Reliability Benefits of Distributed Generation as a Backup Source

I. Waseem, Student Member, M. Pipattanasomporn, Member IEEE and S. Rahman, Fellow, IEEE

Abstract—The power system especially at the distribution level is prone to failures and disturbances due to weather related issues and human errors. Having distributed generation (DG) as a backup source ensures the reliability of electric power supply. Therefore, distributed generation is expected to play a key role in the residential, commercial and industrial sectors of the power system. In this paper, the value of DG installed as a backup generator is quantified in terms of its contribution to the reliability improvement of a residential distribution network. The reliability improvement is measured by reliability indices that include SAIDI, CAIDI and ENS. In addition, the value of placing DG at various distances from the substation, as well as the impacts of installing a large-scale DG vs. several small-scale distributed DGs, are presented. The research findings are expected to be useful to electric utility companies in evaluating the reliability benefits of DG of various sizes and penetration levels installed at various distances from a distribution substation.

Index Terms — Reliability, Distributed Generation, Residential Distribution Network, SAIDI, CAIDI, ENS.

I. INTRODUCTION

As electricity demand is expected to grow at an annual rate of 1.4 percent between now and 2020 [1], Distributed Generation (DG) is expected to play an increasingly important role in the future of power systems. Distributed generation is defined as a small-scale generation unit, i.e. 10MW or less that can be interconnected at or near the customer load. The technologies for DG are based on reciprocating engines, photovoltaics, fuel cells, combustion gas turbines, micro turbines and wind turbines. These technologies are also known as alternate energy systems as they provide alternatives to the traditional electricity sources, i.e. oil, natural gas and coal. In addition to serving as backup power sources, DGs are becoming increasingly popular because they have low emission levels, low noise levels and high efficiency.

Distribution system reliability is an important factor in system planning and operation. The reliability indices such as SAIDI (System Average Interruption Duration Index), CAIDI (Customer Average Interruption Duration Index) and ENS (Energy Not Supplied) presented by the IEEE standard in [2] are used to evaluate reliability of the system. In [2], the IEEE standard for reliability indices, as well as terms and definitions related to them, were presented. Several papers discussed the use of these reliability indices and the data required to evaluate them [3, 4]. The authors of [3] presented methods of data collection to calculate the reliability indices of a distribution system. The paper discussed classes of customers, selection of relevant indices and outage data collection such as the indices reflect the actual customer perceptions. In [4], the author presented a survey of the reliability indices practices in the US. The results showed that SAIDI, SAIFI, CAIDI and ASAI were the most used indices. The paper also discussed outage factors and their roles in reliability calculation.

The calculation of reliability indices can be examined by using commercial softwares. In [5], the author performed a reliability analysis using DISREL – a computer program to calculate predictive reliability indices for an electric distribution system – to show the impact of distributed generation on distribution system reliability. The paper showed that DG was a cost-effective solution that could benefit both utility and customers. The authors of [6] presented modeling techniques for DG, and applied them to a radial network using commercial software tools that shows improvement in the reliability indices. Several papers have presented techniques to evaluate the reliability of the system. In [7], the author presented an analytical approach to calculate the reliability of the system that included some intrinsic attributes of the DG and the distribution system including DG failure, component failure and change in load demand. Many factors were considered for the reliability indices calculation in the proposed technique. In [8], the author presented an analytical and probabilistic approach to calculate the reliability for momentary interruptions. The paper also presented reliability cost evaluation technique that unifies sustained and momentary interruptions costs.

The location for DG placements is of key importance. In [9], the authors studied the effects of DG on system reliability on an Iranian Distribution system. The analysis showed that reliability indices were highly sensitive to location. In [10], the author discussed the DG impacts on reliability, losses and voltage profile of the system. The paper showed that reliability indices could be improved by properly allocating DG.

Properly coordinated distributed generation can have a
positive impact on the system. The author of [11] presented the positive and negative impacts of DG on reliability indices and power quality. The positive impacts included faster restoration and reduced voltage sags, while the negative impacts could be sympathetic tripping and increased fuse blowing. In [12], the author discussed the intentional islanding impacts of DG for reliability improvement. A few papers had presented validation models for calculating reliability indices [13, 14]. In [13], the basic data for reliability assessment of distribution system were presented. The paper also contained basic results of continuity studies for a range of sensitivity analysis and alternate configurations. Also in [14], a validation method for the reliability model was presented. The model determines component reliability data so that the predicted values of reliability indices match with the historical data.

In this paper, a technique based on [15] is used to calculate reliability indices (SAIDI, CAIDI and ENS) in an unbalanced three-phase radial distribution network. A residential distribution network of Virginia Tech Electric Services (VOTES) in Blacksburg, VA is used as a case study. Reliability indices when a DG is installed as a backup generator is quantified. Different DG penetration levels, locations and the impacts of installing a large-scale DG vs. several small-scale randomly distributed DGs are explored.

II. METHODOLOGY

For the purpose of this study, the circuit is classified into sections and distributor laterals as shown in Fig. 1.

![Fig. 1. Definition of sections, load points and distributor laterals](image)

To quantify SAIDI, CAIDI and ENS of a distribution circuit, the failure rate ($\lambda_i$), average annual outage time ($U_i$) and average repair time ($r_i$) of all sections and distributor laterals must be identified.

In this study, it is assumed that: (a) the failure rate for all sections on the main distribution feeder is 0.1 f/yr/km; and that for all distributor laterals is 0.2 f/yr/km; and (b) the repair time of all sections ($r_i$) is 4 hrs and for all distributor laterals is 2 hrs. *f represents failure frequency.

Using assumption (a) and the length of each section and distributor lateral, the failure rate of each section and distributor lateral ($\lambda_i$) is evaluated. Then, the average annual outage time of a section or lateral $i$ ($U_i$) is calculated by multiplying $\lambda_i$ by $r_i$.

Once the parameters $\lambda_i$, $U_i$ and $r_i$ of all sections and distributor laterals are determined, the failure rate of each load point, i.e. load point ‘s’ ($\lambda_s$), can be calculated by adding the failure rates of all sections and distributors ($\Sigma \lambda_i$) that contribute to the unavailability of load point ‘s’, as shown in (1).

Failure rate:

$$\lambda_s = \sum_i \lambda_i$$  \hspace{1cm} (1)

The annual outage time of the load point ‘s’ ($U_s$) can be calculated by adding the annual outage time of all sections and distributors ($\Sigma \lambda_i r_i$), as shown in (2).

Annual outage time:

$$U_s = \sum_i \lambda_i r_i$$  \hspace{1cm} (2)

Lastly, the outage time of load point ‘s’ ($r_s$) can be calculated by dividing the annual outage time ($U_s$) by the failure rate ($\lambda_s$), as shown in (3).

Outage time:

$$r_s = \frac{U_s}{\lambda_s} = \frac{\sum_i \lambda_i r_i}{\sum_i \lambda_i}$$  \hspace{1cm} (3)

Table I illustrates the calculations of failure rate, annual outage time and average outage time of load point ‘s’.

<table>
<thead>
<tr>
<th>Load point ‘s’</th>
<th>Section</th>
<th>$\lambda_i$ (f/yr)</th>
<th>$r_i$ (hours)</th>
<th>$U_i$ (hrs/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>4</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>4</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>4</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Distributor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>2</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
<td>2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$\lambda_s$</td>
<td>$r_s = \frac{U_s}{\lambda_s}$</td>
<td>$U_s = \Sigma \lambda_i r_i$</td>
<td></td>
</tr>
</tbody>
</table>

Three reliability indices, including SAIDI, CAIDI and ENS, are used to measure the reliability of the system. To calculate these indices, customer and load information are required. Let us define $N_c$ as number of customers, i.e. meters, located at load point ‘s’ and $L_s$ as the amount of load (kW) at load point ‘s’. SAIDI, CAIDI and ENS can be calculated as:

- **SAIDI** (System Average Interruption Duration Index) as shown in (4), is calculated by dividing the sum of total customer interruption durations per year and the total number of customers for all load points.

$$SAIDI = \frac{\text{Sum of customer interruption durations}}{\text{Total number of customers}}$$
\[
SAIDI = \frac{\sum U_s N_s}{\sum N_s} \text{ hours/customer year} \quad (4)
\]

- **CAIDI** (Customer Average Interruption Duration Index) as shown in (5), differs from SAIDI only in the value of denominator. CAIDI is calculated by dividing the sum of total customer interruption durations per year and the total number of customers affected. During a year, some customers may not be affected at all.

\[
CAIDI = \frac{\sum U_s N_s}{\sum N_s} \text{ hours/customer interruption} \quad (5)
\]

- **ENS** (Total energy not supplied). As shown in (6), ENS is the sum of load (kW) times its outage duration (hr/yr).

\[
ENS = \sum Load \times Outage \text{ Duration} \\
ENS = \sum L_s U_s \text{ kWh/year} \quad (6)
\]

### III. DISTRIBUTION CIRCUIT DESCRIPTION

A residential distribution network of Virginia Tech Electric Services (VTES) in Blacksburg, Virginia, is used as a case study. VTES comprises twelve distribution circuits as shown in Fig. 2. Different color codes are referred to as different distribution circuits in the area. VTES purchases electricity at 69 kV, which is converted to 12.47kV at two distribution substations, namely Blacksburg and Lane substations.

![Distribution circuit of interest (circuit 9)](source: www.facilities.vt.edu)

Circuit 9 as highlighted is our circuit of interest. According to the data from VTES, this circuit consists of 117 transformers with total capacity of 5,712kVA. The circuit serves a total of 780 customers including mostly residential and a few commercial entities. The length of the main distribution line is 7,200 feet. The connected load specifications of the system used in our study are as follows:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>568.13 kW</td>
</tr>
<tr>
<td>B</td>
<td>461.86 kW</td>
</tr>
<tr>
<td>C</td>
<td>662.31 kW</td>
</tr>
<tr>
<td>Total</td>
<td>1692.30 kW</td>
</tr>
</tbody>
</table>

The circuit of interest consists of 34 sections, 13 load points on the main distribution sections and 27 distributor laterals. Each distributor lateral is considered as one load point. Each load connected to the main distribution line is also considered as one load point. Therefore, the system has the total of 40 load points.

### IV. BASE CASE RELIABILITY EVALUATION

The current configuration of the circuit of interest can be represented by a simple radial system with protection fuses on the laterals, as shown in Fig. 3.

![Fig. 3. A simple radial system with no disconnects on the main line](source: www.facilities.vt.edu)

In this case, there are no disconnects on the main line and if any section on the main distribution line fails; it would result in power outage for all the distributor laterals. Without disconnects on the main line, installing a DG on the main distribution feeder will not improve the system reliability because a failed section on the main line cannot be isolated. Therefore, it is our key assumption that disconnects are added on the main distribution line to analyze the value of DG used as a backup generator.

Once disconnects are in place, the failed section can then be isolated and the rest of the loads can be supplied by both the substation and DG. Fig. 4 shows the same circuit with disconnects on the main line.

![Fig. 4. A simple radial system with disconnects on the main line](source: www.facilities.vt.edu)

The reliability indices for the base case (No DG) in both configurations (with and without disconnects) are shown in Table III.
It can be seen from Table III that adding disconnects on the main distribution line significantly improves the reliability of the system. SAIDI improves from 1.3182 hrs/customer-yr to 0.71344 hrs/customer-yr, which represents 46% improvement. CAIDI improves from 3.4309 hrs/customer-interruption to 1.8602 hrs/customer-interruption, which also represents 46% improvement. And ENS improves from 2303 kWh/yr to 1419 kWh/yr, which represents 38% improvement.

IV. ASSUMPTIONS

Following assumptions are considered for the analysis:
- Disconnects, transformers and fuses are assumed to be 100% available, however the DG’s failure rate is assumed to be 10%.
- The failure rate for the sections on the main distribution line is assumed to be 0.1 f/km-yr while that for distributed laterals is assumed to be 0.2 f/km-yr.
- The total isolation and switching time is 2 minutes for DG.
- The repair time for each section is 4 hours while that for each distributor lateral is 2 hours.
- DGs to be installed on our circuit are used as backup generators.

V. CASE STUDIES & ANALYSIS

In this section, three case studies are discussed. Firstly, the value of placing DG units of various sizes at various distances from the distribution substation is quantified, as discussed in subsection A. Secondly, system reliability indices resulting from an aggregated DG unit and several distributed DG units located at several locations across the circuit are compared. This is discussed in subsection B. Thirdly, system reliability indices resulting from installing an aggregated DG unit (1x300kW) and two DG units (2x150kW) located at the same location are compared. This is discussed in subsection C.

A. Reliability vs. Distance

In this case study, we quantify the value of placing DG units of various sizes (150kW, 300kW and 500kW) at various distances along the main distribution feeder. The failure rate of the DG in this case is assumed to be 10% while the total isolation and switching time in this case is assumed to be 2 minutes. The DGs were first placed at the start of the circuit, close to the substation, and then moved to 5 locations away from the substation towards the end of the line as shown in Fig. 5.

For each case, the reliability indices SAIDI, CAIDI and ENS are calculated and are shown in Tables IV, V and VI, and graphically analyzed in Figs. 6, 7 and 8.
It can be seen from Tables IV, V, VI and Figs. 6, 7, 8 that the DG unit that is installed at the start of the circuit (location A, which is 0.0 mi from substation) will not improve the reliability indices of the system regardless of the DG size. This is because the failure in any section or distributor lateral within the circuit will not be mitigated as the DG unit will just act as an additional source to the distribution substation. However, in case of power interruptions from the main substation, the DG can be used to supply power to the system. This contribution however does not reflect in such customer- and load-oriented indices as SAIDI, CAIDI and ENS.

Significant improvements in the reliability indices can also be observed as the DG unit is placed away from the substation and closer to the end of the line. Table VII summarizes the improvement in reliability indices when DG of various sizes is moved from the distribution substation toward the end of the line.

<table>
<thead>
<tr>
<th>DG Size (end of the line)</th>
<th>SAIDI Improvement</th>
<th>CAIDI Improvement</th>
<th>ENS Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>150kW</td>
<td>7%</td>
<td>7%</td>
<td>9%</td>
</tr>
<tr>
<td>300kW</td>
<td>13%</td>
<td>13%</td>
<td>17%</td>
</tr>
<tr>
<td>500kW</td>
<td>22%</td>
<td>23%</td>
<td>26%</td>
</tr>
</tbody>
</table>

Table VII: Improvement in Reliability Indices

As shown, the average interruption duration for the system (SAIDI) improves by 7% as the 150 kW DG is moved from the start to the end of line. In case of 300kW DG, the SAIDI improves by 13% as the DG is moved from the start to the end of line. Also for the 500kW DG, it improves by 22% from 0.71344 hr/customer-yr to 0.55156 hr/customer-yr.

Similar improvements are observed for the average interruption duration index for customers (CAIDI). In case of SAIDI and CAIDI, we notice that placing the DG at location B (0.5 mi from substation) produces slightly better results than placing it at location C (0.8 mi from substation). This is due to the fact that, in the circuit of interest, the load point around location C includes a park that consumes a lot of power but is considered as one customer in terms of reliability. Since SAIDI and CAIDI are customer related indices, we see higher SAIDI and CAIDI values when placing the DG unit at location C as the DG serves fewer numbers of customers.

The ENS (Energy Not Supplied) improves by 9% from 1419 kWh/yr when a 150kW DG is installed at the start of circuit to 1293.7kWh/yr as it is installed to the end of circuit. In case of 300kW DG, the ENS improves by 17% from 1419 kWh/yr to 1182.7kWh/yr. And finally, in case of 500kW DG, the ENS improves by 26% from 1419 kWh/yr to 1043 kWh/yr.

The following observations can be summarized:
- Reliability indices (SAIDI, CAIDI and ENS) will not be improved if the DG unit is installed at the distribution substation regardless of the DG size.
- Reliability indices (SAIDI, CAIDI and ENS) improve as the DG is installed away from the substation and closer to the loads.
- The best improvement is observed when the DG is placed at the end of the line.
- Customer- and load-oriented indices (SAIDI, CAIDI and ENS) improve as the DG size is increased, except for when the DG unit is installed at the distribution substation.
B. Reliability analysis when 1x300kW and several DGs are installed at distributed locations

The DGs considered in this case study include (a) 1x 300kW DG installed at various distances from substation; and (b) 2x150kW, 3x100kW, 4x75kW, 5x60kW DGs installed at distributed locations, which are randomly chosen. The results are shown in Figs. 9, 10 and 11.

![Fig. 9. Comparison of SAIDI when (a) 1x 300kW DG installed at various distances from substation; and (b) 2x150kW, 3x100kW, 4x75kW, 5x60kW DGs installed at distributed locations.](image)

It can be observed that the SAIDI, CAIDI and ENS calculated when the 1x300kW DG is installed are the same as those presented in subsection A. Again, the load point around location C (0.8 miles from the substation) includes a park that consumes a lot of power but is considered as a single customer. Therefore, higher SAIDI and CAIDI values are observed when placing the DG unit at location C as the DG serves fewer customers.

When several distributed DGs of size 300kW (2x150kW, 3x100kW, 4x75kW, 5x60kW) are installed, SAIDI, CAIDI and ENS appear flat (in Figs. 9, 10 and 11). This is for comparison purpose because several distributed DGs are installed at randomly distributed locations. Therefore, distance from the substation does not apply when SAIDI, CAIDI and ENS are calculated in this case.

According to the results shown in Figs. 9, 10 and 11, installing several distributed DGs of size 300kW can improve the reliability indices as compared to installing an aggregated DG, depending on the locations of DGs, the number of customers and the size of the loads. SAIDI and CAIDI depend on the number of customers at each load point in the circuit. ENS depends on the load connected to each load point. However, the indices improve the most when the aggregated 300kW DG is placed at the end of the line.

C. Reliability analysis when an aggregated DG (1x300kW) and distributed DGs (2x150kW) are installed at the same locations

The DGs considered in this case study include (a) 1x 300kW DG; and (b) 2x150kW installed at the same locations, with various distances from substation. SAIDI, CAIDI and ENS of this case are shown in Figs. 12, 13 and 14.

![Fig. 12. Comparison of SAIDI when a 300kW DG or 2x150kW DGs are installed at the same location](image)

It can be seen from Figs. 12, 13 and 14 that installing a 1x300kW DG or 2x150kW DGs at the same location doesn’t make any significant difference to the overall reliability indices of the system. In fact, installing 1x300kW DG yields better reliability improvement than installing 2x150kW DGs. This is due to the fact that the failure rate of 1x300kW DG is 10%, while the combined failure rate of 2x150kW DGs...
increases to 19% (Note that the probability that both DGs fail at the same time is 1%; the probability that either one of the two DGs fails is 18%). However, for the load points that can be served by a single 150kW DG unit, installing 2x150kW DGs provides better reliability improvement than installing 1x300kW DG. This is because if one DG fails the other DG can still serve the load points partially.

install at the same location

Fig. 13. Comparison of CAIDI when a 300kW DG or 2x150kW DGs are installed at the same location

Fig. 14. Comparison of ENS when a 300kW DG or 2x150kW DGs are installed at the same location

VI. CONCLUSIONS

The research covers several implications of DG installation on a residential distribution system. Research findings include:

- Installation of DG in the traditional distribution feeders that do not have disconnects on the main line will not improve system reliability indices.
- Adding disconnects on the main line will maximize the reliability contribution of DG as a backup generator and increase system reliability. With disconnects, DGs can supply the loads cut off from the substation in the event of section or distributor lateral failures.
- The best location for the placement of the DG is at the end of the line in terms of reliability improvement. Once the failed section is isolated, the downstream customers can be supplied by the DG and the upstream customers can be served by the substation.
- Installing small-scale distributed DGs instead of an aggregated large-scale DG can improve the system reliability indices, depending on the locations of DGs, the number of customers and the sizes of the loads. The index improves if the DGs are located closer to the end of line. However, the reliability indices improve the most when the aggregated DG is placed at the end of the line.
- Installing one aggregated DG or several distributed DGs of the same size at the same location doesn’t make any significant difference to the overall system reliability indices. However, the reliability indices improve for the load points at which multiple DGs are installed. This is because if one DG fails the other DG can still serve the load points partially.

The case studies and analysis presented in this paper is expected to contribute towards enhancing the reliability and resilience of the power grid. The research is very useful for distribution network planning as it quantifies the improvement in reliability indices by installing different DG sizes at various distances from the substation and also performs an analysis on installing a large-scale aggregated DG vs. several small-scale distributed DGs.

VII. REFERENCES


VIII. BIOGRAPHIES

**Irfan Waseem** (S'08 IEEE) is pursuing his M.S. degree in the Department of Electrical and Computer Engineering at Virginia Polytechnic Institute and State University, VA, USA. He received his B.S. degree in Electrical Engineering from Louisiana State University (LSU), Baton Rouge, LA in 2006. His employment experiences include Intern at Siemens, Pakistan. He is a member of the team working on Intelligent Distributed Autonomous Power Systems (IDAPS) project at the Virginia Tech’s Advanced Research Institute. His fields of interest include power distribution, power system protection and renewable energy systems.

**Manisa Pipattanasomporn** (S'01, M'06 IEEE) joined Virginia Tech's Department of Electrical and Computer Engineering as an assistant professor in 2006. She received her Ph.D. in electrical engineering from Virginia Tech in 2004. She received the M.S. degree in Energy Economics and Planning from Asian Institute of Technology (AIT), Thailand in 2001 and a B.S. degree from the Electrical Engineering Department, Faculty of Engineering, Chulalongkorn University, Thailand in 1999. She is currently researching the application of a specialized microgrid called the Intelligent Distributed Autonomous Power Systems (IDAPS) to improve the resiliency of electrical energy infrastructures. Her fields of interest are renewable energy systems, distributed energy resources and critical infrastructures.

**Saifur Rahman** (S’75, M’78, SM’83, F’98 IEEE) is the director of the Advanced Research Institute at Virginia Tech where he is the Joseph Loring Professor of electrical and computer engineering. He also directs the Center for Energy and the Global Environment at the university. Professor Rahman has served as a program director in engineering at the US National Science Foundation between 1996 and 1999. He has served on the IEEE PES Governing Board as VP of industry relations, and VP of publications between 1999 and 2003. In 2006 he served as the vice president of the IEEE Publications Board, and a member of the IEEE Board of Governors. In 2008 he is serving as the vice president for New Initiatives and Outreach for the IEEE Power & Energy Society and a member of its Board. He is a member-at-large of the IEEE-USA Energy Policy Committee. He is a distinguished lecturer of IEEE PES, and has published over 300 papers on conventional and renewable energy systems, load forecasting, uncertainty evaluation and infrastructure planning.