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# Impact of Distributed Generation on Reliability Evaluation of Distribution System

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*Abstract*— **Reliability assessment is of primary importance in designing and planning distribution systems that operate in an economical manner with minimal interruption of customer loads. DG is expected to improve the system reliability as its backup generation. Since DG units are subject to failures as all other generation units, the random behavior of these units must be taken into account in the analysis. Existence of DG units in a distribution system will effect on restoration time of load points. The algorithm for restoration time assessment of load point is developed when DG unit is installed. In this paper, the reliability performance of distribution system is analyzed in terms of SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS, AENS ASAI and ASUI. The Algorithm to calculate the reliability indices for simple 7-bus radial distribution feeder with and without DG was developed. The improvement in the reliability of the feeder was studied for different locations of DG with respect to fault point. All the above analysis is carried out in MATLAB software.**

***Keywords—distribution system, reliability, distributed generation***

## I. INTRODUCTION

In recent years, Distributed Generation (DG) has rapidly become an attractive option for alternative electrical power resources due to its environmental and economical advantages. However, the installations of DGs in electric power systems have been known to have several impacts on the systems. Those impacts include voltage regulations, system losses, power quality, protection schemes and system reliability.

Distributed generation (DG) is normally defined as small generation units (<10 MW) installed in distribution systems. The applications of DG include combined heat and power, standby power, peak shaving, grid support, and stand alone power. The DG technologies include photovoltaic, wind turbines, fuel cells, small and micro-sized turbine packages, internal combustion engine generators, and reciprocating engine generators. Distributed power generation technology in a short period of time to gradually restore the importance of local power grid load, improve the reliability of an important user.

System reliability plays an important role in distribution systems since it has been reported that more than 80% of all customer interruptions occurred due to failures in the distribution systems [1]. Several studies have been illustrated the impacts of the installing DG units on distribution systems reliability [2], [3].

The methods for evaluating distribution system reliability could be categorized into two groups: analytical methods and simulation methods. In analytical methods, the system is presented in a mathematical model and reliability indices are evaluated from this model [4], [5], [6] and [7]. In simulation methods, the actual processes and system behaviors are simulated for estimating the reliability indices [8], [9]. In distribution systems, DG units could be considered as backup generators [4], [5]. The authors in [4] suggested that system reliability indices depended on locations of DG units, the number of DG units at each location and the availability of DG units. In [5], the authors showed the reliability impact of installing a large-scale DG vs. installing several small-scale DG units. Moreover, they calculated the system reliability of placing DG unit at various distances from the substation, where the best location for the DG placement, in terms of reliability improvement, was at the end of line.

In [6], the authors presented an analytical method to calculate the system reliability indices with several DG units. The paper showed that system reliability depended on location of DG unit and DG capacity. In addition, DG should be installed at the end of feeder and the DG small size capacity should be installed at the upstream side of the DG with large capacity. In [7], the authors presented an interval algorithm to deal with the uncertainty of component data to calculate the interval system reliability indices. The paper showed comparison of the interval system reliability indices when DG unit connected in difference locations on distribution system.

In [8], the authors presented the Depth-First Search algorithm to divide distribution system into several smallest units and used the Monte Carlo simulation method to simulate the running status of distribution system with DG unit. The paper compared the reliability indices of the original system to those of the system with additional DG unit. In [9], the authors presented a method that combined the load duration curve with the characteristics of DG operation mode in order to evaluate the reliability. The paper showed the error of reliability indices based on the Monte Carlo simulation method.

In this paper, the analytical method based on [10] is used to evaluate reliability indices, including SAIFI, SAIDI, CAIDI, ENS, AENS, ASAI and ASUI in a radial distribution system, with and without DG installation. Restoration time assessment of each load point is presented when DG unit is installed along the distribution feeder. The DG is assumed to be operating as backup unit for the system. The test system can be studied in two different cases based on different Availabilities of DG. In each Availability of DG, the reliability indices are evaluated on the system without DG unit, and with DG unit being installed at various locations along the feeder.

## II. DISTRIBUTION SYSTEM RELIABILITY EVALUATION

### A. DEFINITIONS

For the purpose of this study, the distribution system is classified into three parts: Sections, Lateral Distributors; and Load Points as shown in Fig. 1 [10].

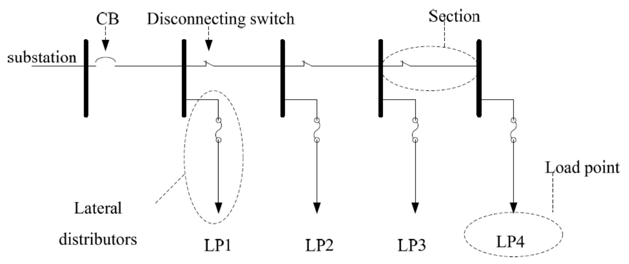


Fig. 1: Definitions of sections, laterals and load points

Restoration time is the time for load re-service after protection device operates to clear a fault. However, restoration time of each load point depends on location of DG and fault location.

### B. Reliability Indices

Reliability indices reflect the reliability level of the power system. In this study, distribution system reliability is classified into three types: load point indices; customer oriented indices; and energy oriented indices [10].

1) Load Point Indices:

Load point indices are used to measure the reliability of each load point in the system. These indices include average failure rate ($\lambda_s$), average outage time ($r_s$), and average annual outage time (Us), at any load point 's'. For the calculation of these indices, failure rate ($\lambda_i$) and repair time ($r_i$) of each component in the system are required. Load point indices calculation are shown in (1)-(3).

$$\lambda_s = \sum_i \lambda_i \quad failures/year$$
(1)

$$U_s = \sum_i \lambda_i r_i \quad hours/year$$
(2)

$$r_s = \frac{U_s}{\lambda_s} = \frac{\sum_i \lambda_i r_i}{\sum_i \lambda_i} \quad hours/interruption$$
(3)

2) Customer Oriented Indices:

Customer oriented indices are used to measure the reliability of the system. These indices are SAIFI, SAIDI and CAIDI. For the calculation of these indices, average failure rate, average annual outage time and customer information are required.

**SAIFI** (System Average Interruption Frequency Index) is the average value of interruption frequency in the system that effects customers during the year, which can be computed as:

$$SAIFI = \frac{\sum_s \lambda_s N_s}{\sum_s N_s} \quad interruptions/customer\ year$$
(4)

**SAIDI** (System Average Interruption Duration Index) is the average value of outage duration time in the system that effects customers during the year, which can be computed as:

$$SAIDI = \frac{\sum_s U_s N_s}{\sum_s N_s} \quad hours/customer\ year$$
(5)

**CAIDI** (Customer Average Interruption Duration Index) is the average value of outage duration time in the system that effects customers per interruption, which can be computed as:

$$SAIDI = \frac{\sum_s U_s N_s}{\sum_s \lambda_s N_s} \quad hours/customer\ interruption$$
(6)

**ASAI** (Average service availability Index) is the customer hours of available service to customer hours demanded, which can be computed as:

$$ASAI = \frac{\sum N_i \times 8760 - \sum U_i N_i}{\sum N_i \times 8760}$$
(8)

**ASUI** (Average service unavailability Index) is the customer hours of unavailable service to customer hours demanded, which can be computed as:

$$ASUI = 1 - ASAI = \frac{\sum U_i N_i}{\sum N_i \times 8760}$$
(9)

3) Energy Oriented Indices:

Energy oriented indices are used to measure the reliability of the system. In this study, these indices include ENS and AENS. For the calculation of these indices, average annual outage time, customer and load information are required.

**ENS** (Energy Not Supplied index) is total energy not supplied by the system during the year.

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$ENS = \sum_s L_s U_s \;\; kwh/year$
(7)

**AENS** (Average Energy Not Supplied index) is the average value of energy not supplied by the system that effects customers during the year.

$AENS = \frac{\sum_s L_s U_s}{\sum_s N_s} \;\; kwh/customer\ year$
(8)

## III. RELIABILITY EVALUATION TECHNIQUE

In this paper, evaluation of reliability indices of distribution system with one DG installed at any load point along the feeder line by considering the two patterns of customers scattering is studied. Total number of customers and the average number of customers of all load points are considered as identical.

In this paper, reliability assessment also considers restoration time calculation for each load point with additional DG, which depends on DG location and fault location. When a fault occurs in any section of the distribution feeder as shown in Fig.1, the main circuit breaker is automatically opened and steps of the restoration process is as follows:

Step 1: Find the location of the fault;

Step 2: If the fault occurs on the upstream side of DG, find the numbers and locations of load points to be served by backup DG;

Step 3: Clear the fault from the system by the isolated switches (upstream and downstream of the fault);

Step 4: Operate the isolated switches in order to eliminate the other load points that DG can't serve;

Step 5: Start up the DG unit to serve load points found in Step 2;

Step 6: Close the main circuit breaker.

The restoration time of the above process is given by:

$$RT_{LP} = \begin{cases} FLT + SWT \;, & if\ LPL < FL \\ FLT + SWT + DG\_SUT \;, & if LPL *< FL \\ FLT + SWT + RPT \;, & otherwise \end{cases}$$

Where,

RT$_{LP}$ --> is the repair time of a load point,
FLT --> is the average fault location time,
SWT --> is the average switching time,
DG_SUT --> is the DG unit start up time,
RPT --> is the average repair time,
LPL --> is the load point location,
LPL$^*$ --> is the load point location restored by DG,
FL --> is the fault location.

The proposed algorithm for reliability assessment can be described as follows

Step 1: Input system parameters. Set DG location index *DGL = 1*;

Step 2: Set failure section index, $F_s = 1$;

Step 3: Calculate failure rate ($\lambda_i$), restoration time ($RT_{LP}$) and average annual outage time ($U_i = \lambda_i\ RT_{LP}$) of affected load points from thesection failure;

Step 4: If failure section index is less than the number of total sections, increase the Index $F_s$, by 1 and go to Step 3;

Step 5: Set failure lateral index, $Fl = 1$;

Step 6: Calculate $\lambda_i$, $RT_{LP}$ and $U_i$ of affected load points from the lateral failure;

Step 7: If failure lateral index is less than the number of total laterals, increase the index, $Fl$, by *1* and go to Step 6;

Step 8: Calculate average failure rate ($\lambda_s$) and average annual outage time ($U_s$) at every load point;

Step 9: Calculate system reliability indices;

Step 10: If DG location index is less than the number of total sections, increase the index *DGL* by *1* and go to Step 2.

## IV. DESCRIPTION OF DISTRIBUTION SYSTEM

The configuration of the distribution system used to illustrate the proposed technique for reliability assessment is shown in Fig. 2. The length of this main feeder and each lateral distributor are 10 km and 2.5 km, respectively. The system has 7 load points which are distributed evenly along the length of the feeder. The total number of customers for this system is 550 with the total load of 1,400 kW.

For the analysis, operating conditions of the components and their parameters are assumed as follows:

- A single DG unit is installed as backup generator, where its operational availability is the availability of DG.
- Circuit breaker, disconnecting switches and fuses of the main feeder has the operational availability of 100%.
- Lateral protecting fuses have the availability of 98%.
- The failure rate of each section is 0.0650 f/km-yr and that of each lateral distributor is 0.2 f/km-yr.
- The average repair time of each section is 2 hours, and that of each lateral distributor is 4 hours.
- The average switching time and average fault location time and DG unit start up time are 0.25, 0.5 and 0.0333 hours, respectively.

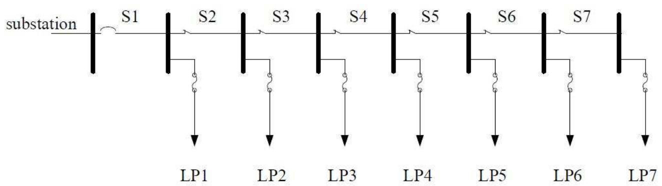


Fig. 2: Test System.

## V. CASE STUDY & ANALYSIS

In this section, two studies are discussed. Firstly, the position of placing DG at various locations from the substation is quantified, as discussed in section A. Secondly the study is based on availability of DG has classified into three cases.
Case –i Availability of DG = 0.69
Case –i Availability of DG = 0.75
Case –i Availability of DG = 0.90
Table-1, shows the number of customers at each load point for two cases.

Table-1: Number of customers in two cases

| **Load Point (LP)** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **Total** |
|---|---|---|---|---|---|---|---|---|
| **No. of customers** | 100 | 100 | 200 | 20 | 100 | 10 | 20 | **550** |

The proposed algorithm is applied to the test system with and without additional DG for different customer scattering patterns. The results of reliability indices are shown and discussed below.

### A. SAIFI

The results show that the system SAIFI is equal to 0.7491 interruptions/customer year for every location of an additional DG and every case of DG availability.

### B. SAIDI

The values of system SAIDI calculated for different Availabilities of DG and DG locations, with and without DG are shown in Table-2.

Table-2: System Average Interruption Duration Index (SAIDI) (in hrs. /cust. Yr)

| DG Location | Case-i | Case-ii | Case-iii |
|---|---|---|---|
| No DG | 1.2681 | 1.2604 | 1.2412 |
| Sect. 1 | 1.2681 | 1.2604 | 1.2412 |
| Sect. 2 | 1.1956 | 1.1817 | 1.1468 |
| Sect. 3 | 1.1395 | 1.1207 | 1.0736 |
| Sect. 4 | 1.0673 | 1.0422 | 0.9795 |
| Sect. 5 | 1.0256 | 0.9969 | 0.9251 |
| Sect. 6 | 1.0208 | 0.9917 | 0.9188 |
| Sect. 7 | 1.0176 | 0.9882 | 0.9146 |

From Table-2, with different Availabilities of DG and DG locations, it is concluded that SAIDI decreases when the DG location is away from substation.

### C. CAIDI

The values of system CAIDI calculated for different Availabilities of DG and DG locations, with and without DG are shown in Table-3.

Table-3: Customer Average Interruption Duration Index (CAIDI) (in hrs. /cust. Int.)

| DG Location | Case-i | Case-ii | Case-iii |
|---|---|---|---|
| No DG | 1.6919 | 1.6817 | 1.6561 |
| Sect. 1 | 1.6919 | 1.6817 | 1.6561 |
| Sect. 2 | 1.5961 | 1.5775 | 1.5309 |
| Sect. 3 | 1.5212 | 1.496 | 1.4332 |
| Sect. 4 | 1.4248 | 1.3913 | 1.3075 |
| Sect. 5 | 1.3692 | 1.3308 | 1.2349 |
| Sect. 6 | 1.3627 | 1.3238 | 1.2266 |
| Sect. 7 | 1.3585 | 1.3192 | 1.221 |

From Table-3, with different Availabilities of DG and DG locations, it is concluded that CAIDI decreases when the DG location is away from substation.

### D. ASAI

The values of ASAI calculated for different Availabilities of DG and DG locations, with and without DG are in Table-4.

Table-4: Average Service Availability Index ($ASAI \times 10^{-3}$)

| DG Location | Case-i | Case-ii | Case-iii |
|---|---|---|---|
| No DG | 999.8552 | 999.8561 | 999.8583 |
| Sect. 1 | 999.8552 | 999.8561 | 999.8583 |
| Sect. 2 | 999.8635 | 999.8651 | 999.8691 |
| Sect. 3 | 999.8699 | 999.8721 | 999.8774 |
| Sect. 4 | 999.8782 | 999.881 | 999.8882 |
| Sect. 5 | 999.8829 | 999.8862 | 999.8944 |
| Sect. 6 | 999.8835 | 999.8868 | 999.8951 |
| Sect. 7 | 999.8838 | 999.8872 | 999.8956 |

From Table-4, with different Availabilities of DG and DG locations, it is concluded that ASAI increases when the DG location is far from substation.

### E. ASUI

The values of ASUI calculated for different Availabilities of DG and DG locations, with and without DG are shown in Table 5.

Table-5: Average Service Unavailability Index ($ASUI \times 10^{-3}$)

| DG Location | Case-i | Case-ii | Case-iii |
|---|---|---|---|
| No DG | 0.1448 | 0.1439 | 0.1417 |
| Sect. 1 | 0.1448 | 0.1439 | 0.1417 |
| Sect. 2 | 0.1365 | 0.1349 | 0.1309 |
| Sect. 3 | 0.1301 | 0.1279 | 0.1226 |
| Sect. 4 | 0.1218 | 0.119 | 0.1118 |
| Sect. 5 | 0.1171 | 0.1138 | 0.1056 |
| Sect. 6 | 0.1165 | 0.1132 | 0.1049 |
| Sect. 7 | 0.1162 | 0.1128 | 0.1044 |

From Table-5, with different Availabilities of DG and DG locations, it is concluded that ASUI increases when the DG location is far from substation.

F. ENS

The values of ENS calculated for different Availabilities of DG and DG locations, with and without DG are shown in Table-6.

Table-6: Energy Not Supplied (ENS) (in kWh/year)

| DG Location | Case-i | Case-ii | Case-iii |
|---|---|---|---|
| No DG | 3214.4 | 1757.2 | 1730..3 |
| Sect. 1 | 3214.4 | 1757.2 | 1730.3 |
| Sect. 2 | 3003.3 | 1631 | 157.9 |
| Sect. 3 | 2820.9 | 1522 | 1448.1 |
| Sect. 4 | 2399.9 | 1270.3 | 1146.1 |
| Sect. 5 | 2259.6 | 1186.4 | 1045.5 |
| Sect. 6 | 2203.5 | 1152.8 | 1005.2 |
| Sect. 7 | 2175.4 | 1136.1 | 985.1 |

From Table-6, with different Availabilities of DG and DG locations, it is concluded that ENS decreases when the DG location is far from substation.

G. AENS

The values of AENS calculated for different Availabilities of DG and DG locations, with and without DG are shown in Table-7.

Table7: Average Energy Not Supplied (AENS) (in kWh/customer year)

| DG Location | Case-i | Case-ii | Case-iii |
|---|---|---|---|
| No DG | 3.2144 | 3.1948 | 3.146 |
| Sect. 1 | 3.2144 | 3.1948 | 3.146 |
| Sect. 2 | 3.0033 | 2.9655 | 2.8709 |
| Sect. 3 | 2.8209 | 2.7672 | 2.633 |
| Sect. 4 | 2.3999 | 2.3096 | 2.0839 |
| Sect. 5 | 2.2596 | 2.1571 | 1.9008 |
| Sect. 6 | 2.2035 | 2.0961 | 1.8276 |
| Sect. 7 | 2.1754 | 2.0656 | 1.791 |

From Table: 7, with different Availabilities of DG and DG locations, it is concluded that AENS increases when the DG location is far from substation.

Table: 8 the comparison of indices with DG and without DG for case i

| DG Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| SAIDI% | 0 | 5.72 | 10.14 | 15.83 | 19.12 | 19.5 | 19.75 |
| CAIDI% | 0 | 5.66 | 10.08 | 15.79 | 19.07 | 19.46 | 19.71 |
| ENS% | 0 | 6.57 | 12.24 | 25.34 | 29.7 | 31.45 | 32.32 |
| AENS% | 0 | 6.57 | 12.24 | 25.34 | 29.7 | 31.45 | 32.32 |
| ASAI% | 0 | -0.83 | -1.47 | -2.3 | -2.77 | -2.83 | -2.86 |
| ASUI% | 0 | 5.73 | 10.15 | 15.88 | 19.13 | 19.54 | 19.75 |

From the table 8 the maximum reliability indices improvement will appear when the DG location is far from the substation.

Table: 9 the comparison of indices with DG and without DG for case ii

| DG Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| SAIDI% | 0 | 6.24 | 11.08 | 17.31 | 20.91 | 21.32 | 21.59 |
| CAIDI% | 0 | 6.19 | 11.04 | 17.27 | 20.86 | 21.28 | 21.56 |
| ENS% | 0 | 7.19 | 13.38 | 27.71 | 32.48 | 34.39 | 35.35 |
| AENS% | 0 | 7.18 | 13.38 | 27.7 | 32.48 | 34.39 | 35.34 |
| ASAI% | 0 | -0.9 | -1.6 | -2.49 | -3.01 | -3.07 | -3.11 |
| ASUI% | 0 | 6.25 | 11.11 | 17.3 | 20.91 | 21.33 | 21.61 |

From the table 8 the maximum reliability indices improvement will appear when the DG location is far from the substation.

Table: 10 the comparison of indices with DG and without DG for case iii

| DG Location | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| SAIDI% | 0 | 7.6 | 13.5 | 21.08 | 25.47 | 25.97 | 26.31 |
| CAIDI% | 0 | 7.56 | 13.46 | 21.05 | 25.43 | 25.93 | 26.27 |
| ENS% | 0 | 8.74 | 16.31 | 33.76 | 39.58 | 41.91 | 43.07 |
| AENS% | 0 | 8.74 | 16.31 | 33.76 | 39.58 | 41.9 | 43.07 |
| ASAI% | 0 | -1.08 | -1.91 | -2.99 | -3.61 | -3.68 | -3.73 |
| ASUI% | 0 | 7.62 | 13.48 | 21.1 | 25.48 | 25.97 | 26.32 |

From the table 8 the maximum reliability indices improvement will appear when the DG location is far from the substation.

## VI. CONCLUSIONS

This paper proposed the improvement in the reliability performance of power distribution system by considering restoration time assessment and the impact of customer scattering on distribution system reliability when DG unit is installed at various locations. The system reliability indices evaluated by the proposed algorithm included SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS and AENS for 3 DG availabilities and 7 possible locations for DG. The results showed the optimal location of DG unit for each availability of DG in terms of reliability assessment.

For all availabilities of DG and location, SAIFI is constant because restoration time assessments do not affect the interruption frequency of the distribution system. The best DG locations for SAIDI and CAIDI maximum improvement varied with availabilities of DG and location. The ENS and

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AENS depended only on the locations of DG and availability of DG the value improves for increase in availability of DG and for DG location away from substation.

This study can be used to identify the optimal location of DG used as backup generator in a distribution system in order to improve reliability indices based on Availability of DG.

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## VIII. BIOGRAPHIES

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