Reliability Evaluation of Active Distribution Systems with Distributed Generations

Azzan Alaskar 1, Abdulaziz Alkuhayli 1

1 Electrical Engineering Department, King Saud University
aalkuhayli@ksu.edu.sa

Abstract. Reliability evaluation is essential in designing, planning, operating modern power systems. System operators must operate the network securely and efficiently with minimal interruption events. With the recent advances in power electronics and control, distributed generations (DG) such as photovoltaic (PV), wind turbine, and storage systems are expected to grow in distribution networks. This high level of distributed generations penetration in the grid can increase the complexity of operating the system. This is caused by intermittent nature of solar irradiance and wind speed. This paper proposes a methodology used to assess distribution networks containing stochastic resources such as photovoltaic. This method will use the Monte Carlo simulation with a stochastic model to evaluate the distribution network’s reliability. The system and load point reliability indices such as frequency of loss of load and expected energy not to supplied will be computed in this technique. In addition, the configuration of distribution networks to improve system’s reliability to facilitate system restoration after pre-fault conditions will be assessed.

1. Introduction

Nowadays, it is evident that all countries are confronted with numerous issues related to rising energy demand and greenhouse gas emissions from traditional power plants. Renewable energy supplies are the best way to address environmental concerns while also meeting rising demand. We have become so reliant as a society that most everyday tasks would be halted if the power supply were to be disrupted. As a result, the impact of integrating renewable energy resources into the power grid must be assessed especially, in the distribution network.

It’s critical to create a better technique to assess the distribution system's reliability using DG. In general, there are two basic ways for assessing the distribution network’s reliability. First, for the systems outage record, the analytical technique employs estimations and assumptions, and the reliability findings obtained are average values [1]. Second, there are methods based on Monte Carlo Simulations [2], which are used for stochastic simulations with random numbers. The reliability of distribution systems has been evaluated including PV and storage systems, using Markov and MCS method models in reference [3]. Overall system reliability has improved, according to the findings. The Monte Carlo simulation has been used in references [4], [5] to evaluate the reliability of distribution networks, containing renewable energy PV systems.

The introduction of PV based distributed generation in the distribution network supports the increasing load demands, according to reference [6]. According to reference [7], the best placement of the DG is determined by the voltage stability index, and the result is confirmed using the Particle Swarm Optimization Technique (PSO). To accurately describe the random occurrence of insolation, it is critical to select an appropriate distribution function. Even though it’s tough to tell, there's a chance to find an...
appropriate distribution empirically. Several distribution functions, such as the Weibull, Beta and normal distribution functions, are widely used in the literature to depict the intermittence nature of PV production.

2. Reliability Assessment
In reliability assessment, mainly, forced power outages are considered. The failure of network equipment causes these interruptions. Some popular indices are used to assess the reliability of electricity networks in this study. The reliability indices EENS, SAIDI, and SAIFI are used to assess the reliability of electrical distribution systems.

2.1. Parameters at Load Point

2.1.1. Average Failure Rate:

The average rate of failure is the probability of a load point failing for a particular period, which can be calculated using

\[ \lambda = \sum_{i=1}^{n} \lambda_i \]  

(1)

Where \( \lambda_i \) is the failure rate

2.1.2. Annual Outage Duration:

The average outage durations \( U \) is the average interruption time for a particular period, which can be expressed as:

\[ U = \sum_{i=1}^{n} \lambda_i r_i \]  

(2)

Where \( r_i \) is restoration time

2.2. Reliability Indices

2.2.1. System Average Interruption Frequency Index:
SAIFI measures permanent interruptions that customers will experience throughout the year.

\[ SAIFI = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customers Served}} \]  

/hr/yr  

(3)

2.2.2. System Average Interruption Duration Index:
SAIDI measures the total duration of permeant interruptions in hours that customers will experience throughout the year.

\[ SAIDI = \frac{\sum_{i=1}^{n} \text{Customer Interruption Durations}}{\text{Total Number of Customers Served}} \]  

/hr/yr  

(4)

2.2.3. Energy Not Supplied Index:
Total energy not supplied by the system (ENS) is used to measure the total energy interruption throughout the year.

\[ ENS = \sum_{i=1}^{k} U_i L_{a(i)} \]  

kWh/yr  

(5)

The annual outage time is \( U_i \) and the load during outage is \( L_{a(i)} \).

3. Photovoltaic stochastic model
The amount of irradiance depends on a variety of factors, including solar elevation angle, latitude, air temperature. The output power of a PV module depends on irradiance, ambient temperature, PV module characteristics and efficiency, and maximum power point tracking algorithm. As a result, a comprehensive model of output power is quite difficult to construct. Therefore, a PV stochastic model is an essential to depict the intermittence nature of solar irradiance [4].

![Figure 1](image_url). The hourly output power of PV.

Despite the fact that the Weibull distribution can generate better results with time series-based data sets in the case of wind speed stochastic modelling it has not been used to model the stochastic nature of PV production [9]. The Beta probability model is used in reference [10] to characterize the variability of solar irradiances around their hourly mean values. For varied weather situations such as sunny and cloudy conditions, the beta distribution model was chosen to predict the solar irradiance level. Local metrological sensors can provide accurate data on solar irradiance, shade, and rainfall.

The current-voltage characteristic of a PV cell in the case of ideal condition can be used to find fill factor, as follows:

\[
FF = \frac{V_{mpp} \times I_{mpp}}{V_{oc} \times I_{sc}}
\]

The output voltage and current of a PV system, can be calculated for the desired condition as follows:

\[
I_{out} = f(a, b)[I_{sc} + k_i(T - 25)]
\]

\[
V_{out} = V_{oc} - k_v T
\]

The total power of the PV module:

\[
P_{total} = I_{out} \times V_{out} \times FF
\]

4. The electricity demand data
The amount of electricity consumed is mostly influenced by two factors: meteorological conditions such as air temperature and the day of the week. Because of high temperature level during the summer in most of Saudi Arabia, the electricity demand peak occurs in the summer. Furthermore, weekly work cycles impact the level of power consumption, implying that electricity consumption is significantly lower on Fridays and Saturdays than on weekdays A load profile for a typical Riyadh home was employed in this research.

5. Monte Carlo simulation
The time sequential simulation is one of the MCS types used to investigate and forecast behaviour patterns in order to acquire the probability distributions of the various reliability characteristics when the system behaviour is dependent on previous events. In this study, the MCS will be used to generate
artificial history to represent the health of equipment depending on the failure rate and restoration time as shown in figure 5.

Time to failure (TTF) is time it takes for a component to fail or to remain in the up state.

\[
T_{TTF}^i = -\frac{1}{\lambda_i} \cdot \ln n
\]  \hspace{1cm} (10)

Where \(\lambda_i\) is the failure rate and \(n\) is a random number that is generated by normal distribution which varies between (0,1) [12].

Time to repair (TTR) is the time it takes to replace or repair a failed element or to remain in the down state.

\[
T_{TTR}^i = -\frac{1}{\mu_i} \cdot \ln u
\]  \hspace{1cm} (11)

Where \(\mu_i\) is the repair rate of component \(i\);

6. Simulation procedure

Two reliability assessment algorithms are employed in this study as follows:

1) Reliability assessment for distribution network with no distributed PV systems,
2) Reliability assessment for distribution network with PV systems.

The algorithms’ results provide a clear picture of how distributed PV systems can affect reliability. To simulate the unpredictability of these resources, MCS is done on the RBTS Bus 2 system using established PV stochastic model.

Since the primary goal of this study is to evaluate the reliability of distribution systems in the presence of distributed PV systems, the following assumptions were made:

- Primary feeder and transformer failures are considered in the analysis.
- Only permanent faults are taken into account in the study.
- Main breakers are able to isolate faults successfully.
- Main feeders are protected by main breaker to isolate faults.
- The restoration in the case of forced outage takes 1 hr to transfer load points to neighbouring feeder.

This step can be done through a NOPs.

Figure 6 shows the proposed algorithm.
Figure 6. The proposed algorithm's flowchart.

7. Case study
In this study, RBTS Bus 2 is used to evaluate the reliability using MCS. RBTS Bus 2 includes 22 load points, 4 main feeders, 22 distribution transformers and 36 lines. The test system has been modified to include 22 PV systems connected to all load point as shown in Fig. 7.

![Modified RBTS Bus 2](image)

Figure 7. Modified RBTS Bus 2.

The lengths of feeders and laterals, the load points data, the failure rate, restoration time, repair time of components, and other reliability data are all given in RBTS Bus 2. To investigate the impact of the integration of distributed PV system on the reliability of distribution network, three different cases are considered as follows:

Case 1: base case with no PV in RBTS Bus 2.
Case 2: 50% of PV penetration in RBTS Bus 2.
Case 3: 100% of PV penetration in RBTS Bus 2.

The reliability assessment of the RBTS Bus 2 is carried without including PV systems. Due to the length of the power outage experienced by the users and absence of backup sources, the EENS values of the system are found to be high in Case 1.
In Case 2, the integration of the PV at 50% penetration level has improved the reliability of the system as observed in Table 1 and Fig. 7, Fig. 8 and Fig. 9. This will reduce the duration of the power outages for the consumers. As observed in Table 1, SAIDI and EENS have dropped by 2% and 4% respectively when compared with Case 1.

In Case 3, it is noticed that an increase in penetration of PV to 100% into the distribution network resulted in a significant improvement in the reliability of the distribution power system. This has further reduced the power outage for most of the consumers.

When comparing the three cases, it is clear that adding PV to the distribution network minimizes outage time and energy not supplied to customers. It is clear from Table 1 that including PV in the system can improve system reliability. The main difference between case 2 and case 3 is the level of PV penetration. When comparing case 2 and 3, the level of PV penetration has an impact on the distribution network’s reliability. The simulation results show that adding more energy resources to a power system at the distribution level can increase its reliability.

**Table 1. Reliability indices.**

| Index  | Case 1 (without PV) | Case 2 (with 50% PV pen.) | Case 3 (with 100% PV pen.) |
|--------|---------------------|---------------------------|---------------------------|
| SAIFI (1/yr) | 0.9957 | 0.9961 | 0.9949 |
| SAIDI (hr/yr) | 2.1079 | 2.0708 | 2.0572 |
| EENS (MWh/yr) | 15.6033 | 15.0730 | 14.9268 |

**Figure 7.** Average failure rate of RBTS Bus 2.
The results obtained from the proposed algorithm prove that the integration of distributed PV systems can improve the reliability of distribution networks by providing a backup source in the event that...
primary source is lost. The MCS can handle the uncertainty associated with the solar irradiance. In addition, random events, variation in PV output power, and maintenance time are taken into account in the investigation.

8. Conclusion
The goal of this study is to investigate how distributed generating can impact distribution system reliability. PV-based distributed generation can support the distribution network during normal and forced outages conditions. In this study, the reliability assessment is done using Monte Carlo Simulation. The results obtained from the MCS have proved that the reliability of distribution system can be improved by utilizing distributed PV systems, which can provide additional energy source to support the grid during forced outages. It is observed that reliability improvement associated in the presence of PV systems in the distribution network depends on the size of the DGs that a higher level of PV penetration can result in improving the system reliability. Random events, PV output power intermittency, and maintenance time are all considered in this investigation.

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