Impact of the Penetration Levels of PV and Synchronous Machine Based DG Sources on the Reliability of a Microgrid

Prajwal Gautam, Keaton A. Wheeler, Rajesh Karki and Sherif O. Faried
Power Systems Research Group
University of Saskatchewan
Saskatoon, Canada
{prajjwal.gautam, keaton.wheeler, rajesh.karki & sherif.faried}@usask.ca

Abstract—This paper investigates the effect of varying photovoltaic and synchronous machine based distributed generation source type penetrations on the reliability of a microgrid. An investigation into the effect of varying the percentage penetrations of photovoltaic and traditional generation sources on the load point reliability indices in a microgrid is conducted under fluctuating solar energy and loading conditions. In the context of this paper, an assessment of the reliability worth for each penetration condition is conducted with consideration to customer outage and environmental costs. Assessments are conducted on a typical microgrid test network utilizing an analytical method based on failure mode and effect analysis approach.

Index Terms—Distribution reliability, photovoltaic, microgrid.

I. INTRODUCTION

Microgrids have become a focal point of recent discussions in the context of grid modernization and distributed generation (DG) source integration. A microgrid can be defined as a low or medium voltage network containing a cluster of local loads with DG sources [1]. Microgrids are capable of performing in either a grid connected or islanded operation mode with the distinction between the two being attributed to the presence of a utility connection or not. In the microgrid context, multiple DG sources are integrated at individual load points yielding numerous benefits including reduction in losses and network congestion prevention [2].

Historically, distribution system reliability is a field of reliability analysis that has been given considerably less attention than that of generation. This is mainly due to the fact that generation inadequacy often has larger scale consequences on the overall power system than that of a distribution network [3]. Although it is considered less, studies have shown that distribution systems make the greatest contributions to unavailability statistics in the context of supply to load points [2] – [3]. It follows that distribution system reliability indices are an important consideration when evaluating network integrity with regards to load supply capability and infrastructure upgrade priorities [2] – [3]. Reliability indices related to the distribution network are now formally regulated and enforced by commissions [4].

Although investigation into DG integration in a grid and microgrid context is relatively new, there have been some examinations into their effects on reliability indices. In reference [2], the benefits of DG integration for use as a backup source in the context of reliability are presented. Authors demonstrate that DG integration is able to improve distribution system reliability indices relative to DG distance from the substation. However, this investigation does not offer any indication as to what connection method or location should be used for DG integration, nor does it investigate the effects of varying network topologies. Although the results of studies are promising, the application is limited as it does not cover multiple network operational scenarios.

Reference [5] reveals a similar result to that of [2] in that it investigates the use of DG sources for improvement of distribution network reliability indices. In comparison to reference [2], reference [5] extends the investigation to include interruption costs. Similar to reference [2], one key criticism of [5] is the lack of diversity in network operational characteristics (looped and radial) as well as a lack of clarification on DG interconnection methods and locations. In reference [6], a method for reliability improvement through optimal placement and sizing of DG sources in distribution networks is presented. A tabu search algorithm is employed to explore solutions. Results from reference [6] demonstrate that DG sources have the capacity to reduce customer interruption costs while improving reliability indices.

In reference [7], the reliability of an islanded microgrid using Monte-Carlo simulation is conducted while accounting for load priorities. A reliability and cost analysis of a small isolated power system is conducted using Monte-Carlo simulation techniques in conjunction with a system well-being model in [8].
Reference [9] demonstrates a multistate capacity level model to capture the intermittency of renewable DG source generation. A key criticism of the approach is the lack of consideration to the correlation between the DG output and loading level. In comparison to [9], [10] models the combined generation to load ratio as a Markov process so as to preserve the correlation between PV source output and load demand in order to assess generation adequacy in an islanded microgrid.

As evident in the literature, DG sources have the capacity to improve load point reliability indices in a distribution system and microgrid context. In this paper, a failure mode and effect analysis (FMEA) [11] based analytical approach is employed to assess the reliability of a microgrid under varying DG penetration conditions. The analysis includes consideration to the effects of varying the penetration of DG source types, namely photovoltaic (PV) and synchronous machine based (SM), on the load point indices in a microgrid. Results also utilize a backward scenario reduction technique [11] – [13] to capture correlation between the variation in energy availability from PV sources and fluctuation in load levels. In addition, an evaluation of the reliability worth is presented for individual load points under varying scenarios.

II. THE APPROACH

A. System Under Study

A typical microgrid setup as shown in Fig. 1 is utilized for the investigations of this paper [1]. The microgrid is connected to the main utility rated at 13.8 kV at the point of common coupling (PCC) through an interconnecting line LU and two radial feeders. It has six main buses each with a load and a DG station that comprises of PV and SM based sources. Each bus has a load as specified in Table I and with a lagging power factor of 0.9.

A tie line exists, connecting line 3 and line 6 which can be closed in 0.5 seconds. For each load there is a protective breaker and transformer that steps the voltage down to a usable level. Each bus and line also has segmenting breakers. When one of the line segments trip on either of the feeders, a signal is sent to the tie lines breakers to close to allow for an alternate feed to be present. The failure probabilities of breakers and buses are typically very small compared to other components, and are therefore, neglected in this study. The failure rate and repair time of the lines are taken 0.065 f/yr-km and 5 hr respectively [14]. For the load point transformers, the failure rate and the replacement time of 0.015 f/yr and 10 hr are used in the study [14]. The utility supply is assumed to have a failure rate of 0.5 f/yr and a repair time of 10 hours [15]. The SM based DG failure rate is assumed to be 0.18 f/yr with a repair time of 12 hours [16].

B. Representation of the PV and Load Models

The correlation between the DG output and loading level should be recognized in a reliability analysis of a distributed generation system consisting of intermittent renewable DG sources such as PV in conjunction with fluctuating load demands. In this paper, rather than representing the DG and load outputs as separate multi-state models, multiple scenarios consisting of PV output and their corresponding loading levels are obtained utilizing the backward scenario reduction technique [11] – [13]. Five years of synthetic hourly solar irradiation data for Swift Current, Saskatchewan was obtained using the WATGEN [17] software developed by the WATSUN Simulation Laboratory, whereas the time varying load for the different group of customers were obtained from [18] - [19]. The original set of scenarios consisting of the hourly solar irradiation and the load was created from this data.

During the night periods where solar irradiation is zero, there is still a correlation amongst the loads and their customer types. The original set of scenarios is divided into
two groups; one with data from the daylight hours and one with data from the night hours. Utilizing the backward scenario reduction method for both sets of original scenarios, typical representative levels of solar irradiation and their corresponding load demands are obtained. These are combined to create twelve representative scenarios used in this paper which are shown in Table II.

**TABLE II: REPRESENTATIVE SCENARIOS OBTAINED FROM THE BACKWARD SCENARIO REDUCTION TECHNIQUE**

<table>
<thead>
<tr>
<th>Scenario number (Sc)</th>
<th>PV output (pu of peak rated capacity)</th>
<th>Residential load (pu of peak load)</th>
<th>Commercial load (pu of peak load)</th>
<th>Govt. &amp; Inst. load (pu of peak load)</th>
<th>Probability of scenario Sc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.301</td>
<td>0.591</td>
<td>0.90</td>
<td>0.90</td>
<td>6.306</td>
</tr>
<tr>
<td>2</td>
<td>0.382</td>
<td>0.464</td>
<td>0.35</td>
<td>0.75</td>
<td>5.297</td>
</tr>
<tr>
<td>3</td>
<td>0.485</td>
<td>0.642</td>
<td>0.89</td>
<td>1.00</td>
<td>6.584</td>
</tr>
<tr>
<td>4</td>
<td>0.017</td>
<td>0.353</td>
<td>0.85</td>
<td>0.8</td>
<td>12.01</td>
</tr>
<tr>
<td>5</td>
<td>0.642</td>
<td>0.506</td>
<td>0.88</td>
<td>0.388</td>
<td>2.411</td>
</tr>
<tr>
<td>6</td>
<td>0.194</td>
<td>0.776</td>
<td>1.00</td>
<td>0.92</td>
<td>14.47</td>
</tr>
<tr>
<td>7</td>
<td>0.790</td>
<td>0.459</td>
<td>0.90</td>
<td>0.85</td>
<td>5.171</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.492</td>
<td>0.025</td>
<td>0.12</td>
<td>11.07</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0.378</td>
<td>0.01</td>
<td>0.40</td>
<td>16.63</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0.568</td>
<td>0.40</td>
<td>0.43</td>
<td>11.21</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0.940</td>
<td>0.95</td>
<td>0.75</td>
<td>5.779</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0.754</td>
<td>1.00</td>
<td>0.294</td>
<td>3.062</td>
</tr>
</tbody>
</table>

C. Reliability Evaluation Framework

An FMEA based analytical approach is used to enumerate each contingency while determining its effect on varying load at each load point and the overall network [11] of the microgrid in Fig. 1. The reliability indices used in evaluation are as follows:

The system average interruption frequency index (SAIFI) is expressed as the number of interruptions per customer year, and can be obtained using (1).

\[
SAIFI = \frac{\sum N_i}{\sum N_i}
\]  

(1)

Where \( \lambda_i \) is the failure rate and \( N_i \) is the number of customers of load point \( i \).

The system average interruption duration index (SAIDI) and is expressed in hours per customer year. It can be calculated using (2).

\[
SAIDI = \frac{\sum U_i N_i}{\sum N_i}
\]  

(2)

Where \( U_i \) is the annual outage time (also called annual unavailability) and \( N_i \) is the number of customers of load point \( i \).

The expected energy not supplied (EENS) is evaluated using (3), and is expressed in kWh per year:

\[
EENS = \sum L_{a(i)} U_i
\]  

(3)

Where \( L_{a(i)} \) is the average load connected to load point \( i \).

The expected cost of interruption (ECOST) is expressed in dollars per year, and calculated using (4).

\[
ECOST = \sum C_{j,i} U_{a(i)} \lambda_j
\]  

(4)

Where \( C_{j,i} \) is the cost of interruption in dollars per kilowatt obtained from the sector customer damage function (SCDF) given in Table III corresponding to the outage duration \( r_j \) [20].

**TABLE III: SECTOR COST OF INTERRUPTIONS IN $/KW**

<table>
<thead>
<tr>
<th>Sector Type</th>
<th>Interruption Duration (minutes)</th>
<th>1</th>
<th>20</th>
<th>60</th>
<th>240</th>
<th>480</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Users</td>
<td></td>
<td>1.005</td>
<td>1.508</td>
<td>2.225</td>
<td>3.968</td>
<td>8.24</td>
</tr>
<tr>
<td>Industrial</td>
<td></td>
<td>1.625</td>
<td>3.868</td>
<td>9.085</td>
<td>25.16</td>
<td>55.81</td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td>0.381</td>
<td>2.969</td>
<td>8.552</td>
<td>31.32</td>
<td>83.01</td>
</tr>
<tr>
<td>Agricultural</td>
<td></td>
<td>0.06</td>
<td>0.343</td>
<td>0.649</td>
<td>2.064</td>
<td>4.12</td>
</tr>
<tr>
<td>Residential</td>
<td></td>
<td>0.001</td>
<td>0.093</td>
<td>0.482</td>
<td>4.914</td>
<td>13.69</td>
</tr>
<tr>
<td>Govt. &amp; Inst.</td>
<td></td>
<td>0.044</td>
<td>0.369</td>
<td>1.492</td>
<td>6.558</td>
<td>26.04</td>
</tr>
<tr>
<td>Office &amp; Building</td>
<td></td>
<td>4.778</td>
<td>9.878</td>
<td>21.06</td>
<td>68.83</td>
<td>119.2</td>
</tr>
</tbody>
</table>

The steps utilized in evaluating the load point indices are as follows:

1. Enumerate the contingencies up to second order minimal cutsets.
2. For each contingency \( i \), find all \( n \) load point(s) capable of forming an island with the corresponding DG(s) based on the protection strategy and the restoration process.
3. For each scenario \( j \), evaluate the total generation capacity available in the island based on the penetration level of PV(s) and SM DG(s) located.
4. Check if the total available generation capacity is less than the total load in the island for scenario \( j \). If yes, the Adequacy violation check flag for contingency \( i \), and scenario \( j \) \( Ad_vio_i \) is assigned 1 otherwise 0.
5. Multiply the probability of scenario \( j \), \( P_i \), with \( Ad_vio_i \) obtained from step 4 to get the probability of the load point \( k \) being not supplied for contingency \( i \) and scenario \( j \), i.e. \( P_{nks_i} \).
6. Repeat step 5 for all \( n \) load point(s).
7. Repeat step 3-6 for all the scenarios.
8. Add the values of \( P_{nks_i} \) for all the scenarios to get the probability of load point \( k \) being not supplied for contingency \( i \), i.e. \( P_{ns_i} \). Repeat this step for all the load points.
9. Use \( P_{ns_i} \) to get the load point indices.
   - Failure rate of a load point \( k \) for the contingency \( i \): \( \lambda_i^k = \lambda_i \times P_{ns_i} \), where \( \lambda_i^k \) is the failure rate of contingency \( i \).
   - Annual outage time of load point \( k \) for the contingency \( i \): \( U_i^k = U_i \times P_{ns_i} \), where \( U_i^k \) is the annual outage time corresponding to contingency \( i \) (\( U_i = \lambda_i \times r_i \), \( r_i \) being the repair time corresponding to contingency \( i \)).
10. Repeat step 2 to 9 to cover all the contingencies.
11. Calculate the rest of the load point and the system indices using the information obtained from the previous
III. THE EFFECT OF PV AND SYNCHRONOUS MACHINE BASED DG SOURCES ON DISTRIBUTION RELIABILITY INDICES IN MICROGRIDS

This section presents the reliability analysis of each case study (CS) for the microgrid presented in Fig. 1 utilizing the methodology specified in Section II.C based on an analytical approach in the MATLAB software.

A. Case Studies

Five case studies are selected for presentation in the section. The first case study (CS-1) demonstrates the reliability indices for no DG penetration in the microgrid where load points are dependent solely on the utility. The remaining case studies (CS-2 to CS-5) demonstrate the effect of varying PV and SM based DG penetrations on the microgrid reliability indices. Each case study is analyzed for the scenarios specified in Table IV.

<table>
<thead>
<tr>
<th>TABLE IV: CASE STUDIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Penetration (%)</td>
</tr>
<tr>
<td>PV Penetration (MW)</td>
</tr>
<tr>
<td>SM Penetration (%)</td>
</tr>
<tr>
<td>SM Penetration (MW)</td>
</tr>
</tbody>
</table>

B. Load Point Reliability Evaluation

Figs. 2 to 5 illustrate the failure frequency, annual unavailability, EENS and ECOST indices for each load point in the microgrid.

The results presented in the figures show that the load point reliability for CS-1 with no DG penetration is the poorest among the five case studies. When the microgrid is operating without any DG source, the load points are completely dependent on the supply from the utility. When there is DG penetration in the microgrid, if the utility fails then the load points are able to rely on their individual DG sources for supply. As a result it can be observed that the inclusion of DG sources improves the overall reliability of the microgrid load points.

C. Microgrid System Reliability Evaluation

In order to capture the cost benefit of introducing DG sources into a microgrid, this paper proposes the use of a methodology that factors in the cost of energy supplied by the utility and the cost of emissions associated to those DG sources. The following data is used:

- Environmental cost of emissions [21]: $0.0000187/gram.
- Emissions per kWh of solar power [22]: 6.15 grams/kWh.

![Fig. 2. Failure frequency for each load point for the five case studies.](image)

![Fig. 3. Unavailability of each load point for each case study.](image)

![Fig. 4. Expected energy not supplied for each load point in each case study.](image)

![Fig. 5. Expected cost of interruption and operation for each load point in each case study.](image)
• Emissions per kWh of gas (SM DG source) [22]: 525 grams/kWh.
• Cost of gas per kWh for gas turbines [23]: 3.82 cents/kWh.
• Cost of electricity from the utility [24]: 13.74 cents/kWh.

The overall cost savings associated to the DG units can be determined using (5),

\[
SAVINGS = E_S - E_V
\]

Where \(E_S\) is the expected savings generated by the DG units obtained using (6), and \(E_V\) is the expected environmental cost calculated using (7). Both of these values are expressed in dollars per year.

\[
E_S = [0.1374 - 0.0382]E_{SM} + 0.1374E_{PV}
\]  

(6)

\[
E_V = 1.87 \times 10^{-5}[6.15E_{PV} + 525E_{SM}]
\]  

(7)

Where \(P_{PV}\) is the expected energy supplied by the PV DG sources to the system in kWh per year, \(E_{SM}\) is the expected energy supplied by the SM based DG sources to the system in kWh per year, and \(E_V\) is the environmental cost in dollars per year.

It should be noted that costs associated with installation, outage repairs and maintenance of the DG sources have not been considered in this paper.

Figs. 6 to 10 illustrate the SAIFI, SAIDI, EENS, ECOST and SAVINGS system indices for the microgrid.

It can be observed from the results that the system reliability is relatively poor in the microgrid with no DG sources when compared to the cases where there is DG penetration. The trend is similar to that presented for the individual load point indices in Section III.B.

A notable observation in Fig. 10 is that the overall system savings can be greatly impacted by the inclusion of DG sources as well as their source types. The figure shows that CS-4 (50% PV and 50% SM) yields the highest cost savings among the five cases studied. This can be attributed to the PV source having a lower emission factor in addition to gaining a higher cost savings benefit due to the fact it requires no fuel. In addition, although CS-5 has a higher PV penetration than CS-4, there is less benefit from a fuel savings context. This can be attributed to the fact that the PV sources have a weaker capacity factor when compared to SM based DG sources. This results in increased reliance on the utility for energy supply yielding lower savings benefits.

It is apparent from the observation of Figs. 6 to 10 that although CS-4 yields the highest cost savings, it is out performed in all other system reliability indices by CS-2 and CS-3. This is due to CS-2 and CS-3 having lower PV penetrations which results in a reduction of DG supply unavailability.
IV. CONCLUSION

This paper investigates the effect of varying PV and SM based DG source type penetrations on the load point and system reliability indices of a microgrid. Results obtained from selected case studies demonstrate that DG penetration in a microgrid context yields an improvement in the load point and system reliability indices. Additionally, this study presents an analytical approach that incorporates the intermittency and correlation of renewable DG sources and load demand. Furthermore, studies conducted incorporate the variation in load demand based on consumer group loading profiles. Results obtained demonstrate the effect of variation in DG percentage penetrations when factoring costs associated to environmental impacts of the source types in addition to the savings generated from non-reliance on a utility supply. The results show that although PV DG sources offer relatively less improvement in load point and system reliability, they can offer significant cost savings due to the non-reliance on a fuel source. The results and considerations that are discussed in this paper offer significant value to potential DG owners and utility operators in the context of microgrid integration feasibility planning.

REFERENCES