

Modeling the Output Power of PV Farms for Power System Adequacy Assessment

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Abstract—This paper presents a method to model the expected output power of PV systems and to evaluate their effect on power system reliability. Grid level PV systems are usually constructed from a large number of electronic components and converters. Modeling of these systems in power system reliability is a complex task due to the dependency of the output power on an intermittent source (solar) and the availability of a large number of system components. An analytical method to construct a capacity outage probability table (COPT) that captures both the intermittency of the input source and component failures was proposed to model PV systems in power system adequacy assessment. The intermittency of the input source and component availabilities were modeled separately and then convolved to construct a single COPT. The resulted COPT can be viewed as a single PV system with multi-derated states. System reliability indices were evaluated using discrete convolution method. Monte Carlo simulation was used to validate the results of the proposed method. The proposed method was implemented on the IEEE-RTS and Roy Billinton test system (RBTS) with a wind farm of 30 MW. The obtained results were very close to those obtained using Monte Carlo simulation with less computation effort.

Index Terms—PV-system, adequacy assessment, reliability evaluation.

I. INTRODUCTION

Penetration level of renewable energy sources such as PV systems has been in a continues increase. Despite their environmental and economic advantages, the penetration level of these sources is usually limited by technical constraints such as stability and reliability of the main grid. Due to the intermittency and uncertainty of the output power of these sources, as the penetration level of these sources increases, challenges of maintaining the operation and power quality aspects of the main grid becomes more evident.

In general, grid connected PV systems are constructed from a large number of components such as power electronic circuits and solar panels. The reliability of such components are highly dependent upon the operation and ambient conditions. Operational and environmental factors may lead to overall reduction in the output power and failure of system components [1]–[3]. Given the large number of components involved in PV systems and the intermittency of the source (solar), modeling of these systems in reliability evaluation studies is a complex task.

From the reliability point of view, the output of PV systems is modeled based on the availability of the input (solar) and the availability of the components. In general, Monte Carlo simulation is usually considered as an appropriate approach for modeling the uncertainty of PV systems. One of the advantages of Monte Carlo simulation is the ability to capture a wide range of modeling details and system dependencies. On the other hand, the solution accuracy using Monte Carlo simulation depends mainly upon the number of samples performed to converge to a specified tolerance. The computation time using simulation approaches, especially when it is implemented on large and complex systems, is of concern [4], [5].

In the literature of the reliability aspects of PV systems, most of the presented work have considered the effects of power electronic components and circuits such as capacitors, IGBTs or the entire inverter to assess the reliability of PV systems [6]–[8]. Monte Carlo simulation technique has been used in [9] for reliability assessment of a hybrid system of wind and PV systems. A combination of deterministic and probabilistic techniques has been used in reliability evaluation of these systems. In [10], the hourly mean solar radiation data has been used as a main input and Monte Carlo simulation technique was implemented to evaluate the system reliability. In [11], an analytical method has been used to model the availability of the PV systems in the reliability assessment. In [12], reliability of a wind and solar system has been evaluated using Monte Carlo simulation technique. In [13], a methodology for photovoltaic system reliability and economic analysis has been introduced. The method proposed in [13] aimed to model the availability of reliability and maintenance of a PV system that could be utilized to estimate life-cycle energy cost. In [14], the reliability evaluation of grid-connected PV systems has been conducted. In the work presented in [14], the state enumeration technique has been utilized to model the output power of PV systems considering the dependency of failure rates of system components on ambient conditions.

The purpose of this work is to construct a model that sorts the output power of PV farms into clusters considering the effect of the input variation and failure of system components. Two COPTs are constructed: (1) the outage due the unavailability of the input, and (2) the outage due to failure of

system components. These two COPTs are then combined to produce a single COPT that can be viewed as a single source with multi-derated states. In this context, an analytical method, which is based on discrete convolution, is adopted to estimate the reliability of the main grid in the presence of PV systems. Monte Carlo simulation is used in this paper for validating the results of the proposed method.

The rest of the paper is organized as follows. Section II presents the modeling of PV output power. Section III explains the reliability aspects of PV systems. Section IV shows a case study to demonstrate the effectiveness of the proposed method. Section V concludes the paper.

II. PV SYSTEM FARMS AND OUTPUT POWER

Different typologies of PV systems have been addressed in literature [15]–[17]. In general, typologies of PV systems are mainly classified based on the arrangement of PV panels and DC/DC and DC/AC converters. These arrangements are usually set up to enhance the system's efficiency, reliability, etc.

A. PV Farm Structure

In general, a PV farm is constructed from a large number of PV panels arranged in arrays and connected to DC/DC and DC/AC converters as shown in Fig. 1. PV arrays are constructed from PV panels which in turn are connected to the main grid through DC/DC and DC/AC converters. The set of N panels in each array is called sub-array. PV panels are constructed from a large number of solar cells in series-parallel configurations. At the higher level, the output of the PV system is then connected to the grid through a power transformer [18].

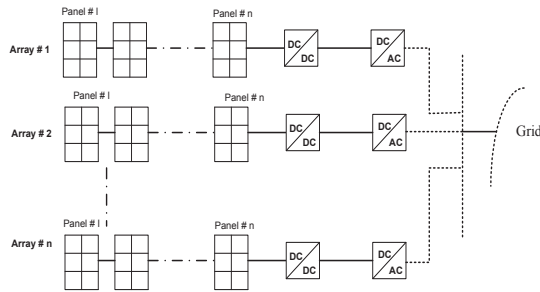


Fig. 1. Schematic presentation of PV system with N arrays

The amount of the output power of a PV farm at a certain location depends on the input availability (mainly solar radiation) and the availability of system components. In a PV farm, since PV panels are placed adjacent to each other, all PV panels are assumed to have the same solar radiation, and approximately experience the same operational and environmental factors that may affect the output of the farm.

B. Output Power of PV Systems

The maximum output power ratings of PV systems are provided by the manufactures and usually are expressed in peak-watt (W_P). The current-voltage characteristics ($I - V$ characteristics) under the standard test conditions (the radiation level of $1kW/m^2$ is given for temperature of $25^\circ C$) can be calculated using the following relationships [19]:

$$I = s [I_{sc} + K_I(T_c - 25)] \quad (1)$$

$$V = V_{oc} - K_V T_c \quad (2)$$

where s is the radiation level, I_{sc} is the short circuit current, K_I is the short circuit current temperature coefficient in A/C° , V_{oc} is the open circuit voltage, K_V is the open circuit voltage temperature coefficient in V/C° and T_c is the cell temperature in C° which can be expressed as follows [19]:

$$T_c = T_a + s \left(\frac{T_{no} - 20}{0.8} \right) \quad (3)$$

where T_a is the ambient temperature and (T_{no}) is the nominal operating temperature of the cell (C°).

The output power (P_{pv}) for a given radiation level, ambient temperature and the current-voltage characteristics can be calculated using the following relationships [19]:

$$P_{pv} = N \times FF \times I \times V \quad (4)$$

where N is the number of panels and FF is the fill factor, which depends on the module characteristics, and can be expressed as follows [19]:

$$FF = \frac{V_{mpp} I_{mpp}}{V_{oc} I_{sc}} \quad (5)$$

where V_{mpp} and I_{mpp} are the current and voltage at the maximum power point.

III. RELIABILITY MODELING OF PV FARMS

The output power of a PV farm is represented in this paper in terms of COPT. A COPT represents a combination of capacity levels with the probabilities of existence and cumulative probabilities to represent the probability distribution function of the outage states. The COPT of a PV system and the COPT of the conventional generators are convolved with load levels using discrete convolution technique to evaluate the overall system adequacy to meet the demand.

A. Component Reliability

In a PV farm, power electronic devices are considered as major components. The power electronic circuits deliver the output power of PV panels to the load or to the main grid. Reliability assessment of power electronic circuits of large-scale grid-connected PV systems for different typologies have been addressed in literature [15], [16], [20]. In the literature, the mean time to failure (MTTF) has been used as an indication for system reliability; the overall reliability of a circuit has been calculated by summing the failure rates (the failure rate is reciprocal of the MTTF) of the components [21]–[23]. However, this is true if a failure of a component

leads to overall failure of the power electronic circuit. In some cases such as multilevel inverters, a redundancy exists in power electronic topologies and their desired function is not totally affected by a component failure [24]. In this case, there are several possible different paths that can still produce an acceptable output voltage level. In such configurations, the overall failure cannot be assumed by summing the failure rates of the components. Analytical techniques can be used to estimate system reliability such as reliability network analysis, minimal cut set, minimal path set and state enumeration techniques [25].

In general, the reliability function (availability), $R(t)$, indicates the probability that the system will operate without failures over a time interval $[0, t]$. The failure rate of a system component during the useful lifetime is usually considered independent of time. The reliability of system components can be expressed as an exponential function of their constant failure rate during the useful lifetime as follows:

$$R(t) = e^{-\lambda_i t} \quad (6)$$

where λ_i is the constant failure rate of a power electronic component.

From reliability point of view, the availability of a system consists of N components that are connected in series is given by:

$$R_{sys}(t) = \prod_{i=1}^N R(t) \quad (7)$$

The mean time to repair (MTTR) has been considered small enough and can be neglected [26]. This could be a valid assumption for a small system or a system with a few components where the time required to repair or replace a component is small comparing to MTTF. However, for large systems, neglecting the repair time could produce optimistic results. In this paper, the MTTR is included in modeling PV systems. System availability and unavailability as functions of MTTF and MTTR are described by (8) and (9).

$$p = \frac{\mu}{\lambda + \mu}, \quad (8)$$

$$q = 1 - p = \frac{\lambda}{\lambda + \mu} \quad (9)$$

where p is the probability of component availability, q is the probability of component failure and μ is the repair rate (reciprocal of $MTTR$).

For a system with N components connected in series, system availability (p_{sys}^s) can be calculated by (10).

$$p_{sys}^s = \prod_{i=1}^N p_i \quad (10)$$

where p_i is the probability of availability of component i .

For parallel configuration, there might be a tolerance for the desired output, and the reliability of the system is the probability of all possible successful paths that can provide

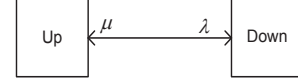


Fig. 2. State transition of a two-state component

the desired output. system availability (p_{sys}^s) can be calculated by (11).

$$p_{sys}^p = 1 - \left[\prod_{i=1}^N (1 - p_i) \right] \quad (11)$$

In the cases of series-parallel reliability configuration, it is useful to use network reduction techniques (NRT). The availability and unavailability can then be calculated by combining all series and parallel configurations to a equivalent unit using (10) and (11).

Reliability modeling of large systems such as PV system with a large number of system components could result in a large number of system states and increase modeling complexity. Therefore, the equivalent MTTF and MTTR for subsystems are needed to drive an equivalent failure rate λ and repair rate μ . The availability of system components can be modeled as a Markovian with two states, “up” and “down” with known failure and repair rates as showing in Fig. 2.

B. Reliability Modeling of Major Components of PV Systems

In the PV systems, the major components that contribute to system failure are power electronic circuits. In power electronic systems, components that contribute predominantly to system failure are IGBTs/MOSFETs, diodes and capacitors. The reliability performance of these components are affected by environmental and stress factors. One of the documents that provides reliability data and modeling of power electronic components is the military handbook, MILHDBK-217F [27]. According to the MILHDBK-217F, the failure rates of these components are described as shown below.

1) *Power electronic circuit components:* Since the MILHDBK-217F military does not provide data for IGBTs, it was assumed that the estimation of failure rates of MOSFETs are applicable for IGBTs.

For switches (MOSFET/IGBTs), the failure rate is described by:

$$\lambda_{IGBT} = \lambda_{IGBT_b} \pi_T \pi_Q \pi_E \quad \text{Failures}/10^6 \text{ hours} \quad (12)$$

where λ_{IGBT_b} is base failure rate of the IGBT, π_T temperature factor, π_Q quality factor and π_E environmental factor.

Similarly, failure rates of diodes are given by:

$$\lambda_{diode} = \lambda_{diode_b} \pi_T \pi_S \pi_C \pi_Q \pi_E \quad \text{Failures}/10^6 \text{ hours} \quad (13)$$

where λ_{diode_b} is base failure rate of the diode, π_S voltage stress factor, π_C contact construction factor and π_T , π_Q and π_E are as for IGBTs.

Capacitor failure rate is given by,

$$\lambda_{cp} = \lambda_{cp_b} \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E \quad \text{Failures}/10^6 \text{ hours} \quad (14)$$

where λ_{cpb} is base failure rate of the capacitor, π_V voltage stress factor, π_{SR} series resistance factor and π_T, π_C, π_Q and π_E are as for IGBTs.

2) *Reliability of PV Panels*:: The PV panels are constructed from n parallel branches; each branch is constructed by connecting m series solar cells. The equivalent failure rate of a branch can be calculated by summing the failure rates of the m series solar cells. The failure of a solar branch leads to the failure of the PV panel. Thus, the availability and unavailability of PV panels can also be calculated using (8) and (9). In this paper, the *MTTR* for system wiring and fuses are considered to be small enough and don not have a significant effect on system reliability estimation.

C. Capacity Outage Probability Table

The availability of the output power of a PV farm is characterized by the forced outage rate (FOR) of system components and the input availability. Therefore, it is desirable to consider the effect of both, FOR of system components and input availability on assessing the output power of a PV farm.

The failures of the components a PV system are assumed independent events; availabilities of system components can also be modeled as Markovian components with two states, “up” and “down” with known failure and repair rates. The assessment of the availability of the system output is addressed by separately modeling the independent failures of system components and the dependency on the input availability. As it was explained in the previous section, the equivalent availability and unavailability of system components can be estimated by calculating the equivalent failure and repair rates. A system with N parallel arrays with a capacity of (XMW) each is shown in Fig. 1. For each array, the MTTF and MTTR for M components can be calculated as mentioned in the previous sections. Each array can then be represented by equivalent MTTF and MTTR.

The COPT can be constructed for a PV farm with N arrays based on FOR by adding new units sequentially to the table with the capacity model building approach [28]. In general, the following expressions can be used to build the COPT [28].

$$P(x) = \bar{P}(x)(1 - q) + \bar{P}(x - C)q \quad (15)$$

where (9) can be initialized as follows,

$$\bar{P}(x) = \begin{cases} 1, & \text{if } x \leq 0 \\ 0, & \text{otherwise} \end{cases} \quad (16)$$

where $P(x)$ and $\bar{P}(x)$ denote the cumulative probabilities of the capacity outage state before and after the units are added, and q is the forced outage rate. The cumulative probability $P(x)$ for a forced outage of X MW or greater can be in general represented by (17).

$$P(x) = \sum_i P(X_i), \quad \forall X_i \leq x \quad (17)$$

where

$$\bar{P}(x) = 1, \quad \forall x \leq C$$

In the cases of generating units with derated states, equation (9) can be modified as follows to include a multi-state unit.

$$P(X) = \sum_{i=1}^n P_i \times \bar{P}(x - C_i) \quad (18)$$

where n is the number of unit states, C_i is the capacity outage of state i for the unit being added and P_i is the probability of existence of the unit in state i .

D. Capacity Outage Probability Table of a PV Farm

In this work, all system components are assumed to be identical and located at the same region. Therefore, all PV panels will experience the same input. The output power of each PV panel will be approximately the same. To compensate for the input uncertainty and variation, the hourly output power of PV panels constructed from installed capacity is sorted into several clusters using the clustering approach as explained in [29], [30]. The following steps can be used to cluster the output of a PV farm into a finite number of bands as following:

- 1) Calculate the hourly output power of PV panels.
- 2) Select initial cluster mean values M_i , where i donates cluster $i = 1, 2, \dots, X$.
- 3) Calculate the variation distance D_{ji} for each hour to each cluster mean M_i by (19).

$$D_{ij} = |M_i - X_j| \quad (19)$$

- 4) All points grouped by assigning them to the nearest cluster and then calculate the means of the new clusters by (20).

$$M_i = \frac{\sum_{j \in K_c} X_j}{X_i} \quad (20)$$

where X_j is the number of output power points in the i^{th} cluster and K_c denotes the set of the PV power points in the i^{th} cluster. Repeat Steps 2 and 3 until all cluster means become small enough and remain unchanged between iterations.

The clustered output power is represented by a finite number of bands. The transition rate of PV power between bands is considered stationary for the time period of study. The COPT of a PV farm considering the input uncertainty and component availability can be obtained by convolving the COPT over each band. The following expressions are used to construct the COPT of a PV farm considering both the FOR and the input variation.

$$MCOPT_{A(i,j)} = \frac{C_{PVCA(i)}}{C_{RPV}} \times C_{PV(j)} \quad (21)$$

where $MCOPT_{A(i,j)}$ is the modified available capacity of i^{th} state in the COPT of PV panels, $C_{PVCA(i)}$ is the available capacity in state i , C_{RPV} is the rated capacity of PV panel and $C_{PV(j)}$ is the available power at state j .

$$P_{MCOPT(i)} = P_{COPT(i)} \times P_{PV(j)} \quad (22)$$

where $P_{MCOPT(i)}$ is the probability of being in state i and $P_{PV(j)}$ is the probability of band j .

The new outage capacity of state i of COPT being in band j is given by:

$$C_{PVCO(i,j)} = C_{RPV} - MCOPT_{A(i,j)} \quad (23)$$

The probability of outage capacities of states i being in band j , is given by:

$$P_{MCOPT(i,j)} = \sum P_{PV(j)} \times P_{COPTO(i)} \quad (24)$$

where $P_{PV(j)}$ is the band probability and $P_{COPTO(i)}$ is the COPT state outage probability.

The cumulative outage probability of an outage X can be obtained by scanning through all bands; whenever an outage state with outage capacity greater than X is encountered, its probability is accumulated as follows,

$$P(C_o \geq X) = \sum_{i=1}^n \sum_{j=1}^m P_{MCOPT(i,j)} \quad (25)$$

where n is the number of COPT states, and m is the number of bands.

By scanning through all bands, whenever encountering states with equal outages, their probabilities are combined and the duplicated states are eliminated.

IV. CASE STUDY

In this paper, the size of the PV farm was assumed 30 MW. The parameters and structure of the PV farm were adopted from [11] to illustrate the proposed method. The PV farm is constructed from 50 arrays, each array has a capacity of 600 kW. Each sub-array is constructed by connecting 40 panels in series, which are connected to a 12 kW DC/DC converter. Finally, 50 arrays are connected in to the grid through a 600 kW inverter per array. In this paper, the solar radiation data for SANTA MARIA, CA region were taken from [31]. The data obtained from [31] for one year are utilized to estimate the output power of a PV farm.

In this paper, the failure rate of system components were assumed as follows: for DC/AC inverters and DC/DC converter are 0.000027 failures per hour, and for solar panels are 0.000011 failures per hour [32]. The repair rates of the DC/AC inverters and DC/DC converter were assumed 0.1 repair per hour. For the PV panel, the repair rate were assumed 0.2 repair per hour.

Using the proposed method, the hourly output of solar panels is clustered into 8 bands, as shown in Table I.

A. Reliability Indices of the Test Systems

The proposed formulation was applied on the IEEE RTS [33] and RBTS [34]. The Both systems have been extensively tested for power system reliability analysis. IEEE RTS consists of 24 buses, 33 transmission lines, and 32 generating units on 10 buses. The total generation of this system is 3405 MW, and total peak load is 2850 MW. RBTS consists of 240 MW installed capacity and 185 MW annual peak load.

TABLE I
PV OUTPUT BANDS AND STATE PROBABILITY

Bands	Output power (MW)	Individual Probability	Cumulative Probability
1	0	0.4803	1
2	1.2294	0.0421	0.5196
3	5.4883	0.0607	0.4776
4	10.2269	0.0574	0.4169
5	15.4480	0.0489	0.3595
6	20.5176	0.0618	0.3106
7	24.4482	0.0747	0.2488
8	27.0527	0.1741	0.1741

The COPT of the PV farm was constructed for 50 arrays. The obtained COPT was then convolved over the clustered bands to construct MCOPT for the PV farm. The obtained MCOPT for PV farm was then convolved with the conventional generators using the concept of the multi-state to build a unified COPT [35]. The resulted COPT was then combined with the system load to calculate the reliability indices. The reliability indices calculated in this paper are; loss of load probability (LOLP), loss of load expectation (LOLE), loss of energy expectation (LOEE) and energy demand not supplied (EDNS).

1) *Reliability Indices of IEEE-RTS with 30 MW PV Farm:* The reliability indices of the IEEE-RTS were calculated with and without considering the forced outage rates of system components. Monte Carlo simulation was used to validate the results. The reliability indices are shown in Table II.

TABLE II
RELIABILITY INDICES OF IEEE-RTS WITH 30 MW PV FARM

Method	LOLP	EDNS (MW/yr)	LOEE (MWh/yr)	LOLE (h/yr)
Base Case				
Dis. Convolution	0.001072	0.135206	1181.158	9.3681
MCS	0.0011102	0.139648	1219.964	9.6096
PV Power Only				
Dis. Convolution	0.00098	0.12262	1071.22082	8.5613
PV Power with Inclusion of (FOR)				
Dis. Convolution	0.001020	0.12762	1114.93122	8.91072
MCS	0.001040	0.12878	1125.02208	9.0854

Reliability indices calculated using the proposed method and MCS are shown in Table II. The obtained results using the proposed method are close to the results obtained using MCS. Also, system indices show improvement when the PV farm was added. Reliability indices for the case of considering the failure of system components are higher than for the case ignoring failure of system components. However, the overall improvement of the reliability indices is not significant. This is due the fact that the IEEE-RTS is considered as a large and reliable system.

2) *Reliability Indices of RBTS with 30 MW PV Farm:* The PV farm with 30 MW was added to the RBTS. The reliability indices were calculated with and without including the FOR of system components. The reliability indices are given in Table III.

From Table III, it can be seen that the system indices showed

TABLE III
RELIABILITY INDICES OF RBTS WITH AND WITHOUT PV POWER

Case study	LOLP	EDNS (MW/yr)	LOEE (MWh/yr)	LOLE (h/yr)
Base Case	0.000121	0.00121	10.58	1.05390
Considering FOR	0.00008	0.00075	6.55	0.69888
PV power Only	0.00005	0.00056	4.89	0.4368

improvement when PV power was added. Also, neglecting the effect of component failures produced more optimistic results.

V. CONCLUSION

Integration of renewable generation such as PV systems into power system grids increases the necessity to develop an appropriate reliability model that takes into account the input availability and system component availability. In this work, an analytical method to construct COPT of a PV farm was introduced to model the intermittency of these sources and failures of system components. Failures of system components were represented by an equivalent failure and repair rates. The dependency of the output on the input and system components availabilities were modeled separately and then convolved to construct a single COPT. The proposed method was implemented on the IEEE-RTS and the RBTS with 30 MW PV farm. The proposed method produced very close results to those obtained using Monte Carlo simulation with less modeling complexity.

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