The Reliability Assessment of Central Photovoltaic Inverter in Electric Power System

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***Abstract* — The electric power system produced by Photovoltaic (PV) system is being gradually utilized in power system network with different Photovoltaic configuration. The central Photovoltaic inverter system is designed in large scale of solar power. This system has a different impact on system reliability than conventional generation due the intermittent nature of geographical locations and the availability of PV electronic system. It is therefore vital to evaluate the reliability contribution of central PV system in electric power system network taken into account entire PV system components. This project uses a probabilistic and Part-Count approach to develop the output power of central PV system. A developed model is then applied to Small Isolated Power System (SIPS) to study the system adequacy and the capacity credit of installing Photovoltaic units.**

***Index Terms* —Capacity Outage Table (COPT), Loss of Load Expectation (LOLE), Loss of Energy Expectation (LOEE), Capacity Credit (C.C), Incremental Peak Load Carrying Capability (IPLCC).**

I. INTRODUCTION

Currently, pollution of the environment is recognized as big challenges facing humanity. The production of electricity using renewable energy has been increasing due to the negative impact associated with the usage of fossil fuel. Generation of electric power by solar cell technology is considered to be an essential contributor to the future world's energy supply due to technological and environmental benefits. There is evidence of global support of PV system, and many governments and organizations around the world have applied energy policies to support its growth. Different factors such as no moving parts, zero carbon dioxide emission and noise, 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. Fig. 1 [1] represents the PV capacity installed around the world. Obviously, the total PV capacity has been increasing exponentially from 1400 MW into 102.156 GW in 2000 to 2012, respectively.

Solar power differs from electric power produced by conventional generation source because solar power is not always available on demand. The output power of central PV system is highly variable and cannot be predicted easily as conversational generation due to the performance and operating characteristics of solar power system and the high Force Outage Rate (FOR) [2] or unviability and availability associated with central PV system components [3, 4]. The central PV system is collected from vulnerable electric components [5, 6].

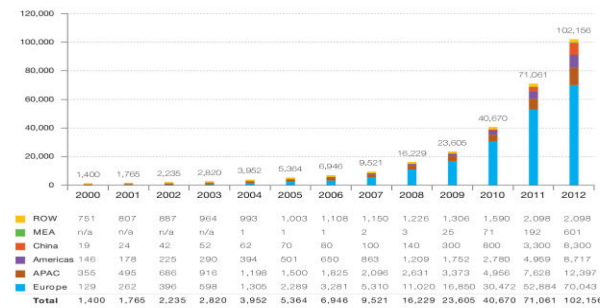

Fig. 1. The PV global cumulative capacity 2000-2012 (MW) [1]

There is lack of research in considering entire central PV system components in analyzing the overall system adequacy of integrating PV system to electric power system network. It is therefore importance to assess the reliability contribution of adding PV units considering the schematic construction of central PV system. Actual solar irradiating data is utilized at this work for a specific location. These data has the solar irradiation, wind speed and temperature from 2000 to 2005 for different sites for each 5 minutes [7]. The solar irradiation is an importance element at a specific location to estimate the out power of PV cell.

This paper presents the reliability contribution process of a central PV system in SIPS. The failure rate (λ) is calculated in this work in order to build Capacity Outage Probability Table (COPT) [2]. The rounding technique [2] is utilized to establish developed appropriate multi-state PV system models. This work involve the evaluating system reliability indices of the loss of load expectation (LOLE) and the loss of energy expectation (LOEE) obtained by combining the system load model with the developed generation model. The PV system capacity is calculated in this work as well.

II. SYSTEM ADEQUACY AND CAPACITY VALUE

Power system adequacy indices can be defined as an integral element in determining the facilities required in a power system to satisfy the load requirement in a reasonably continuous manner [8, 9]. The first step is to develop a system generation model for power system networks. In this step, the

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availability and unavailability of critical electrical components of PV system such as capacitance, switching and transformer are evaluated. The developed system generation model is then combined with load model to evaluate the system risk indices. The terms of LOLE and LOEE are used to quantify the reliability contribution of PV system indices [2]. The LOLE is known as the expected number of days or hours in a year that the system generation cannot meet the system load demand. The LOEE can be defined as is the expected energy curtailed in a year and provides information on the magnitude of energy curtailment. The LOLE and LOEE are determined using (1) and (2) as shown in Fig. 2.

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

$$LOEE = \sum_{k=1}^{n} p_k \times E_K \tag{2}$$

Where:

n = the number of capacity outage states.

p_k = probability of the capacity outage O_k .

t_k = the time for which load loss will occur due to O_k .

P_k = cumulative outage probability for capacity state O_k .

E_k = energy not supplied.

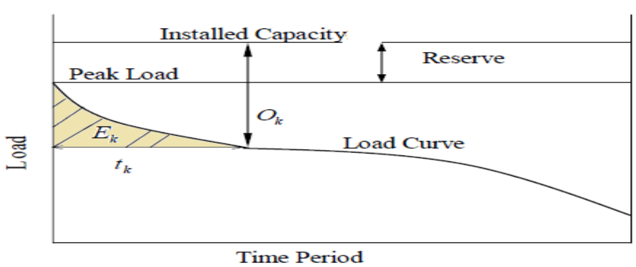

Fig. 2. Evaluation of LOLE and LOEE using an hourly load curve

The terms of capacity credit and IPLCC are used in this work to calculate the capacity value of added PV unit. The physical model of IPLCC is shown in Fig. 3 [10, 11]. The capacity credit (C.C) of PV system is obtained using (3).

$$C.C = \frac{IPLCC}{C_A} * 100 \tag{3}$$

C_A is the rated capacity of the added generating unit.

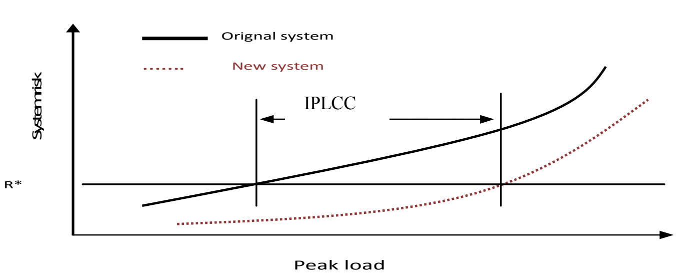

Fig. 3. Evaluation of IPLCC[10, 11]

III. Generation and Load Model

The test system model used in this project is composed of conventional generators, PV plant system and load model.

A. SIPS and Load Model

The SIPS utilized in this work has one 70 kW and two 40 kW [12] generation units with a total system generation capacity of 150 kW. Each generating unit has unavailability of 5%. This system meets the deterministic loss of the largest unit or N-1 criterion, so the peak load is 80 kW [12]. The IEEE-RTS annual chronological hourly load profile is used in this work [13].

B. Central PV System Model

A central PV system constructed by ABB is used in this paper as shown in Fig. 4 [14]. The solar cell, over voltage protection (SPD), DC load breaker switch, Fuses and Auxiliary Disconnect switch components are not considered in modeling the COPT of PV system due to their low failure rate. This section is divided into two subsections.

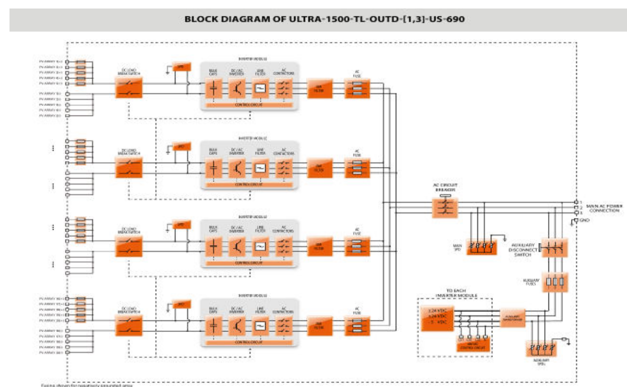

Fig. 4. Block Diagram of Central power Inverter [14]

1. The output power of solar cell

The analytical model described in [15] is utilized in this paper to create the multi-state model of the output power of solar cell. This model depends on solar cell efficiency and irradiation. The efficiency of a solar cell differs with the amount of solar irradiation, and it can be calculated using (4) and (5). The solar power from a solar cell can be evaluated using (6)-(8).

$$Eff = \frac{\eta_c}{R_c} \times G_{bi} \qquad 0 \le G_{bi} < R_c \tag{4}$$

$$= \eta c \qquad R_c \le G_{bi} \tag{5}$$

$$P = P_{sn} \times \frac{G_{bi}^{\,2}}{G_{std} \times R_c} \qquad 0 \le G_{bi} < R_c \tag{6}$$

$$= P_{sn} \times \frac{G_{bi}}{G_{std}} \qquad R_c \le G_{bi} < G_{std} \tag{7}$$

$$= P_{sn} \qquad G_{bi} > G_{std} \tag{8}$$

Where P is the output power of solar cell, G_{bi} is hourly solar irradiation (W/m^2), G_{std} is solar irradiation in a standard environment set as 1000 (W/m^2), R_c is a certain irradiation

The multi-sates of capacity outage level and corresponding probabilities are created with dividing the output states of solar into segments. A step size of 50W/m^2 is utilized in this analysis. The number of obtained states is 22-states model as zero output power is a unique state. The probability for each state or level of solar irradiation is given by (9). Where N_i is the number occurrences of each state

$$\Pr obability_i = \frac{N_i}{5*24*365*12} \quad (9)$$

A historical solar irradiation data of Al-Madinah Al-Munawarah located in Saudi Arabia is used in this work [7]. The COPT of solar cell device is shown in Fig. 5. The probability of zero output is 0.461 where it is not displayed in this Figure. This COPT is used in this study and different PV capacities are considered to assess the impact of PV capacity of system reliability.

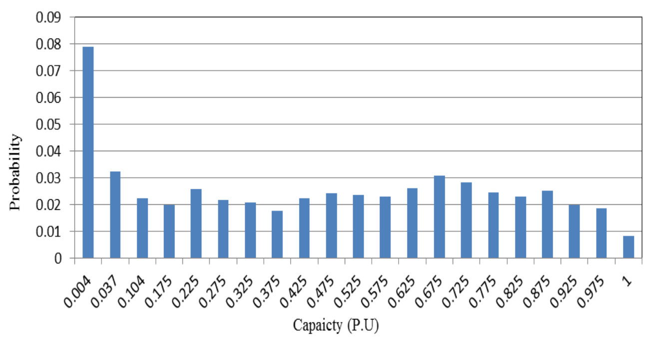

Fig. 5. The PV generation model.

2. The Output Power Model of a Central PV System

The central PV system consists of solar array, bulk dc-link capacitance, inverter, line filter, AC switch, EMI filter, AC fuse, AC circuit breaker and transformer. The reliability molding of PV system components can be formed as the component level or system level. References [16, 17] have been focused on modeling the failure rate of conductor, capacitor and magnetic device. Field experiences have proved that electrolytic capacitor and switching devices are the most vulnerable component [18]. There are several reliability models available for power electronic and high power voltage. MIL-HDBK-271 is the military handbook for the reliability component prediction for power electronic components [19]. This handbook provides an extensive reliability database for power electronic components. This database is used in this work to evaluate the failure rate of power electronic components.

➢ *Solar panel*

A solar panel is combined of number of solar array. This solar cell has high reliability and most manufactures propos a warranty from 20 to 25 years of solar cell. It is therefore not essential to consider this device in building COPT.

➢ *Dc-link Capacitor*

This device is critical component as it leads to the failure of PV system. Different material can used to make a capacitance such as electrolytic capacitor, paper, plastic film, tantalum and ceramic [20]. The electrolytic capacitor is considered in this work. The inductance has not been considered since it has low failure rate [21]. The prediction method to evaluate the failure rate can be found in MIL-HDBK-217 [19]. The failure rate format for capacitor is shown in Table I [22-24]. The n is the total number of component in system; λ_{base} is the base failure rate of capacitance which is 0.0314 occur/y; π_E is the effect of environment stress which is 1; π_Q is the quality factor which is 1; and T_j is the junction temperature which is 50°C.

➢ *Inverter*

The 3-phase 2-level voltage-source inverter is utilized in this paper. This inverter has six switches and diodes. This work considers each device inside inverter as a major factor failure. The Reliability Block Diagram (RBD) [25, 26] is utilized in this paper. In this technique, switching and diodes are connecting in series and this is known a series RBD as shown in Fig. 6. The failure rate of inverter (λ_{inv}) can be defined using (10). The prediction method to evaluate the failure rate of each component can be found in MIL-HDBK-217 [19].

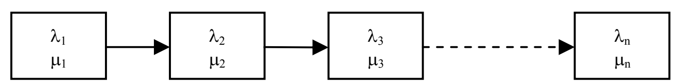

Fig. 6. Series configuration with n subsystems.

$$\lambda_{inverter} = 6*\lambda_{diode} + 6*\lambda_{switch} \quad (10)$$

➢ *Diode*

The failure rate format for diode is shown in Table I [22-24]. The n is the total number of components in a system; λ_{base} is the base failure rate of diode which is 0.025 occur/y; π_E is the effect of environment stress which is 6; π_S is the electric stress factor; the operating voltage and rated voltages are 607 V and 690 V, respectively; π_Q is the quality factor which is 5.5; π_j is the temperature stress factor; T_j is the junction temperature which is 50°C; and π_c is the contact construction factor which is 1.

➢ *Switch*

The failure rate of switch is described in Table I. The λ_{base} is the base failure rate of switch which is 0.012 occur/y; π_{E} is the effect of environment stress which is 6; π_Q is the quality factor which is 5.5; π_A is the effect of environment stress which is 10 since the rated power is greater than 250 W; π_j is the temperature stress factor; and Tj is the junction temperature which is 50°C. The total failure rate of inverter equal to 0.4328 occur/y.

Table I: Failure Rate Equations

Components	Failure Rate (λ)	
Capacitor	$\lambda_{cap} = n * \lambda_{base} * \pi_{cv} * \pi_{Q} * \pi_{E} * \pi_{T}$	$\pi_{cv} = 0.34 * C^{0.18}$ $\pi_{T} = \exp^{-4061.74 * (\frac{1}{T_j + 273} - \frac{1}{198})}$
Diode	$\lambda_{diode} = n * \lambda_{base} * \pi_{s} * \pi_{Q} * \pi_{E} * \pi_{T} * \pi_{c}$	$\pi_{T} = \exp^{-3091 * (\frac{1}{T_j + 273} - \frac{1}{198})}$ $\pi_{s} = \begin{Bmatrix} 0.054 & ----V_S \le 0.3 \\ V_s^{2.43} & ----0.3 \le V_s \le 1 \end{Bmatrix}$ $V_s = \frac{OperatingVolatge}{RtaedVoltage}$
Switch	$\lambda_{switch} = n * \lambda_{base} * \pi_{A} * \pi_{Q} * \pi_{E} * \pi_{T}$	$\pi_{T} = \exp^{-1925 * (\frac{1}{T_j + 273} - \frac{1}{198})}$

➢ *AC Circuit Breaker and Transformer*

The reliability database provided by [27] is used to calculate the probability of success and fail of these components.

There are three types of system-level reliability models: part-count methods, combination models and states-space models. Part-Count is implemented in this project as this method can provide adequate reliability evolution. Three assumptions are considered to apply Part Count model: the system will fail if any component or subsystem fails the failure rate of each component remains constant during useful life time, and the overall system is treated as series structure RBD. The probability of up (P_{up}) and down (P_{dwon}) states can be evaluated using (11) and (12).

$$P_{Up} = \frac{\mu_1}{\mu_1 + \lambda_1} * \frac{\mu_2}{\mu_2 + \lambda_2} * \frac{\mu_3}{\mu_3 + \lambda_3} + \frac{\mu_n}{\mu_n + \lambda_n} \tag{11}$$

$$P_{Down} = 1 - P_{up} \tag{12}$$

The reliability data of common PV system component is shown in Table II. The probability *Up* and *Down* states of central PV system is shown in Table III. Then this Table is combined with model shown in Fig. 5 to build the overall central PV system model. This model represents the multi-states model of the output power of central PV system including the component failure factors.

Table II: Failure and Repair data.

Parameters	Value	Description	Component
λ_{cap} (f/y)	0.9349	Failure Rate	Capacitance
r_{cap} (Hours)	100	Repair Time	
λ_{diode} (f/y)	0.0149	Failure Rate	Diode
r_{diode} (Hours)	96	Repair Time	
λ_{switch} (f/y)	0.0572	Failure Rate	IGBT
r_{switch} (Hours)	513	Repair Time	
$\lambda_{AC\ Breaker}$ (f/y)	0.003	Failure Rate	Circuit Breaker
$r_{AC\ Breaker}$ (Hours)	54	Repair Time	
$\lambda_{AC\ Switch}$ (f/y)	0.006	Failure Rate	AC Switch
$r_{AC\ Switch}$ (Hours)	24	Repair Time	
$\lambda_{Transformer}$ (f/y)	0.006	Failure Rate	Transformer
$r_{Transformer}$ (Hours)	168	Repair Time	

Table III: Two States model of central PV system components.

States	Probability
Up	0.9688
Down	0.0312

The process of evaluating the reliability contribution of PV in SIPS is summarized in the flowchart shown in Fig. 7.

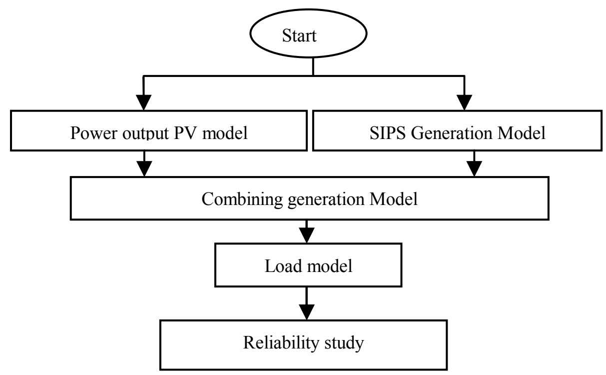

Fig. 7. A flowchart of the evaluation steps

IV. Reduction Method

A simplified reduction model using rounding approach [2] is applied in this work to reduce the multi-states model of PV system by an acceptable reduced number of de-rated states. This technique is based on sharing the ratio of probability. Fig. 8 shows the physical model of rounding approach. Equation 13 and 14 describe the mathematical calculation of the probability of new sates. Where P is the probability of selected state and C is the capacity in W.

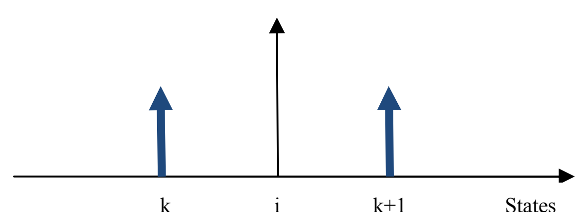

Fig. 8. Block Diagram of Central power Inverter

$$P_{k+1} = \frac{C_i - C_k}{C_k - C_{k+1}} \times P_i \tag{13}$$

$$P_k = \frac{C_{k+1} - C_i}{C_{k+1} - C_k} \times P_i \tag{14}$$

In this study, the adequacy impact of adding 15 kW of PV capacity to SIPS was analyzed using different PVCS multi-states models. The annual system LOLE for a peak of 80 kW is used in this step. Table IV shows that the LOLE fluctuates slightly due to using different number of states. This study also indicates that using 2-states model provide pessimistic assessment of the system adequacy. The results clearly show that 5-states model representation provides appropriate assessment of the system adequacy.

Table IV: The Annual system indices with Reduction Method

States	LOLE (h/y)
Original States (22-states)	28.0122
20-states	27.9911
18-States	28.0204
16-states	28.107
12-states	28.3231
9-states	28.6038
7-states	28.611
5-states	28.9948
4-states	30.5038
3-states	31.6377
2-states	22.8800

V. Case Study

This work discusses the application of developed model in SIPS including a PV system. The system adequacy of LOLE and LOEE are calculated considering different studies. The impact of system peak load variation and PV installed PV capacity on LOLE and LOEE are evaluated. In this study, the peak load is varied from 80 to 118 kW. The system adequacies of LOLE and LOEE before adding PV system are 32.26h/y and 483.46kWh/y respectively. The PV farm is connected to SIPS to investigate the system reliability contribution with adding PV unit. Three different installed PV capacities are examined in this work. The results of these analyses are shown in Figs. 9 and 10. Clearly, these two Figures point out that the system risk level as the peak load increase. Moreover, there is improvement in system adequacy with adding more PV system.

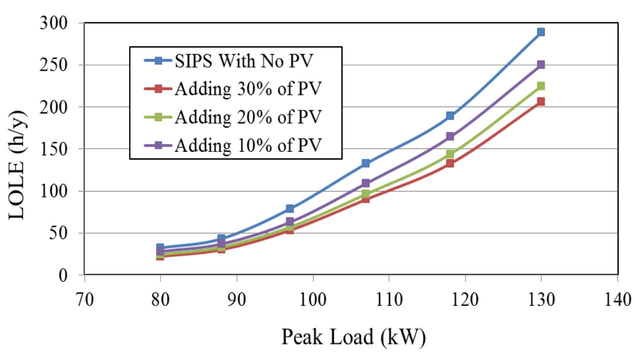

Fig. 9. System peak load with system risk level of LOLE

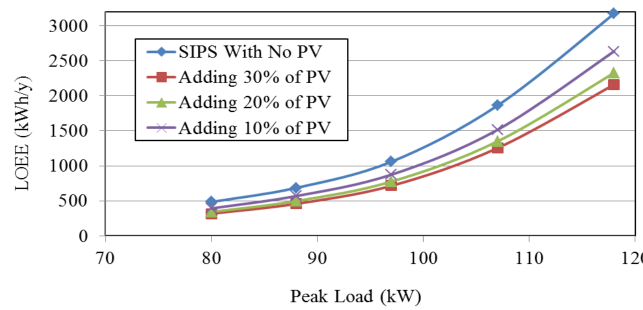

Fig. 10. System peak load with system risk level of LOEE

The system benefits in the form of IPLCC are analyzed in this study to compare the system adequacy effect of installing different PV system capacity. The same test system used in previous case study is applied in this case. The system peak load is fixed at 80 kW and different system PV capacity ranging from 10% to 30% is applied to SIPS. It can be seen from Fig. 11 that there is load carrying capability benefit from PV additions. The study shows that the combined system of SIPS and PV carry peak load of 3.4, 4.3 and 5.6 kW with adding 15, 30 and 45 kW of PV systems. The results prove that there is improvement in system adequacy with installing more PV system to SIPS.

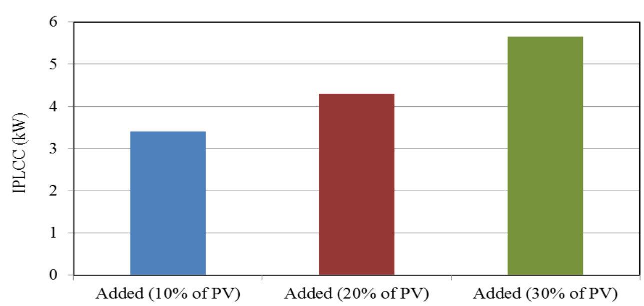

Fig. 11. Incremental peak load carrying capability at different PV capacity

The impact on the PV capacity credit of the various installed PV capacity are calculated. Installed PV capacity level of 15, 30 and 45 kW corresponding to approximately 10%, 20% and 30% respectively of the SIPS capacity are considered. The results from Fig. 11 are utilized to estimate the C.C of PV using (equation). Fig. 12 shows the C.C of PV. The relative system adequacy contribution as measured by C.C decrease as more PV capacity is installed.

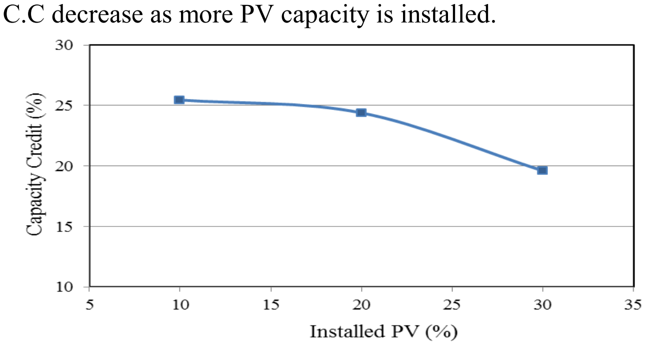

Fig. 12. Capacity credit for three different added PV

VI. Conclusion

This work provides a practical technique to reliability analysis of central PV inverter and can be applicable to other PV topology. A developed reliability model of PV system is presented and discussed in this project. This model involves all critical electric components in PV system. The reliability and capacity value of PV farm benefit is analyzed and quantified. The variation in LOLE for different PV multi-states model is investigated. The results show that five-state model is reasonable reduction model to be used for system reliability assessment. There is reliability improvement with adding solar power to electric power system. However, this improvement decreases at certain percentage of solar power.

Acknowledgments

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