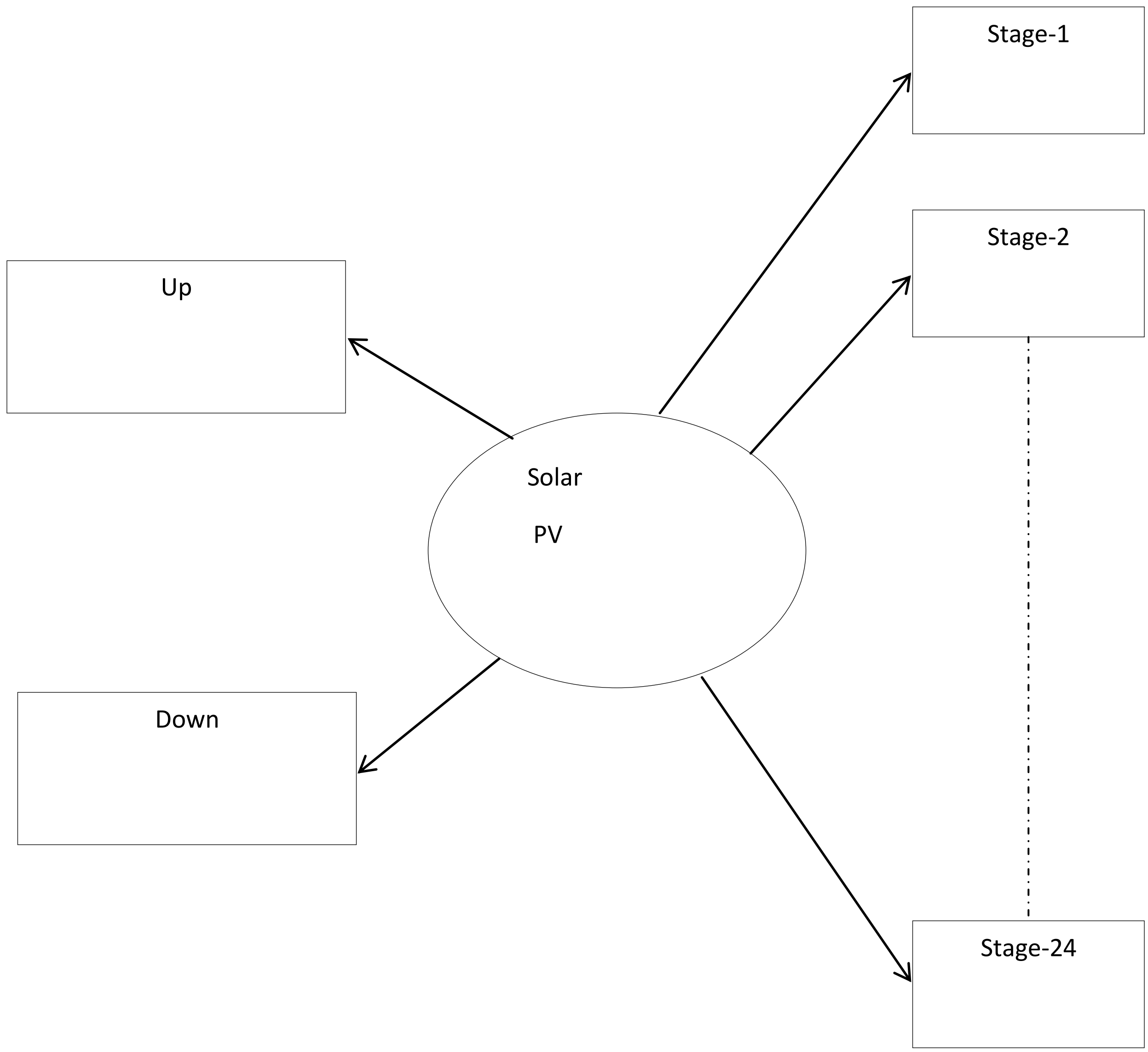

Fig. 2.7 24-state model of solar PV

Hourly average percentage radiation factor A_i is obtained from the trend shown in Fig.2.7.This factor is then used to obtain corresponding solar PV hourly power generation as shown in table 2.5. Thus, the PV generation model is developed based on solar irradiance received during different times of the day.

Table 2.5 Hourly solar radiation Vs. PV Output

24 hours solar radiation Vs. PV Output			
Hour-of-day	%Radiation	Radiation Factor (Ai)	PV Capacity (MW)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	7	0.07	3.5
6	12	0.12	6
7	15	0.15	7.5
8	20	0.2	10
9	40	0.4	20
10	80	0.8	40
11	100	1	50
12	100	1	50
13	100	1	50
14	100	1	50
15	70	0.7	35
16	50	0.5	25
17	31	0.31	15.5
18	17	0.17	8.5
19	3	0.03	1.5
20	3	0.03	1.5
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0

2.5 Analytical Reliability Evaluation of IEEE 14-bus system

As described in section 2.4 Modified IEEE 14-bus system shown in Fig 2.8 is used for reliability analysis. Bus and line data is given in Appendix A. The system peak load is 285 MW and IEEE Reliability Test system [11] load model is used. Synchronous generators are placed at buses 1 and 9 and solar PVs are placed at three different buses. Generation system data is shown

in table 2.5. The MTTF and MTTR values in Table 2.6 for synchronous generators are obtained from IEEE reliability test system [11] whereas these values for solar PV generators are assumed to be the same as 150-MW synchronous generators.

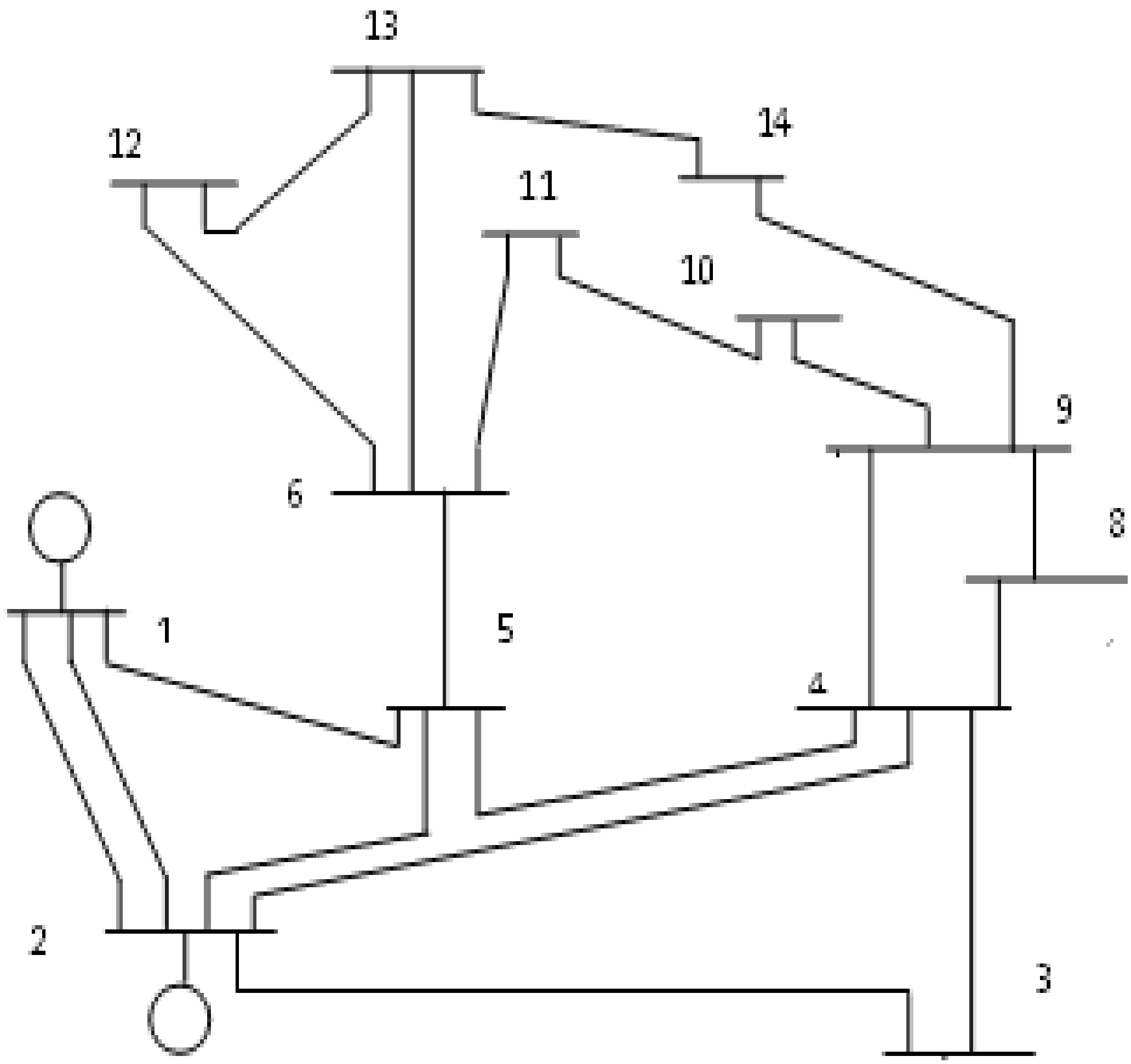

Fig.2.8 IEEE 14-bus System

Table 2.6 Generator Reliability Parameters

Unit Type	No of Units	Unit Size(MW)	Forced Outage Rate	MTTF (Hours)	MTTR (Hours)
Synchronous Generator	2	150	0.04	960	40
Solar PV	3	50	0.04	960	40

The first step in analytical reliability evaluation of reliability system is to develop capacity outage table. This study consider two different cases 1) IEEE 14-bus system with only 2 synchronous generators, and 2) IEEE 14-bus system with 2 synchronous generators and 3 solar PVs. Later in chapter 3 these two cases are evaluated with Monte Carlo simulation.

2.5.1 Case 1- IEEE 14-bus system with only 2 synchronous generators

EENS calculation illustrated in section 2.3.2 makes use of daily peak load duration curve. Here we are making use of actual hourly load [11], as actual hourly load gives much accurate estimation of reliability index EENS than daily peak load. To calculate EENS for all 24 hours of the day each hour load duration curve is plotted for 364 days period. For example, Fig 2.9 shows load duration curve of hour 1; i.e., 1:00 am every day for one year (364 days) period. This load duration curve is used to calculate EENS for hour 1:00 or 1 am. Capacity outage table and corresponding EENS are shown in table 2.7. Similarly, the capacity outage table and EENS are calculated for all 24 hours of the day. These individual hourly EENSs are then gathered together to obtain total yearly EENS as shown in table 2.8.

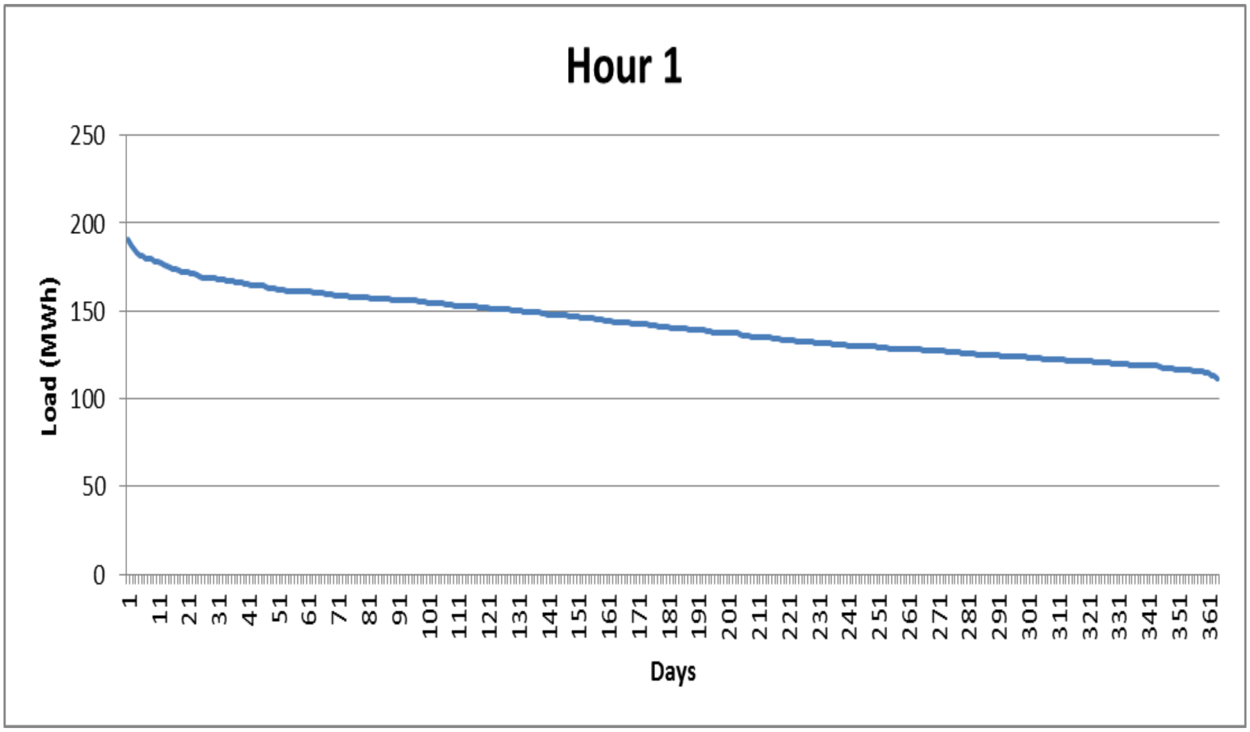

Fig 2.9 Load duration curve for hour 1:00 of everyday

Table 2.7 Capacity outage table and EENS for hour 1

Capacity Outage table	Hour 1:00 (1 a.m)			
Capacity out (MW)	Capacity in service (MW)	Probability	Energy curtailed (MWh)	Expectation (MWh)
0	300	0.9216	0	0
150	150	0.0768	3089	237.2352
300	0	0.0016	51755	82.808
EENS-Hour1				320.0432

Table 2.8 Two synchronous generators EENS for 24 Hours

Hour-of-day	EENS (MWh)
1	320
2	123
3	92
4	84.84
5	84.8
6	93.1
7	325.5
8	824.0
9	1302.5
10	1537.4
11	1634.4
12	1629.2
13	1500.9
14	1479.8
15	1403.2
16	1344.9
17	1473.4
18	1581.0
19	1618.7
20	1597.8
21	1469
22	1200
23	736.5
24	259.5
Total EENS (MWh)	23715.3

2.5.2 Case 2- IEEE 14-bus system with 2 synchronous generators and 3 solar PVs

In this case, 3 PVs are added to the system presented in case-1. Two-state model for synchronous generators and 24-state model for Solar PVs as explained in section 2.4.1 and 2.4.2 are used for building capacity outage table and calculating EENS. Similar to case-1, capacity outage table for each hour of the day is built and EENS is calculated. In this case, capacity

outage table is a combination of synchronous generator's and solar PV's outages together. Table 2.9 shows capacity outage and EENS for hour 12:00 (noon) when PVs are added to system. As shown in table 2.4 PV output at 12:00 hours is 100% ; i.e., radiation factor of 1 . Each PV produce, 50 MW at 12:00 hour, hence total installed capacity of system with three PVs and two synchronous generators of 150 MW each will be 450MW.

Table 2.9 Capacity outage table and EENS for Hour 12

Capacity Outage table		Hour 12:00 (Noon)		
Capacity out (MW)	Capacity in service (MW)	Probability	Energy curtailed (MWh)	Expectation (MWh)
0	450	0.8153	0	0
50	400	0.1018	0	0
100	350	0.00282	0	0
150	300	0.0768	0	0
200	250	0.00848	112	0.94976
250	200	0.000235	5457	1.28239
300	150	0.0016	19668	31.4688
350	100	0.000178	37777	6.72430
400	50	0.00000492	55977	0.27540
450	0	1.022E-07	74177	0.007580
			EENS(MWh)	40.70824

Similarly, capacity outage table and EENS are obtained for all 24 hours of the day. This individual hourly EENSs are collected together to obtain total yearly expected energy not supplied as shown in table 2.10.

Table 2.10 24-Hours EENS for two synchronous generators and three PVs

Hour-of-day	EENS (MWh)
1	320
2	123
3	92
4	84
5	76.55
6	74.07
7	161.1
8	355.5
9	292.42
10	63.82
11	41.07
12	40.7
13	37.54
14	37.08
15	79.58
16	232.02
17	616.9
18	1083.9
19	1677
20	1642
21	1469
22	1200
23	736.5
24	259.5
Total EENS (MWh)	10795.25

CHAPTER 3
RELIABILITY EVALUATION- SIMULATION TECHNIQUE

3.1 Monte Carlo Simulation

Monte Carlo method is a stochastic simulation technique, using random numbers [4]. A simple example will illustrate the basic concept of the Monte Carlo simulation. A fair die is thrown. The probability of a "one" occurring on upper face is 1/6 as each of the six faces has equal probabilities of occurring. This probability can be estimated by sampling simulation. Throw the die N times and record the number of times number "one" occurs. Let this be f times. The estimation of the probability is f/N. As N increases sufficiently, f/N approaches 1/6. Figure.3.1 shows the convergence process of a typical Monte Carlo simulation.

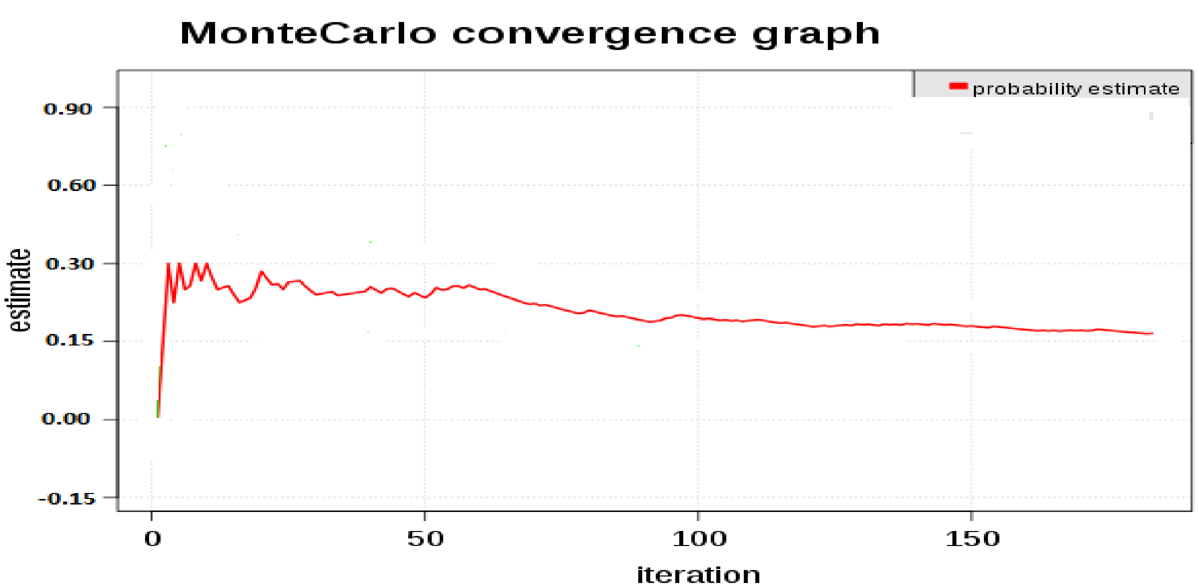

Fig.3.1 Monte Carlo simulation convergence graph

This method is suitable for power system reliability as the failures in power system are also random.

3.2 System Modeling

3.2.1 Modeling of Synchronous Generators

The conventional generators are modeled as two-state models as shown in Fig. 2.2. In order to consider the availability of the generators, (i.e., up or down states as shown in Fig. 2.1,) operating and repair times are chosen as exponentially distributed events [4]. In Fig. 2.1 MTTF and MTTR can be obtained from the up and down durations which in turn can be verified by failure rate λ and repair rate μ, respectively. That is, MTTF=1/λ and MTTR=1/μ. Then, time-to-failure (Tup) and time-to-repair (Tdown) can be calculated by using equations (3.1) and (3.2) [11] as

$$Tup = -MTTF \ln U_1 \tag{3.1}$$

$$Tdown = -MTTR \ln U_2 \tag{3.2}$$

where, U_1 and U_2 are uniformly distributed random numbers in the range [0,1]. Figure 3.2 shows sample operating cycles of the generators with up and down states referred to 1 and 0, respectively, using equations (3.1) and (3.2).

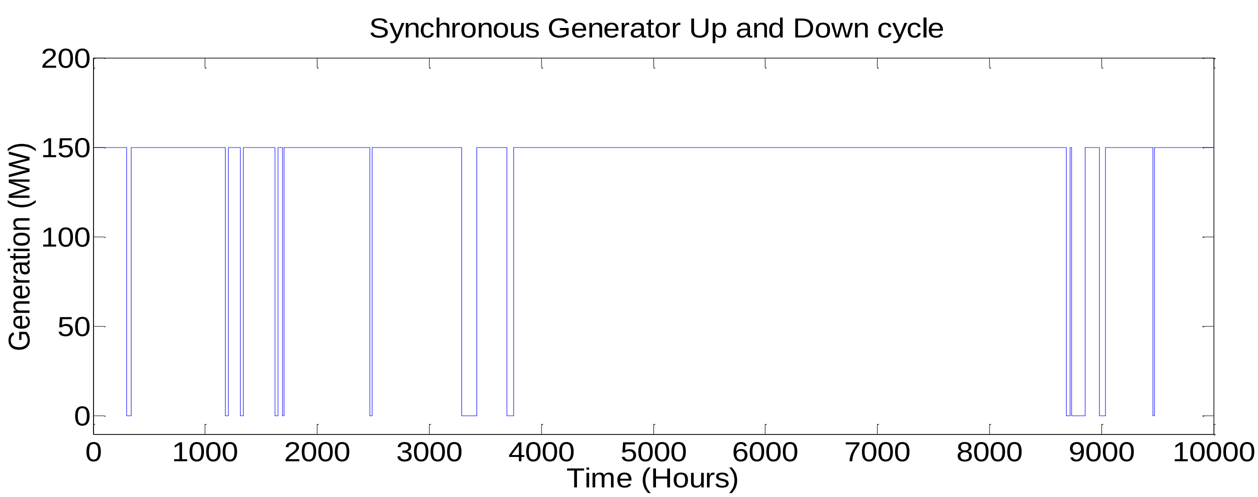

Fig. 3.2 Typical operating cycle of a generator

3.2.2 Modeling of Solar Photovoltaic Generators

As explained in section 2.4.2, solar PVs are modeled as 24 state generators. The MTTF and MTTR form generator reliability parameter (Table 2.5) is used to generate exponentially distributed up and down times. Using equations (3.1) and (3.2), the PV up and down times are calculated as

$$Tup = -MTTF \ln U_1$$

$$Tdown = -MTTR \ln U_2$$

where, U_1 and U_2 are uniformly distributed random numbers in the range [0,1]. Figure 3.3 shows typical 24-state operating cycles for PVs.

In conducting reliability evaluation in power system using Monte Carlo simulation, system state sampling is required. Sampling techniques include random number generation (or variate) and variance reduction techniques as well as stratified and dagger sampling [4].

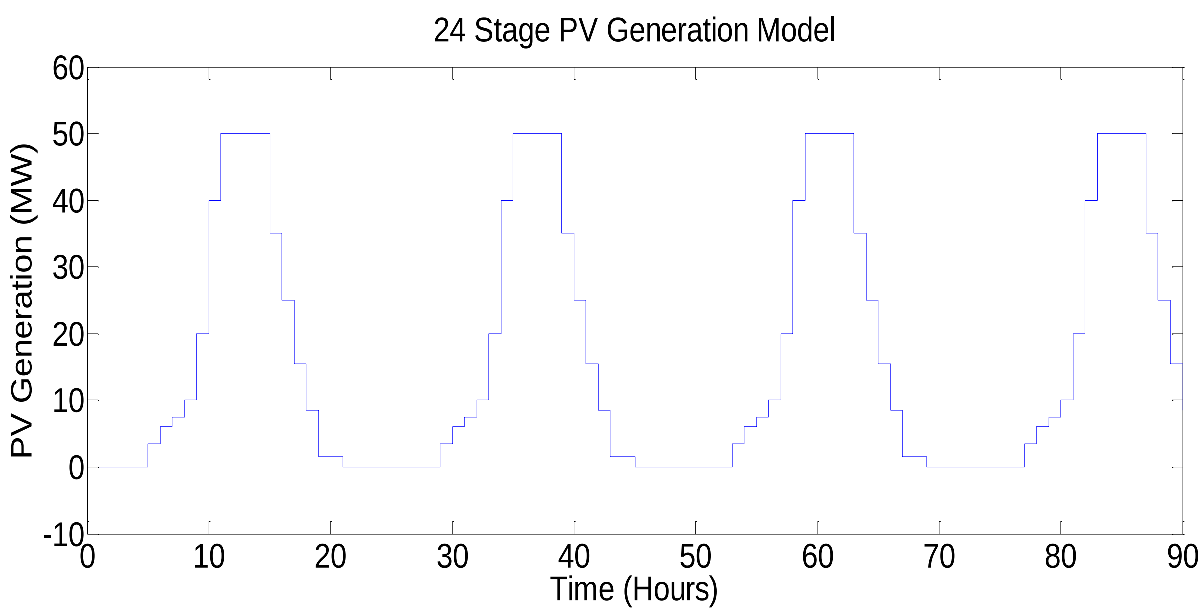

Fig. 3.3 Typical solar PV up and down cycles

3.3 Sampling Techniques

The system state is a combination of all individual component states. For example, suppose that a system has components A, B and C each with two states ON and OFF. Consider at least two components are required to be in ON state for system to operate. In this case system is in success or ON state, when either AB or BC or CA combination is in ON state; otherwise the system is said to be in OFF state. In case the of power system it is the combination of all network elements such as generators, lines, transformers, and switches which are connected together to deliver power from sources to load points. System State is determined by sampling its probability of being in a particulate state. Three different sampling techniques are used to determine system states [4] which are

i) State Sampling,

ii) State Duration Sampling, and

iii) System State Transition Sampling

3.3.1 State Sampling

The behavior of each component can be defined [4] by uniform distribution in the range [0, 1] such that each component has two states of up (success) and down (failure) where the component can represent a generator, lines, switches etc. Let S_i denotes the state of i th component and PF_i denotes its failure probability. Drawing a uniformly distributed random number U_i in the range [0, 1] for the i th component yields,

$$S_i = \begin{cases} 0 & \text{(success state)} \quad \text{if } U_i \geq PF_i \\ 1 & \text{(failure state)} \quad \text{if } 0 \leq U_i < PF_i \end{cases} \tag{3.4}$$

The states of the system containing m components can be given by vector S as

$$S = (S_1, ..., S_i, ... S_m) \tag{2.2}$$

If each system state S_i has a probability of $P(S_i)$ and the reliability index function $F(S_i)$, the mathematical expression for the expectation of all system states can be given by

$$E(F) = \sum_{S \in G} F(S_i) P(S_i) \tag{3.5}$$

where, G is the set of system states. Substituting the sampling frequency of state S for its probability $P(S)$ gives

$$E(F) = \sum_{S \in G} F(S_i) \frac{n(S_i)}{N} \tag{3.6}$$

where, N is the number of samples and $n(S_i)$ is the number of occurrences of state S .

3.3.2 State Duration Sampling

This method is based on sampling the probability distribution of the component state duration. In this method, first chronological state transition is simulated for individual components. Then, the system chronological state transition is obtained by combining all components' chronological state transitions [4]. This method uses component state duration distribution function to find the actual duration of each state in a chronological manner. For example, in two-state representations for two components such as generators, the states are the operating (up) and repair (down) conditions. The state duration functions are normally defined by exponential distribution given as

$$T = -\frac{1}{\lambda} \ln U$$

where U is the uniform distribution function used to provide a random duration in the range $[0, \infty]$ in time domain. The following steps explain state duration sampling approach in more details.

Step 1: Specify the initial state of each component, generally it is success or up state.

Step 2: Sample the duration of each component residing in each state. Given exponential distribution, sampling value of state duration is

$$T_i = -\frac{1}{\alpha_i} \ln U_i$$

where U_i is a uniformly distributed random number between [0,1] corresponding to the i th component. If the present state is the up state, α_i is the failure rate of the i th component; if the present state is the down state, α_i is the repair rate of the i th component;

Step 3: Repeat step 3 for a given time span in years and record sampling values of each state. The chronological state transition process for each component can be obtained and has the forms shown in Fig. 3.4

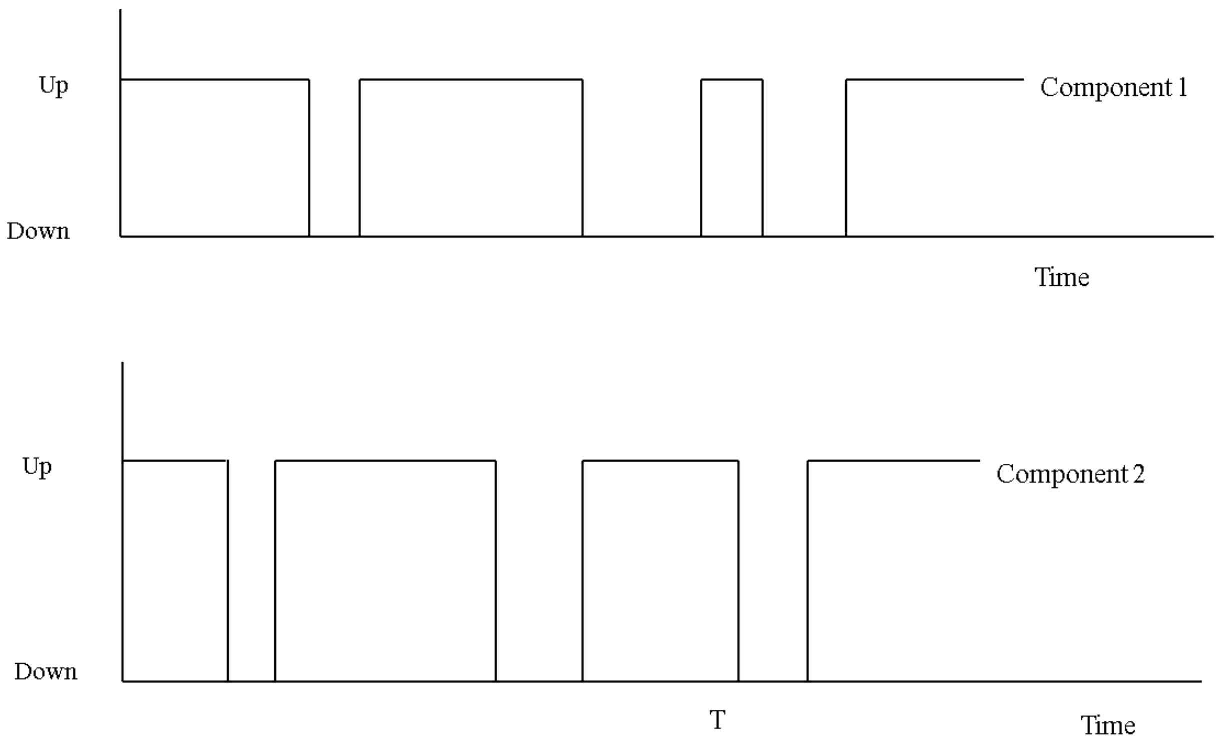

Fig.3.4 Chronological Component State Transition Process

Step 4: The chronological system state transition can be derived by combining individual components, which will have the shape as shown in Fig. 3.5 for two components.

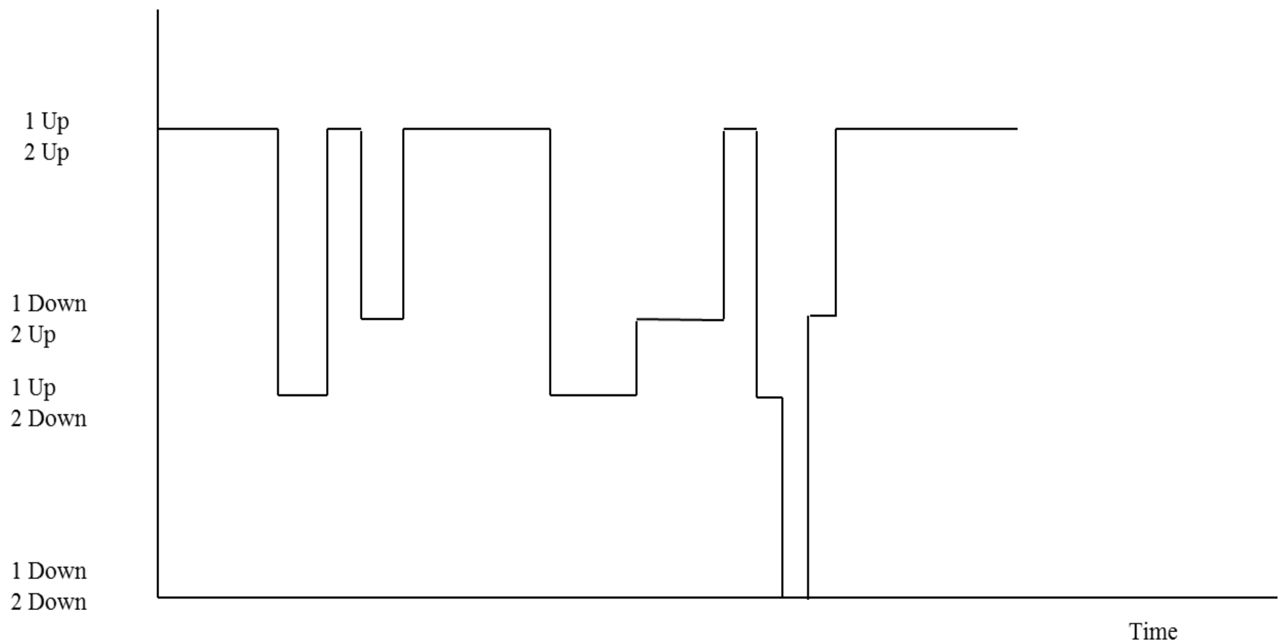

Fig.3.5 Chronological System State Transition Process

3.4 Monte Carlo simulation procedure

The first step in performing Monte Carlo simulation is to generate operating histories of each generating unit by drawing time to repair and time to failure [4] as illustrated in sections 3.2.1 and 3.2.2 for synchronous generators and PVs, respectively. The operating history of each unit is in the form of chronological up and down states as shown in Fig 3.4. The system available capacity can then be obtained by combining the operating cycles of all the units as shown in Fig 3.5. The second step is to superimpose the obtained system available capacity curve on the

chronological hourly load curve to obtain the system available margin model. A positive margin denotes that the system generation P_{Gi} is sufficient to meet load demand P_{Di} for hour i, while negative margin implies that load exceeds generation and load curtailment is required. Figure. 3.6 shows superimposition and energy not supplied (ENS).

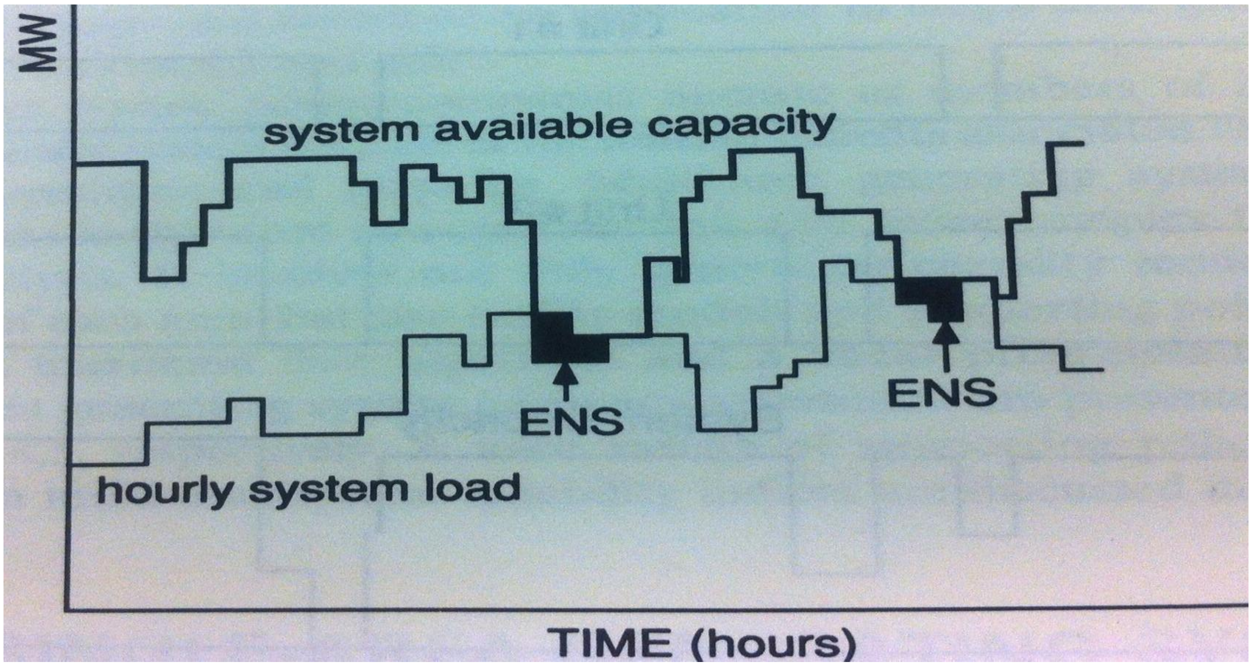

Fig. 3.6 Superimposition of system available capacity on the load curve

The third step is to calculate appropriate reliability indices. In each sampled year i, the expected energy not supplied (EENS) can be obtained by observing the negative margin. Thus, EENS can be calculated

$$\text{EENS}=\frac{\sum_{i=1}^{n} ENS_i}{N} \tag{3.7}$$

Where, ENS_i is the negative margin associated with year i, n is the total number years with negative margin, and N is the total number of years under in period under simulation. Here, Monte Carlo simulation is performed for two cases evaluated analytically in chapter 2 to explain

the method. The two cases are, 1) IEEE 14-bus system with only 2 synchronous generators, and 2) IEEE 14-bus system with 2 synchronous generators and 3 solar PVs.

3.4.1 Case 1- IEEE 14-bus system with only 2 synchronous generators

A MATLAB program is developed for Monte Carlo simulation, where the two synchronous generators operating histories were generated using random number and exponentially distributed time-to-failure and time-to-repair as explained in section 3.2.2. Generation capacity margin as shown in Fig. 3.7 is obtained by superimposing available capacity and hourly load curve. The Monte Carlo simulation is performed for 1000 years. Then, EENS is calculated using relationship (3.7).

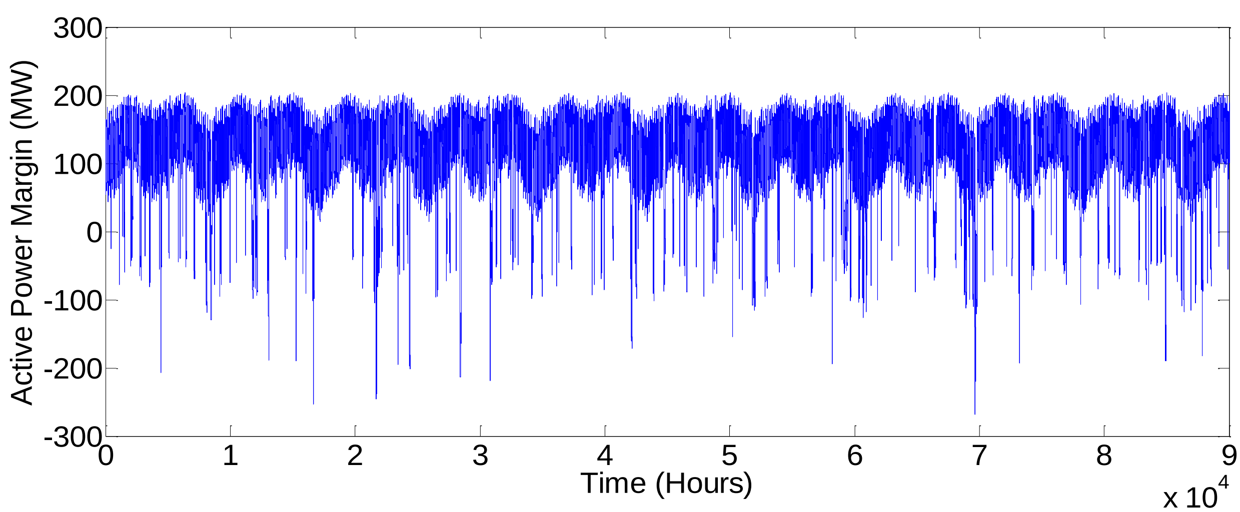

Fig.3.7 Active power margin without PV

Finally, Simulation results of expected energy not supplied are tabulated in Table 3.1

Table 3.1 EENS Simulation results for case 1

EENS Simulation two generators		
No of Years	Total EENS (MWh)	EENS/year (MWh)
100	2345900	23459
1000	23193000	23193

3.4.2 Case 2- IEEE 14-bus system with 2 synchronous generators 3 solar PVs

Similar to case 1 Monte Carlo simulation is performed in MATLAB for the IEEE 14-bus system with two synchronous generators and three solar PVs. The available capacity margin is obtained through simulation as shown in Fig. 3.8. The simulation results for 1000 years are tabulated in Table 3.2.

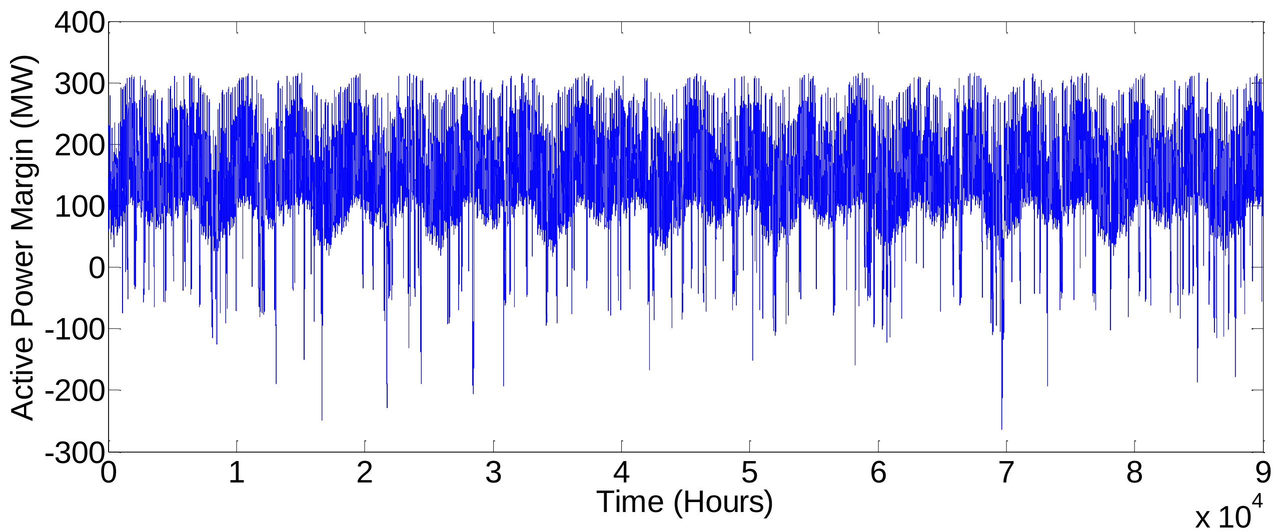

Fig.3.8 Active power margin with PV

Table 3.2 EENS Simulation results for case-2, with 2 generators and 3 PVs

EENS Simulation two generators + three PVs		
No of Years	Total EENS (MWh)	EENS/year (MWh)
100	1248600	9989
1000	9692400	9692

3.5 Simulation Results Verification

Table 3.3 shows the comparison of simulation and analytical results for two cases, 1) IEEE 14-bus system with only 2 synchronous generators, and 2) IEEE 14-bus system with 2 synchronous generators and 3 solar PVs. It can be observed that the results obtained through simulations for two cases are similar to the analytical ones. Thus, Monte Carlo simulation provides acceptable accuracy for large and complicated systems.

Table 3.3 EENS Simulation vs. Analytical results

EENS Simulation Vs. Analytical		
Case No	Analytical EENS (MWh)	Simulation EENS (MWh)
1	10795	9989
2	23715	23459

If we consider simulation results from Table 3.3, then it is observed that 33.33 % additional capacity by PVs in the network reduce the EENS to almost half.

CHAPTER 4
REACTIVE POWER ASPECTS OF RELIABILITY

4.1 Introduction

The reactive power has a great impact on the reliability of power system as it plays an important role in maintaining power system voltage stability. Reactive power is often supplied in parts locally as transfer of total reactive power over long distances is not efficient. During the contingency situations such as failure of the synchronous generators or an element in the system which leads to network voltage violations, sufficient reactive power reserve is required to meet the demand and maintain the voltage in the proper range. Reliability evaluation techniques considering active power shortage are well developed [4, 5, 6, 9]. However, less attention has been given to reactive power aspects in conventional reliability evaluation techniques. Proper power systems modeling schemes assign limitations on the maximum and minimum reactive powers supplied by the synchronous generators and take into account the effect of reactive power shortage and voltage violations in the network for reliability analysis [7-8].

During the normal operation of power system, the reactive power demand is majorly supplied by conventional generators and compensators in the system. In the contingency situations, reactive power flow changes significantly due to voltage variations as well as lines and shunt capacitors reactive power changes. Sufficient reactive power reserve is required to supply reactive power essential to maintain network voltage and system stability [10]. Reactive power delivery by network depends on the reactive power demand as well as the location of reactive power sources, network configuration, etc.

4.2 Reactive Power Issues in Solar Photovoltaic System

It is observed in chapter 3 that adding distributed generation resources in the form of renewables such as PV cells improves the net available active power in the network during failure of network elements such as synchronous generators. However, the additional capacity from the renewables might not be utilized to the fullest because of reactive power shortage during the contingency events. Commercial PVs connected to grid through grid-tied-inverters (GTI) operate at unity power factor and they are not usually a source of reactive power. Figure . 4.1 shows that in some failure events even though there is a positive active power margin, reactive power margin is negative. This additional active power in the network is due to the solar PV addition, but as PVs do not contribute to any reactive power, the reactive power is not sufficient.

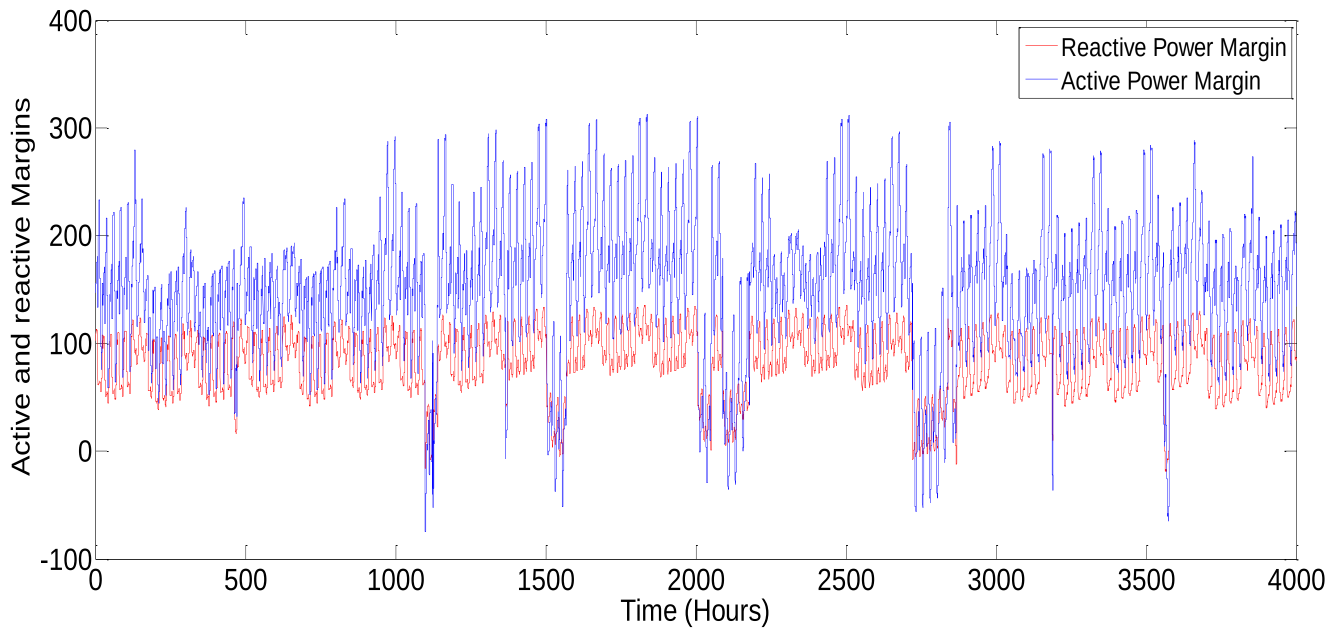

Fig. 4.1 Active and reactive power margins

This research focuses on reliability evaluation of power systems regarding the reactive power constraints of solar photovoltaic system. Although the addition of solar PVs can

potentially increase the generation capabilities of the system, this additional power from PVs cannot be fully utilized because of failure of the major reactive power source such as the synchronous generator. Reactive power shortage may result in voltage violations at some buses in the network. Therefore additional load curtailment is required to restore voltage within acceptable limits. The additional load curtailment to restore voltages within acceptable limits lowers the reliability of the system. In order to check the voltage in failure events, a typical load-flow program is used to calculate the node voltages following the contingency and the amount of load curtailment essential to restore voltages to acceptable levels is calculated. In this case load curtailment results in active and reactive power demand reduction so that the power system bus voltages stay within the acceptable range.

The conventional reliability indices mentioned in Section 1.5 does not have provision to accommodate the additional load curtailment and expected-energy-not-supplied (EENS) because of reactive power shortage. Therefore new reliability indices defined in [7] are used to calculate EENS because of real power shortage $EENS_P$, as well as EENS because of reactive power shortage $EENS_Q$. Similar to chapter 3 IEEE 14-bus system is used to evaluate reactive power constraint on the reliability of power system.

4. 3 Reliability Indices

In order to evaluate the reliability when there is reactive power shortage, certain indices are defined in [8]. Based on failure rate λ and repair rate μ, MTTF and MTTR can be calculated as $1/\lambda$ =MTTF and $1/\mu$ =MTTR. In order to calculate EENS, the real power load curtailment due to active and reactive power shortage are considered. Then, the EENS is defined as $EENS_P$

and $EENS_Q$ due to active power shortage and due to reactive power shortage, respectively. The above indices can be defined as

$$EENS_P = \sum_{i=1}^{8760} LC_{Pi} \tag{4.1}$$

$$EENS_Q = \sum_{i=1}^{8760} LC_{Qi} \tag{4.2}$$

where, LC_{Pi} and LC_{Qi} are the real power load curtailment due to real power shortage and reactive power shortage for state i, respectively. In calculating the indices $EENS_P$ and $EENS_Q$, a two-step procedure is adopted; first, the load curtailment is performed to reach a positive active power margin followed by further load curtailment to provide a positive reactive power margin. That means, the active load is curtailed by considering a constant power factor such that the total active power demand is not greater than the total available active power. At this stage, all the node voltages and the total reactive power demand are checked for appropriateness. A load flow program is used to obtain active and reactive power-flow and network bus voltages. In the case the total reactive power demand or the network bus voltages do not satisfy the requirements, in the next step, more active power demand is curtailed in very small steps to bring the total reactive power demand within limits and maintain all the bus voltages above 0.95 per unit using load-flow at each step.

4.4 Contingency Screening

In large practical power systems the total number of states of all the network components can be very high. Also, not all contingencies result in network violations and reactive power shortage. Therefor contingency selection criterion is required to select only those contingencies which are significant for reliability. Most popular contingency selection techniques are based on

probabilities of contingency states [8]. This research is using contingency selection criterion proposed in [8], which is explained here. The severity index is introduced, which is the ratio of total real power capacity of the failed generator to the total system capacity. Hence, here the most severe contingencies are selected; that is, the synchronous and solar PV generators failure. Load-flow determines the active and reactive power requirements in the network due to the active and reactive power demands based on the hourly load curve.

4.5 Case Study

The modified IEEE 14-Bus system is used to determine effect of reactive power shortage on reliability analysis of power systems with Solar Photovoltaic generators. System consists of two synchronous generators and three solar PV generators. The system is sufficiently complicated to actually take into account real power system behavior. Also it is important to note here that larger power systems need more computational time as the possibilities contingencies are higher. A typical load flow program is used to analyze the network violations and reactive power shortage. The IEEE reliability test system [11] load model is used with peak load of 285 MW. Monte Carlo simulation is performed to calculate reliability indices mentioned in section (4.3).

4.5.1 Case Study-System Modeling

Case 2 in chapter 3; i.e., IEEE 14-bus system with two synchronous generators and three solar PVs is used here to study the effect of reactive power shortage on the reliability of power system with solar PV penetration. All the system specifications such as system topology, number of synchronous generators and solar PVs, and the failure and repair rates are same the as in chapter 3. In modeling generating units, maximum active and reactive power limits are assigned

based on the P-Q curve of the generators. Generator model from ETAP software is used to assign active and reactive power limits. Figure 4.2 shows a typical capability curve for 150 MW synchronous generators in ETAP. The assigned active and reactive power limits are shown in Table 4.1

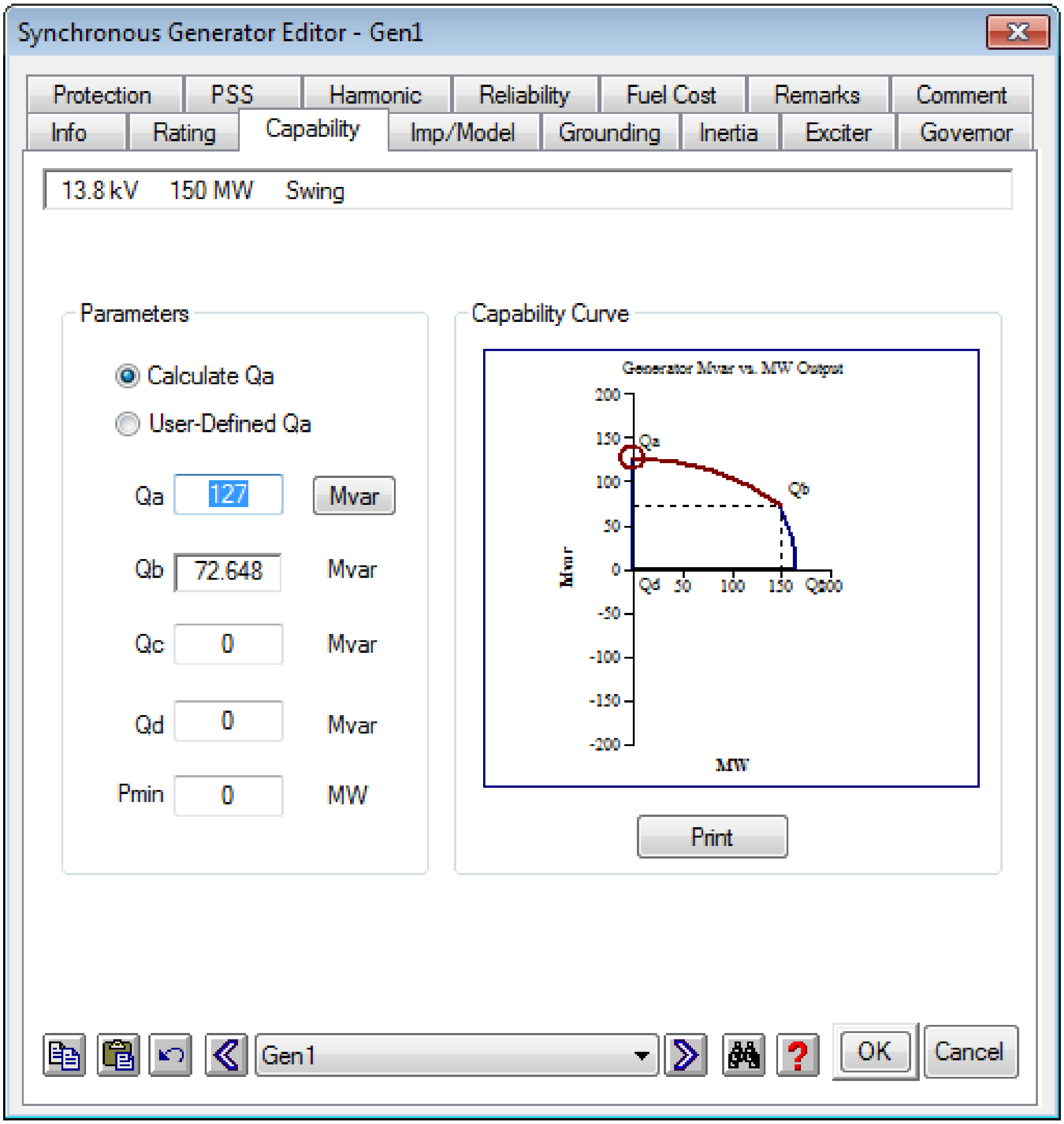

Fig. 4.2 Generator capability curve

Table 4.1 Generator reactive power limits

Generator Type	No. of units	Unit Size (MW)	P_{max} (MW)	Q_{max} (MVAr)
Synchronous Generator	2	150 MW	150 MW	72 MW
Solar Photovoltaic	3	50 MW	50 MW	-

4.5.2 Contingency Selection

As mentioned, in large power systems the total number of states of the network component is very high. Hence, here the most severe contingencies are selected; that is, the synchronous and solar PV generator failures. Load-flow determines the active and reactive power requirements in the network due to the active and reactive power demands based on the hourly load curve. PV placement in the network is random across the buses. Table 4.2 shows the load-flow solution before the contingencies when PVs are placed at buses 5, 10, and 13 as shown in Fig. 4.3.

The hourly generation is based on the synchronous generators active and reactive power limits and PV generators active power limits, at different times of the day. Those contingencies, which violate the maximum generator active and reactive power capacities, are selected. Two step load curtailment approach is utilized, first real power load is curtailed such that all

generators reach its maximum active power limit. At this point reactive power limit and bus voltages are checked, if they are in limit no additional load curtailment is done. If, the network voltages are not within the limits additional active load is curtailed to restore system voltage to acceptable limit, in this case 95%. These two load curtailments are called, active load curtailment because of active power shortage LC_{Pi} and active load curtailment because of reactive power shortage LC_{Qi} respectively.

Table 4.2 IEEE 14 Bus system load flow data

Bus No	Voltage	Angle	PG	QG	PL	QL
1	1.06	0.00	1.232	0.496	0.000	0.000
2	1.02	-2.51	0.000	0.000	0.220	0.136
3	1.00	-6.20	0.000	0.234	0.480	0.232
4	1.00	-4.62	0.000	0.000	0.440	0.203
5	1.01	-3.23	0.500	0.000	0.320	0.145
6	1.01	-2.94	0.000	0.122	0.120	0.099
7	1.00	-6.90	0.000	0.000	0.170	0.082
8	1.01	-9.40	0.000	0.174	0.250	0.091
9	1.00	-5.45	0.000	0.271	0.260	0.130
10	1.01	-3.54	0.500	0.000	0.100	0.048
11	1.00	-3.75	0.000	0.000	0.100	0.020
12	1.00	-2.51	0.000	0.000	0.060	0.010
13	1.02	-1.49	0.500	0.000	0.080	0.015
14	1.00	-4.32	0.000	0.000	0.080	0.020

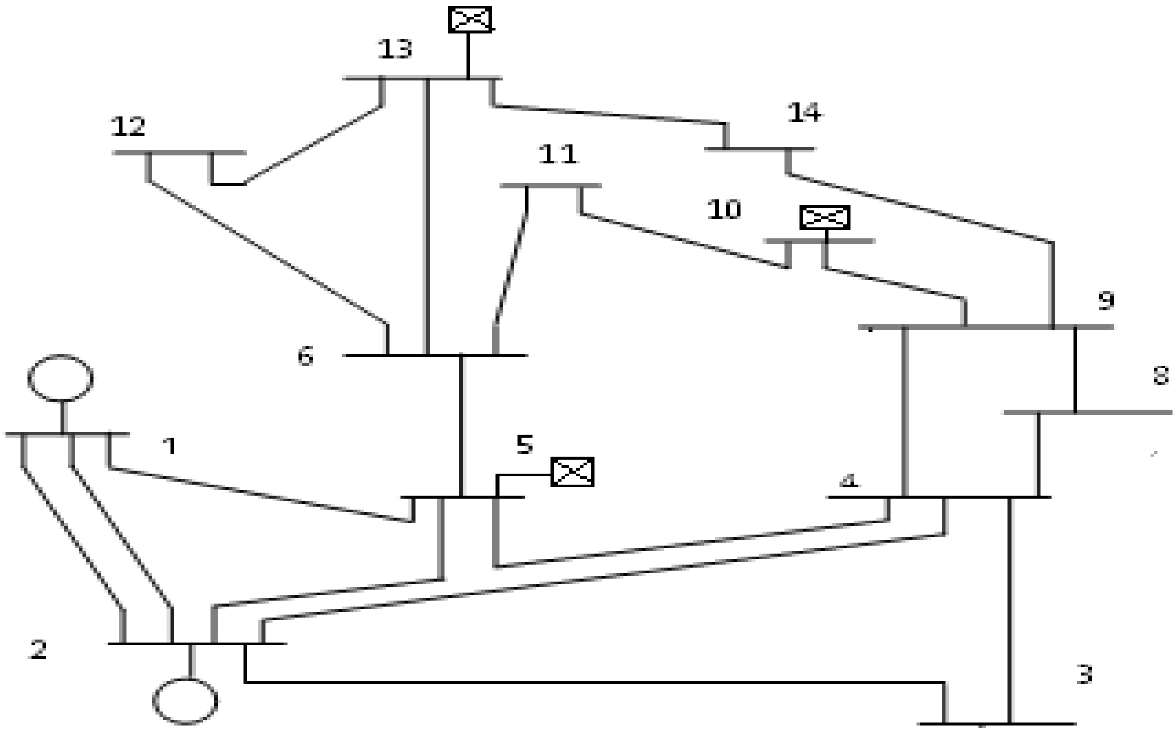

Fig.4.3 IEEE 14-bus system with synchronous generator and PVs

4.5.3 Reliability Evaluation Procedure

The reliability evaluation procedure is explained in the following algorithm in order to calculate reliability indices explained in section 4.3

Step 1) Calculate the instantaneous load active and reactive power demand P_{Di} and Q_{Di} from hourly load curve,

Step 2) Calculate the total required generators active power P_{Gi} and reactive power Q_{Gi} for hour i, from load-flow,

Step 3) Check the generator’s active and reactive power limits and network voltages. If they are within the specified limits go to step 8.

Step 4) If there are active power limit violations (because of active power shortage,) curtail the load proportionally at all buses till P_{Gi} fall below the active power limits, then update reliability index $EENS_P$,

Step 5) If there are reactive power or voltage violations (because of active or reactive power shortage,) curtail additional load proportionally at all buses till P_{Gi} and Q_{Gi} fall below the generators limits, then update reliability indices $EENS_P$ and $EENS_Q$,

Step 6) If all the contingencies are checked, go to step 7; otherwise, go to step 3,

Step 7) Increment the time instant and repeat steps 1 through 6 till the time period under consideration is covered,

Step 8) Finish.

Table 4.3 shows reliability indices when PV generators are placed at bus 6, 10 and 12 for 0.9 and 0.85 power factors.

Table 4.3 Reliability Indices for different power factors

Expected energy not supplied	Power factor 0.9	Power factor 0.85
$EENS_P$ (MWh/year)	10910.55	10791.09
$EENS_Q$ (MWh/year)	193.02	2442.77
EENS Total (MWh/year)	11103.57	13233.86

It is evident from Table 4.3 that lower power factor contributes to more load curtailment because of reactive power shortage and results in overall more EENS. This is because the lower power factor causes more the reactive power demand and the more power loss in the network.

4.5.4 PV Placement in the network

The solution proposed in the past to overcome reactive power shortage is temporary reactive power injection [8] at buses with network violations. In order to inject required reactive power into the network additional compensators provision is required. However this may not be the most economical solution because such incidents are very few in power system. We observed that even though PVs are not a source of reactive power their proper placement can reduce the reactive power demand to a great extent. This is due to the reduction in network reactive power losses. Figure 4.4 and Fig. 4.5 show EENS obtained for different PV locations for power factors 0.9 and 0.85, respectively.

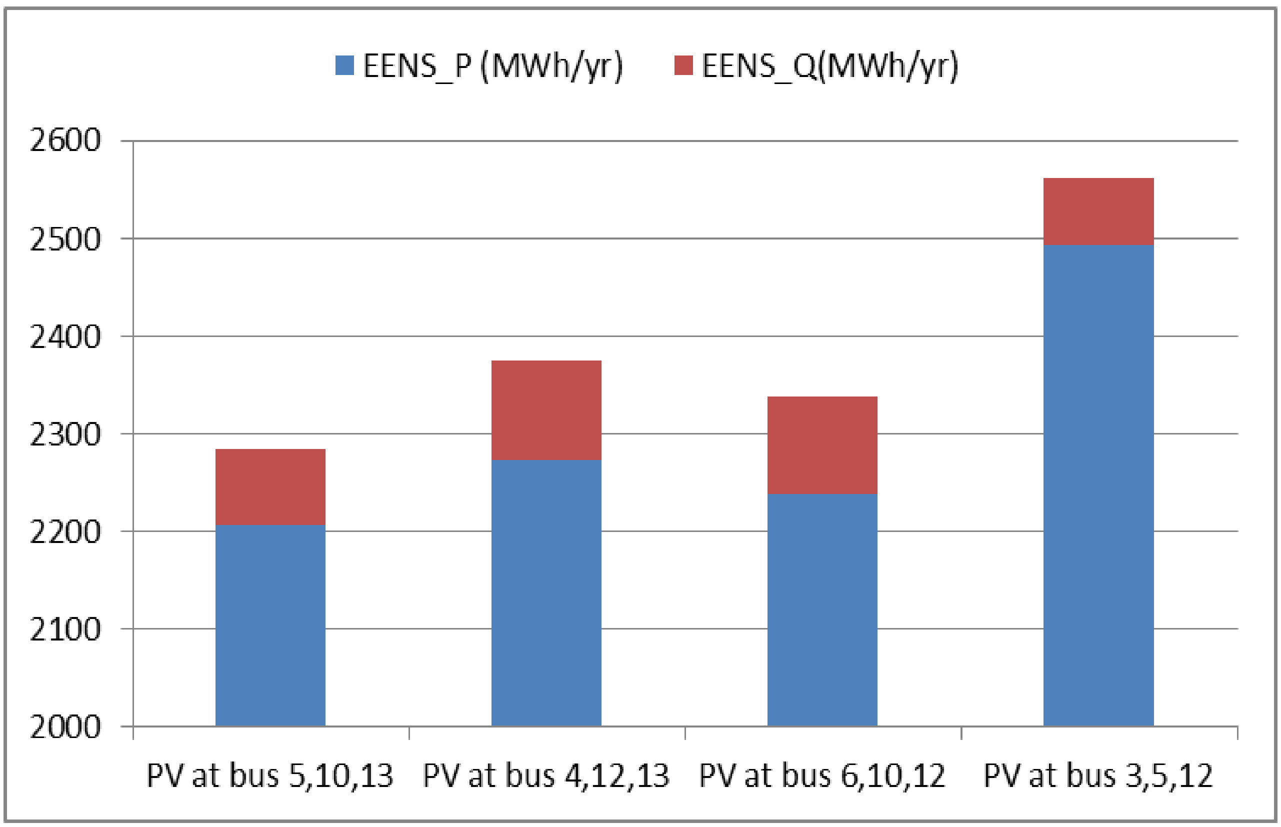

Fig.4.4 PV locations and EENS for 0.9 Power factor.

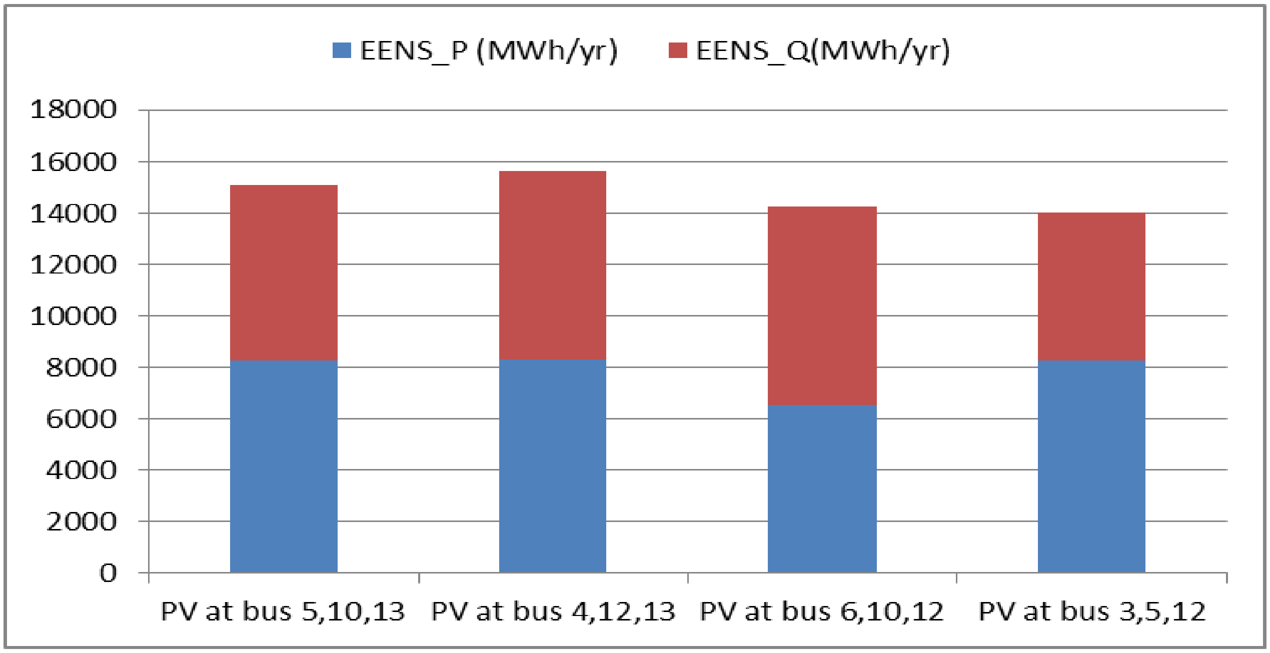

Fig.4.5 PV locations and EENS for 0.85 Power factor.

For the power factor of 0.9 the best locations for solar PV generators are found to be at buses 5, 10, and 13, whereas for 0.85 power factor the best PV locations are at buses 3, 5 and 12. It is important to note that instead of having large PV generators at one bus, a few smaller PVs distributed across the network at different buses will improve the reliability even more. That is, local PV generation results in reduced active and reactive power demand on account of reduced network losses. Therefore, it is very important to take into account the location of generation sources and system load characteristics while designing power systems.

CHAPTER 5
CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Reliability of power system comprising time varying and intermittent renewables sources such as solar photovoltaic system is evaluated in this work. Modified IEEE 14-bus system is used to evaluate reliability analytically and through Monte Carlo simulation. The solar PV is modeled as 24-stage generator to evaluate reliability. It is observed from the results that an additional 33 % PV generation capacity in the network can improve reliability by 57 % if only active power shortage is considered. It is also observed that even though addition of PVs can enhance generation capabilities of the network, sufficient reactive power margin is required to maintain system security. In addition, from the simulation it is observed that the low power factors results in more load curtailment due to reactive power shortage and in turn deteriorate the overall system reliability.

Moreover, it is observed that even though the solar PVs are not a source of reactive power their proper placement in the network can improve reliability to a good extent. Network configuration, placement of generation resources in the network, and system power factor play very important roles in active and reactive power demand and network losses. Therefore it is important form the reliable network planning perspective to take into account the placement of such renewable energy sources.

5.2 Future work

In this research the reactive power aspect of reliability of solar photovoltaic system is investigated through simulation. Future work includes the development of general mathematical relationship which can be applied to any time varying source of power to calculate $EENS_P$

and $EENS_Q$. Also, this study has used only three PVs placed at three different buses; future work includes smaller capacity PVs distributed all over the network.

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APPENDIX A
IEEE 14 bus system –Bus and line data

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 08/19/93 UW ARCHIVE           100.0  1962 W IEEE 14 Bus Test Case
BUS DATA FOLLOWS                            14 ITEMS
   1 Bus 1     HV  1  1  3 1.060    0.0      0.0      0.0    232.4   -16.9     0.0  1.060     0.0     0.0   0.0    0.0         0
   2 Bus 2     HV  1  1  2 1.045  -4.98     21.7     12.7     40.0    42.4     0.0  1.045    50.0   -40.0   0.0    0.0         0
   3 Bus 3     HV  1  1  2 1.010 -12.72     94.2     19.0      0.0    23.4     0.0  1.010    40.0     0.0   0.0    0.0         0
   4 Bus 4     HV  1  1  0 1.019 -10.33     47.8     -3.9      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.0         0
   5 Bus 5     HV  1  1  0 1.020  -8.78      7.6      1.6      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.0         0
   6 Bus 6     LV  1  1  2 1.070 -14.22     11.2      7.5      0.0    12.2     0.0  1.070    24.0    -6.0   0.0    0.0         0
   7 Bus 7     ZV  1  1  0 1.062 -13.37      0.0      0.0      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.0         0
   8 Bus 8     TV  1  1  2 1.090 -13.36      0.0      0.0      0.0    17.4     0.0  1.090    24.0    -6.0   0.0    0.0         0
   9 Bus 9     LV  1  1  0 1.056 -14.94     29.5     16.6      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.19        0
  10 Bus 10    LV  1  1  0 1.051 -15.10      9.0      5.8      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.0         0
  11 Bus 11    LV  1  1  0 1.057 -14.79      3.5      1.8      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.0         0
  12 Bus 12    LV  1  1  0 1.055 -15.07      6.1      1.6      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.0         0
  13 Bus 13    LV  1  1  0 1.050 -15.16     13.5      5.8      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.0         0
  14 Bus 14    LV  1  1  0 1.036 -16.04     14.9      5.0      0.0     0.0     0.0  0.0       0.0     0.0   0.0    0.0         0
-999
BRANCH DATA FOLLOWS                         20 ITEMS
   1    2  1   1 1 0  0.01938   0.05917    0.0528     0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   1    5  1   1 1 0  0.05403   0.22304    0.0492     0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   2    3  1   1 1 0  0.04699   0.19797    0.0438     0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   2    4  1   1 1 0  0.05811   0.17632    0.0340     0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   2    5  1   1 1 0  0.05695   0.17388    0.0346     0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   3    4  1   1 1 0  0.06701   0.17103    0.0128     0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   4    5  1   1 1 0  0.01335   0.04211    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   4    7  1   1 1 0  0.0       0.20912    0.0        0     0     0     0 0  0.978     0.0 0.0    0.0     0.0    0.0   0.0
   4    9  1   1 1 0  0.0       0.55618    0.0        0     0     0     0 0  0.969     0.0 0.0    0.0     0.0    0.0   0.0
   5    6  1   1 1 0  0.0       0.25202    0.0        0     0     0     0 0  0.932     0.0 0.0    0.0     0.0    0.0   0.0
   6   11  1   1 1 0  0.09498   0.19890    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   6   12  1   1 1 0  0.12291   0.25581    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   6   13  1   1 1 0  0.06615   0.13027    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   7    8  1   1 1 0  0.0       0.17615    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   7    9  1   1 1 0  0.0       0.11001    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   9   10  1   1 1 0  0.03181   0.08450    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   9   14  1   1 1 0  0.12711   0.27038    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
  10   11  1   1 1 0  0.08205   0.19207    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
  12   13  1   1 1 0  0.22092   0.19988    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
  13   14  1   1 1 0  0.17093   0.34802    0.0        0     0     0     0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
-999
LOSS ZONES FOLLOWS                     1 ITEMS
  1 IEEE 14 BUS
-99
INTERCHANGE DATA FOLLOWS                 1 ITEMS
 1    2 Bus 2     HV    0.0  999.99  IEEE14  IEEE 14 Bus Test Case
-9
TIE LINES FOLLOWS                     0 ITEMS
-999
END OF DATA
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VITA

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