

Modeling and Evaluating the Capacity Credit of PV Solar Systems Using An Analytical Method

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Abstract—This paper introduces an analytical method to calculate the capacity credit of PV system in a manner that considers both the effect of input uncertainty and system components availability. The intermittency of the input source and system components availability were modeled separately and then convolved to construct a single capacity outage table. The discrete convolution method has been used in this work to build a generation model in the form of a capacity outage probability table. The proposed method is applied on the RBTS. The obtained results are compared to the results obtained by Monte Carlo simulation. The proposed method reduces the complexity of calculating the capacity credit of PV system considering the effect of system components availability.

Index Terms—Capacity credit, PV system, adequacy assessment.

I. INTRODUCTION

Reliability methods for power system adequacy assessment play a major role in assessing the contribution of intermittent resources such as wind and PV systems to the power grids. The term capacity credit is usually used to measure of the capacity contribution of variables resources to power system capacity planning. The evaluation process in this manner is carried out to make sure that the system reliability will be maintained when the intermittent resources are introduced to the power grid.

The grid connected PV systems are constructed from a large number of components such as power electronic circuits and solar panels. The functionality 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]–[4]. 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 due to the dependency of the output power on an intermittent source (solar) and the availability of a large number of system components. In addition, in a PV farm, PV panels are placed adjacent to each other, all PV panels will be subjected to the the same solar radiation, and approximately experience the same operational and environmental factors that may affect the output of the farm. From reliability assessment point of view, the modeling considerations in this process should be able to take into account not only the stochastic nature of the

inputs, but also the failures of the system component and the output correlation between the individual generating units.

In the literature, 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 [5], [6]. Monte Carlo simulation technique has been used in [7] 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 [8], 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 [9], an analytical method has been used to model the availability of the PV systems in the reliability assessment. In [10], reliability of a wind and solar system has been evaluated using Monte Carlo simulation technique. Monte Carlo simulation is able to capture a wide range of modeling detail and system dependencies. On the other hand, the solution accuracy depends mainly on the number of sampling performed to produce the output. This becomes time consuming, especially when implemented in a large and complex system. This work develops a method to model the output of PV systems in terms of COPT to evaluate the capacity value of PV system. The proposed method takes into consideration the stochastic nature input as well as the failures of system components. For this purpose, discrete convolution method is adopted to calculate the capacity credit of PV power plants.

II. PV SYSTEM FARMS AND OUTPUT POWER

Different typologies of PV systems have been addressed in literature [11]–[13]. 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. [12], [14].

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. 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 [15]. 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 (functionality) 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 [16]:

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

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

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 [16]:

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

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 [16]:

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

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 [16]:

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

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 [11], [14]. 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 [17]. 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 [18]. 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 [19].

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 [20]. 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 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.

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 [21]. 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_{cp_b} 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 do not have a significant effect on system reliability estimation.

IV. MODELING APPROACH

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, at the lower level of subsystem, the equivalent availability and unavailability of system components can be estimated by calculating the equivalent failure and repair rates. The PV system can be represented by N parallel arrays with a capacity of (XMW) each. 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 equivalent FOR by adding new units sequentially to the table with the capacity model building approach [22].

A. 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 [23], [24]. 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 system components availability and the input variation.

$$M^{ac(i,j)} = \frac{S_c^{(i)}}{R_{cpv}} \times B_{pva}^{(j)} \quad (15)$$

where $M^{ac(i,j)}$ is the modified available capacity of i^{th} state in the COPT of PV system being in band j , $S_c^{(i)}$ is the available capacity in state i , R_{cpv} is the rated capacity of PV system and $B_{pva}^{(j)}$ is the available power at band j .

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

$$M_{C_{outage}}^{(i,j)} = R_{cpv} - M^{ac(i,j)} \quad (16)$$

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

$$P_{C_{outage(i,j)}} = \sum P_{B(j)} \times P_{COPT(i)} \quad (17)$$

where $P_{B(j)}$ is the band probability and $P_{COPT(i)}$ 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 grater than X is encountered, its probability is accumulated as follows,

$$P(C_o \geq X) = \sum_{i=1}^n \sum_{j=1}^m P_{C_{outage(i,j)}} \quad (18)$$

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.

V. CASE STUDY

In this paper, Roy Billinton Test System (RBTS) [25] is used to illustrate the proposed method. The proposed method is used in conjunction with discrete convolution method to evaluate the capacity credit of PV system. The size of the PV farm was assumed 30 MW. The parameters and structure of the PV farm were adopted from [26] 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 [27]. The data obtained from [27] 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 [28]. 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.

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 first step in calculating the reliability indices is to convolve the clustered output power of PV system with the availability of system components to create a COPT that reflects both the stochastic nature of the input and the availability of the components. The obtained COPT of PV system is then convolved with the conventional generators using the concept of the multi-state to build a unified COPT. The resulted COPT is then combined with the system load to calculate reliability indices. Reliability indices calculated in this work are Loss of Load probability (LOLP), Loss of Load Expectation (LOLE), Loss of Energy Expectation (LOEE) and energy demand not supplied (EDNS). The reliability indices of the RBTS 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 RBTS WITH 30 MW PV FARM

Method	LOLP	EDNS (MW/yr)	LOEE (MWh/yr)	LOLE (h/yr)
Base Case				
Dis. Convolution	0.000121	0.00121	10.58	1.05390
MCS	0.000120	0.00119	10.39	1.04832
PV Power Only				
Dis. Convolution	0.00005	0.00056	6.55	0.69888
PV Power with Inclusion of (FOR)				
Dis. Convolution	0.000050	0.00056	4.892	0.43680
MCS	0.000049	0.00057	4.979	0.42806

The capacity value of PV power has been used to measure the contribution of PV power plants to the adequacy of the generation to meet the demand. Effective load carrying capability is generally considered more applicable for determining the capacity value of PV power [29]. In this work, we have used the effective load carrying capability approach (ELCC) presented in [30] to estimate the capacity value of PV power. The LOLE index is used to calculate the capacity value. The peak load was incremented by a ΔL using an iterative process, and the LOLE is recalculated at each step until the target values of LOLE is reached. The target values of LOLE is the values prior to adding PV power. The increase in peak load that achieves the reliability target is considered the capacity value of the PV power as shown in figure 1.

It can be seen from figure 1 that the capacity credit of PV power shows a significant diversity. In the case of assuming the PV system is perfectly reliable, the capacity value, about 9.8 MW of load increase can be compensated by 30 MW of PV

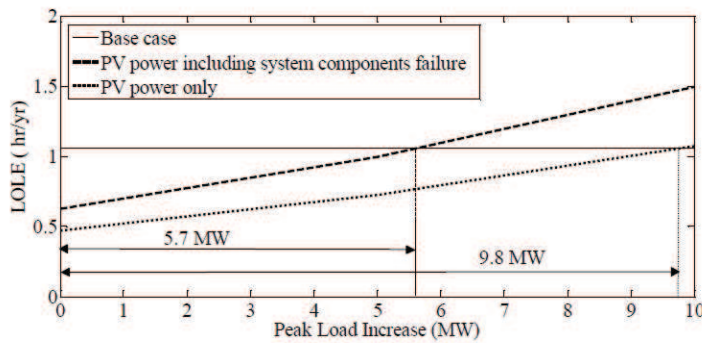


Fig. 1. RBTS-LOLE as a function of peak load increase

power for RBTS. On the other hand, when system components failures are considered, about 5.7 MW of load increase can be compensated by 30 MW.

VI. 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 uncertainty and system components availability. In this work, an analytical method to model and to evaluate the capacity value of PV power plants was introduced. The proposed method takes into account the intermittency of these sources and failures of system components in the evaluating process of the capacity value of PV systems. 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 Roy Billinton Test System (RBTS) with 30 MW PV farm. The presented method produced very close results to those obtained by Monte Carlo simulation with less modeling complexity and computational cost. In addition, the results show that ignoring system components failures of PV system is not advised and produces conservative results to the capacity value estimation.

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