Distribution System Reliability with Distributed Generation Based on Customer Scattering

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DOI: 10.15598/aeee.v13i2.1025

Abstract. *This paper presents the reliability improvement with effect of customer scattering on distribution system with Distributed Generation (DG). The test system is studied in six different cases based on different customer scattering patterns. Each customer scattering case is analyzed for finding the reliability indices of the distribution system without DG, and with installation of DG at various locations along the feeder. In addition, the algorithm for assessment of average restoration time of load point is presented when DG is installed. The proposed algorithm is tested on a simple system consists of nine load points. The reliability improvement is measured by reliability indices that include SAIFI, SAIDI, CAIDI, ENS and AENS. On the other hand it provides some useful conclusions such as the customer scattering and restoration time effect the optimal location of DG in terms of system reliability.*

Keywords

Customer scattering, distributed generation, distribution system, reliability, reliability indices.

1. Introduction

Distributed generation (DG) is normally defined as small generation (<10 MW). Distributed Generation is installed in distribution systems due to its technical and economic point of view. However, the installations of DG in electric power systems have been known to have several impacts on the systems. Those impacts include system losses, voltage regulation, power quality, protection scheme and system reliability. In the 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].

The paper discussed several studies have been illustrated the impacts of the installing DG on distribution systems reliability including distribution network system stability and protect the distribution network carried out a detailed exposition [2]. There are two methods for evaluating distribution system reliability firstly, analytical methods and simulation methods. In analytical methods, the system is presented in a mathematical model. Whereas simulation method; the actual process and system behavior are simulated for estimating the reliability indices. In distributed systems, DG could be considered as backup generators.

The paper contained reliability indices depended on locations of DG units, the number of DG units at each location and the availability of DG unit used an algorithm based on analytical method [3]. Impact of installed a large-scale DG vs. installing several small-scale DG units on distribution system [4]. In addition to, the paper showed they calculated the system reliability of placing the 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 the line. The authors presented an analytical method to calculate the system reliability indices with several DG units based on short term analysis [5]. The author described for distribution system reliability with DG used FMEA technique [6].

The paper also presented a detailed reliability model for the assessment of the reliability impact of the DG on distribution system. The author presented an interval algorithm is presented to deal with the uncertainty of component data and comparison of the interval system reliability indices when the DG unit connected in different locations on the distribution system and also showed that system reliability depended on the location of DG unit and DG capacity [7]. In addition, DG should be installed at the end of the feeder and the DG small size capacity should be installed at the upstream side of the DG with large capacity. The author performed an analytical approach for investigating impacts of distributed generation (DG) on distribution system [8]. The author studied to calculate reliability indices of distribution feeder consisting of DG; which apply frequency and duration technique. The author suggested that reliability evaluation method for distribution network with distributed generation running in two different modes separately, in theses case RBTS test system was used to show the feasibility and accuracy [9].

The paper showed the state of art of research work carried out for the optimal planning of distributed generation (DG) systems under different aspects, covers the review of basics of DG, DG definition, current status of DG technologies, potential advantages, disadvantages and review for optimal placement of DG systems [10]. The author presented distribution feeder reconfiguration (DFR) problem [11]. Moreover the paper discussed from the reliability enhancement point of view. This paper, proposes an analytical method is used to evaluate reliability indices, including SAIFI, SAIDI, CAIDI, ENS, and AENS, in a distribution feeder with connection of DG based on customer scattering [12]. The restoration time assessment algorithm is proposed to evaluate the reliability of distribution feeder. The proposed method is applied to test system, which is nine sections, nine load points with single DG [13]. The test system can be studied in six different cases based on different customer scattering patterns. In each customer scattering pattern, the reliability indices are evaluated in the system without DG, and with DG being installed at various locations along the feeder.

2. Reliability Indices of Distribution System

A Sample distribution test system is shown in the Fig. 1. A distribution feeder consists of a set of series components, including lines, cables, breakers, etc.

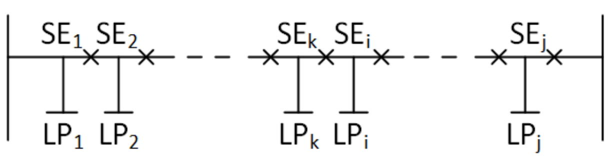

Fig. 1: Sample distribution system.

A customer connected to any load point of such system requires a set of component between load and supply points to be operating. These states are designated as cut-sets. The reliability of load point LPi can be calculated using minimal cut-set techniques. The reliability indices are mainly categorized into three types.

2.1. Classification of Reliability Indices

1) Basic Indices

Average failure rate (λ_s), average outage time (r_s), and average annual outage (U_s) at load point LP_i calculated as follows:

$$\lambda_s = \sum_{i=1}^{N} \lambda_i \left[\mathrm{f} \cdot \mathrm{yr}^{-1}\right], \qquad (1)$$

$$U_s = \sum_{i=1}^{N} \lambda_i r_i \left[\mathrm{hrs} \cdot \mathrm{yr}^{-1}\right], \qquad (2)$$

$$r_s = \frac{U_s}{\lambda_s} \left[\mathrm{hrs}\right], \qquad (3)$$

where λ_i is the failure rate of component i, r_i is the repair time of component i of the load point LP_i and can be interpreted as the average time during a calendar year in which the load point LP_i is not energized.

2) Customer-Orientated Indices

Upon computing above indices, the customer (performance) related indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) Customer Average Interruption Duration Index (CAIDI), Energy Not Supplied (ENS), and Average Energy Not Supplied (AENS) can be computed.

System Average Interruption Frequency Index (SAIFI):

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} [\mathrm{interruption} \cdot \mathrm{cust}^{-1} \cdot \mathrm{yr}^{-1}], \qquad (4)$$

where λ_i is the failure rate and N_i is the number of customers of load point LP_i.

System Average Interruption Duration Index (SAIDI):

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} [\mathrm{hrs} \cdot \mathrm{cust}^{-1} \cdot \mathrm{yr}^{-1}], \qquad (5)$$

where U_i is the annual outage time and N_i is the number of customers of load point i.

Customer Average Interruption Duration Index (CAIDI):

$$CAIDI = \frac{\sum U_i N_i}{\sum \lambda_i N_i} [\text{hrs} \cdot \text{cust}^{-1} \cdot \text{interruption}^{-1}], \quad (6)$$

where U_i is the annual outage time, λ_i is the failure rate and N_i is the number of customers of load point i.

3) Load and Energy-Orientated Indices

Energy Not Supplied (ENS):

$$ENS = \sum L_{a(i)} U_i \ [\text{kWh} \cdot \text{yr}^{-1}], \quad (7)$$

where $L_{a(i)}$ is the average load U_i is the annual outage time of load point i.

Average Energy Not Supplied (AENS):

$$AENS = \frac{\sum L_{a(i)} U_i}{\sum N_i} \ [\text{kWh} \cdot \text{customer}^{-1} \cdot \text{yr}^{-1}], \quad (8)$$

where $L_{a(i)}$ is the average load U_i is the annual outage time and N_i is the number of customers of load point i.

3. Sample Distribution System with DG

A sample distribution system is shown in Fig. 2. This is used to suggest a framework for the assessment of the reliability impact of DG on the distribution system. The model should consider intrinsic attributes of DG and the way it applied in the distribution system.

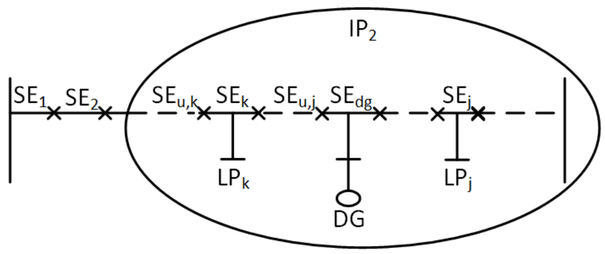

Fig. 2: Sample distribution system with DG.

The system is used to deduce models and relations. In this system, sick is a feeder section ended with circuit breakers. It is also assumed that all failures are active. Therefore, in the event of a contingency on any section, both circuit breakers as its ends should be opened immediately.

The following assumptions are made in the derivation and evaluating the proposed method:

- Continuity between load point and utility/DG is the sole reliability criterium.
- DG can continue is landed operation if its output generated is greater than the load demand.
- DG can energize the feeder during contingencies unless the contingency occurred on the DG section.
- All the load points are assumed to have the same load duration patterns and the feeder load is assumed to be uniformly distributed along the feeder.

Therefore, each section is dedicated to load point, as in Fig. 2. It should be noted that DG could only help load points in the event of faults on the upstream side of the DG. In such cases, like the island IP2 shown in the Fig. 2 an island may forms and the DG supplies the load demand on the island during loss of the main supply. Thus, there must be at least one other sectionalizing device between DG and main circuit breaker in order to permit island formation during the repair time of damaged components.

4. Evaluation of Distribution Reliability Considering Customer Scattering and DG Impacts

The customer scattering patterns determined in this study are uniform distribution, normal distribution, skewed to the right and skewed to the left distributions, as shown in Fig. 3. Note that the total number of customers and the average number of customers of all load points are the same.

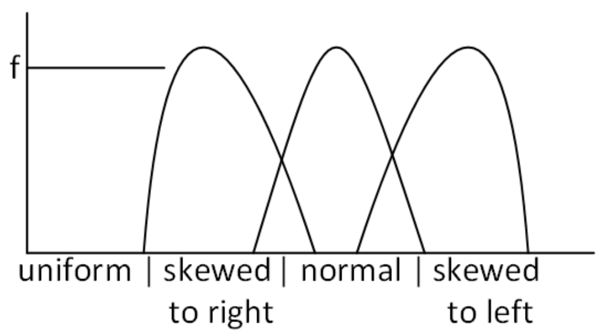

Fig. 3: Different types of customer scattering patterns.

$$RT_{LP} = \begin{cases} FLT + SWT, & \text{if } LPL < FL \\ FLT + SWT + DG\_SUT, & \text{if } LPL > FL \\ FLT + SWT + RPT, & \text{otherwise} \end{cases}. \quad (9)$$

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 (Fig. 1), the main circuit breaker is automatically opened and steps of the restoration process are:

- Find the location of the fault.
- If the fault occurs on the upstream side of DG, find the numbers and locations of load points to be served by backup DG.
- Clear the fault from the system by the isolated switches (upstream and downstream of the fault).
- Operate the isolated switches in order to eliminate the other load points that DG cannot serve.
- Start up the DG unit to serve load points found in Step 2.
- Close the main circuit breaker.

The restoration time of the above process is given by Eq. (9), 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,
- λ_s is the average failure rate,
- U_s is the annual outage time.

The proposed algorithm for reliability assessment can be described as follows:

- Input system parameters. Set DG location index $DGL = 1$.
- Set failure section index $F_s = 1$.
- Calculate failure rate (λ_i), Restoration time ($RTLP$) and annual outage time ($U_i = \lambda_i \cdot RTLP$) of affected load points from the section failure.
- If failure section index is less than the number of total sections, increase the index, F_s, by 1 and go to Step 3.
- Set failure lateral index $F_l = 1$.
- Calculate λ_i, $RTLP$ and U_i of affected load points from the lateral failure.
- If failure lateral index is less than the number of total laterals, increase the index, F_l, by 1 and go to Step 6.
- Calculate average failure rate (λ_s) and average annual outage time (U_s) at every load point.
- Calculate system reliability indices.
- If DG location index is less than the number of total sections, increase the index DGL by 1 and go to Step 2.

5. Case Study

The configuration of the distribution system used to illustrate the proposed technique for reliability assessment is shown in Fig. 4.

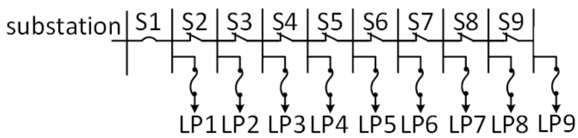

Fig. 4: Test system.

The length of this main feeder and each lateral distributor are 45 km and 10 km, respectively. The system has 9 load points which are distributed evenly along the length of the feeder. The total number of customers for this system is 603 with the total load of 1.800 kW for the analysis, operating conditions of the components and their parameters are assumed as follows:

- A single DG unit is installed as a backup generator, where the unit capacity is 20 % of feeder load, and its operational availability is 100 %.
- Circuit breaker, disconnecting switches and fuses have the operational availability of 100 %.

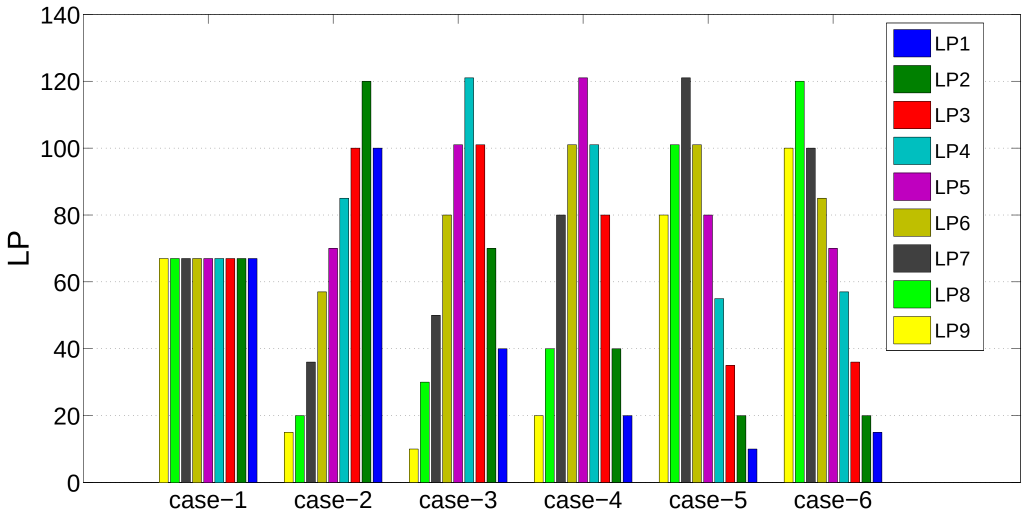

Fig. 5: Patterns of customer scattering.

- The failure rate of each section is 0.1 f·km^{-1}·yr^{-1}, and that of each lateral distributor is 0.2 f·km^{-1}·yr^{-1}.
- The average repair time of each section is 2 hours, and that of each lateral distributor is 4 hours.
- The average switching time, average fault location time and DG unit start up time are 0.25, 0.5 and 0.0333 hours, respectively.

The most important feature for reliability evaluation in this study is the customer scattering. Here, six patterns of customer scattering are considered, by distributing the number of customers at each load point as shown in Fig. 5.

In all six cases the total number of customers is same, is equal to 603 with the average value of 67. Table 1 shows the number of customers in six cases at each load point.

Tab. 1: Number of customer in six cases.

LP	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
1	67	100	40	20	10	15
2	67	120	70	40	20	20
3	67	100	101	80	35	36
4	67	85	121	101	55	57
5	67	70	101	121	80	70
6	67	57	80	101	101	85
7	67	36	50	80	121	100
8	67	20	30	40	101	120
9	67	15	10	20	80	100
Total	603	603	603	603	603	603

6. Results and Discussions

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

6.1. SAIFI

The results show that the system SAIFI is equal to 6.5 interruptions/customer years for different locations of the DG and different customer scattering cases.

6.2. SAIDI

The values of system SAIDI calculated for different locations of the DG and different customer scattering cases are in Tab. 2.

Tab. 2: SAIDI calculated for different locations of an additional DG and different customer scattering cases.

DG loc.	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
No DG	16.38	15.05	15.74	16.38	17.60	17.70
S-1	16.38	15.05	15.74	16.38	17.60	17.70
S-2	16.20	14.89	15.56	16.18	17.41	17.50
S-3	16.05	14.77	15.40	16.08	17.22	17.32
S-4	15.92	14.49	15.27	15.86	17.05	17.14
S-5	15.81	14.61	15.18	15.74	16.89	17.14
S-6	15.72	14.57	15.12	15.66	16.43	16.86
S-7	15.65	14.54	15.09	15.51	16.66	16.75
S-8	15.61	14.53	15.08	15.59	16.60	16.68
S-9	15.59	14.53	15.08	15.59	16.58	16.65

From Fig. 6(a) to Fig. 6(f) show that the values and trends of SAIDI vary with the patterns of customer

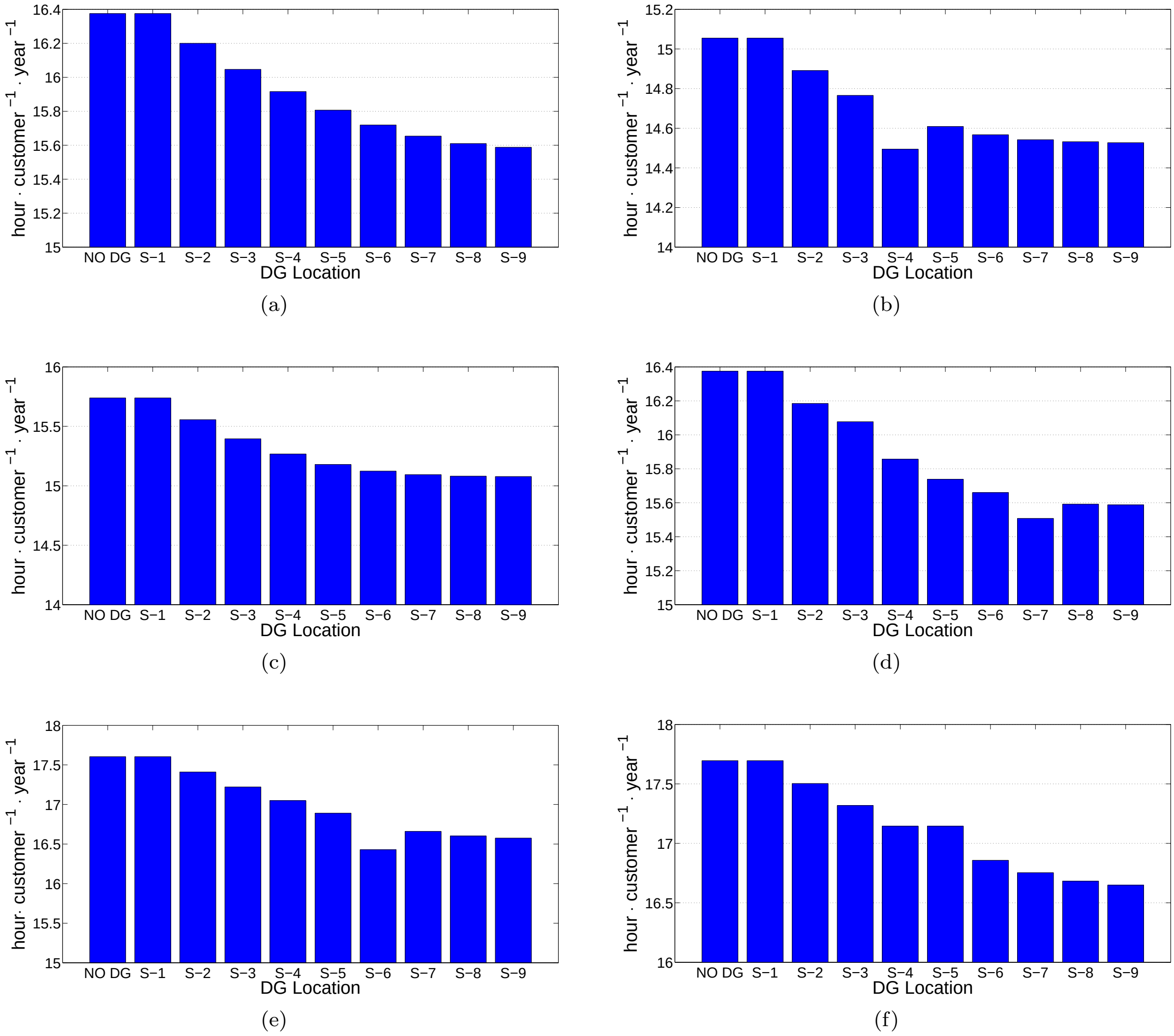

Fig. 6: (a) SAIDI for customer scattering case-1, (b) SAIDI for customer scattering case-2, (c) SAIDI for customer scattering case-3 (d) SAIDI for customer scattering case-4, (e) SAIDI for customer scattering case-5, (f) SAIDI for customer scattering case-6.

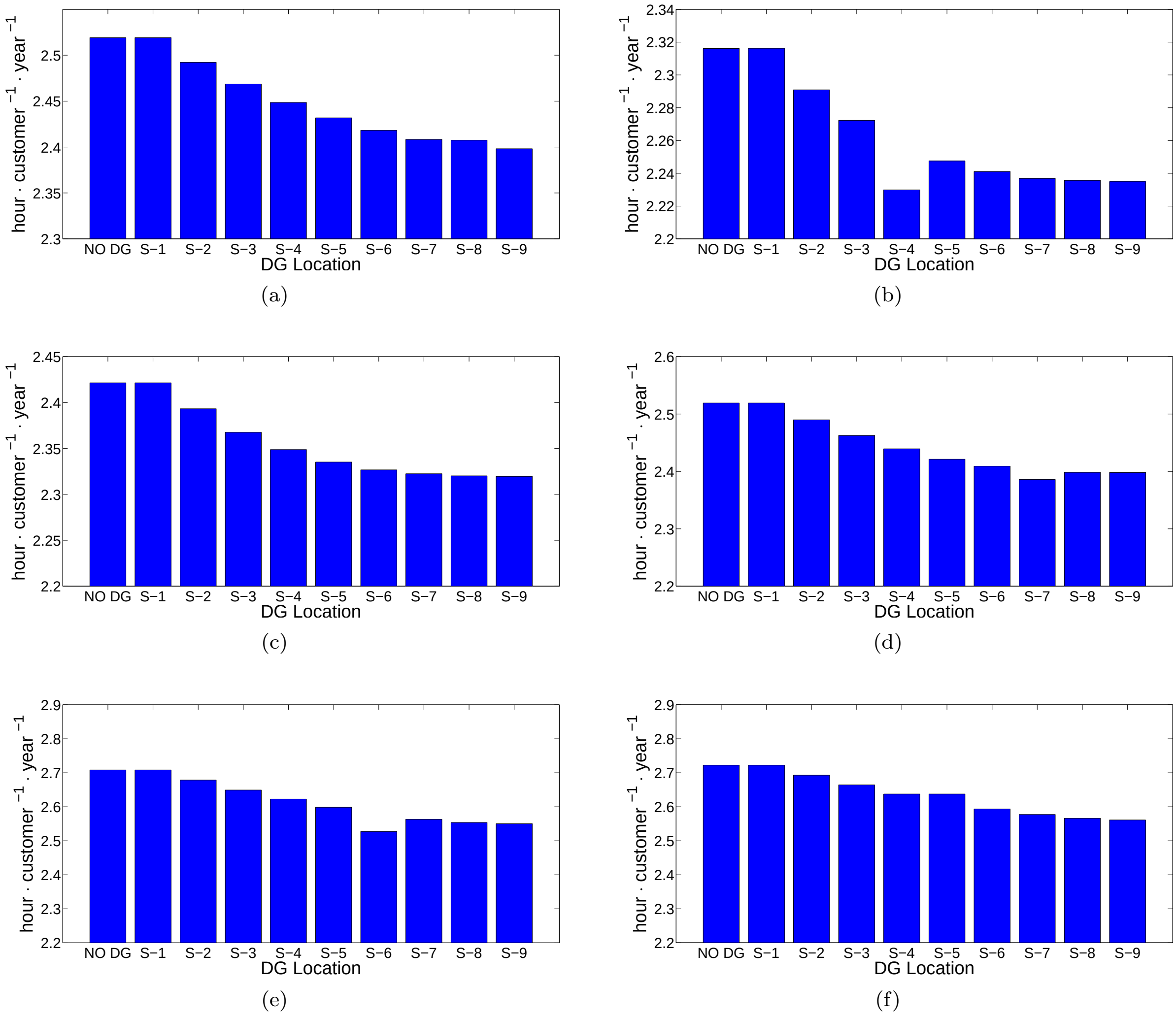

Fig. 7: (a) CAIDI for customer scattering case-1, (b) CAIDI for customer scattering case-2, (c) CAIDI for customer scattering case-3 (d) CAIDI for customer scattering case-4, (e) CAIDI for customer scattering case-5, (f) CAIDI for customer scattering case-6.

scattering and DG locations, which can be summarized as follows In case that the pattern of customer scattering is uniformly distributed (case 1), SAIDI decreases when the DG location is far from substation.

- If the number of customers is high around the front half of system feeder (cases 2 and 3), the best values of SAIDI occur when DG is installed around the middle of the feeder.
- If the pattern of customer scattering is a normal distribution (case 4), the best value of SAIDI does not occur when DG is installed at the middle section where the number of customers are the highest. Instead, it occurs when DG is installed at the next section.
- If the number of customers is high around the back half of system feeder (cases 5 and 6), the best values of SAIDI occur when DG is installed at the locations with highest numbers of customers.

The comparison of SAIDI without DG and DG installed at various locations for every pattern of customer scattering is shown in Tab. 3.

Tab. 3: The comparison of SAIDI without DG and with DG.

DG	Case [%]					
loc.	1	2	3	4	5	6
S-1	0	0	0	0	0	0
S-2	1.06	0.73	1.20	1.19	1.09	1.05
S-3	2.00	1.53	2.22	2.29	2.17	2.10
S-4	2.80	2.13	2.99	3.16	3.15	3.08
S-5	3.46	2.62	3.55	3.88	4.04	3.083
S-6	4.00	2.88	3.41	4.36	6.67	4.71
S-7	4.40	2.75	2.36	3.92	5.32	5.71
S-8	4.67	1.89	2.10	2.85	5.69	6.11
S-9	4.80	1.05	1.25	1.36	5.84	5.91

6.3. CAIDI

Values of CAIDI are shown in Tab. 4.

Tab. 4: CAIDI results in all cases.

DG loc.	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
No DG	2.519	2.316	2.422	2.519	2.708	2.722
S-1	2.519	2.316	2.422	2.519	2.708	2.722
S-2	2.492	2.291	2.393	2.490	2.679	2.693
S-3	2.469	2.272	2.368	2.463	2.649	2.664
S-4	2.449	2.230	2.349	2.439	2.623	2.638
S-5	2.432	2.248	2.335	2.421	2.599	2.638
S-6	2.418	2.241	2.327	2.409	2.527	2.594
S-7	2.408	2.237	2.323	2.386	2.563	2.577
S-8	2.408	2.236	2.320	2.398	2.554	2.566
S-9	2.398	2.235	2.320	2.398	2.550	2.561

6.4. ENS and AENS

For each DG location, the ENS as well as the AENS values are the same in every case of customer scattering. The results of ENS and AENS for different DG locations are shown in Tab. 6, where the plots of ENS and AENS are shown in Fig. 8 and Fig. 9, respectively. The values of ENS and AENS tend to decrease when DG locations are further down the feeder, which result from the restoration time assessment.

Tab. 5: Comparison of CAIDI without DG and with DG.

DG	Case [%]					
loc.	1	2	3	4	5	6
S-1	0	0	0	0	0	0
S-2	1.06	1.088	1.1645	1.163	1.100	1.084
S-2	2.004	1.891	2.226	2.247	2.182	2.131
S-4	2.802	3.722	3.002	3.168	3.167	3.111
S-5	3.469	2.962	3.564	3.886	4.054	3.111
S-6	4.005	3.238	3.915	4.366	6.679	4.732
S-7	4.402	3.420	4.109	5.291	5.358	5.323
S-8	4.434	3.471	4.183	4.795	5.705	5.738
S-9	4.803	3.505	4.208	4.807	5.841	5.914

Tab. 6: ENS and AENS for different DG locations.

DG loc.	ENS	AENS
No DG	29654	49.17
S-1	29181	49.17
S-2	29189	48.41
S-3	29025	48.13
S-4	28717	47.62
S-5	28610	47.45
S-6	28435	47.16
S-7	28263	46.87
S-8	28229	46.81
S-9	28201	46.76

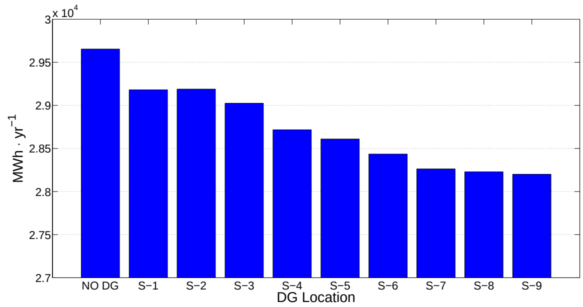

Fig. 8: Trend of ENS.

7. Conclusions

In this paper, a methodology for evaluation of distribution system reliability indices is developed. The impact of DG on the distribution system reliability by considering CUSTOMER SCATTERING is used to evaluate reliability indices, including SAIFI, SAIDI, CAIDI,

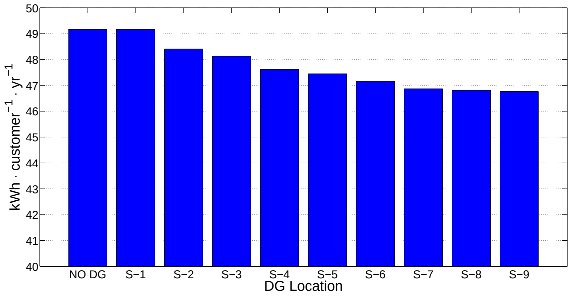

Fig. 9: Trend of AENS.

Tab. 7: Comparison of ENS and AENS without DG and with DG.

DG	ENS [%]	AENS [%]
S-1	0	0
S-2	1.56	1.54
S-3	2.12	2.11
S-4	3.15	3.15
S-5	3.52	3.49
S-6	4.11	4.08
S-7	4.69	4.67
S-8	4.80	4.79
S-9	4.89	4.90

ENS and AENS, in a radial distribution system, without DG and with DG installation. Restoration time assessment of each load point is presented when DG is installed along the distribution feeder.

Reliability evaluation is done for two different cases i.e. (i) Without DG (ii) with DG and the results showed the optimal location of DG unit for each pattern of customer scattering in terms of reliability assessment.

From the results it can be seen that for all patterns of customer scattering, SAIFI is constant because restoration time assessment does not affect the interruption frequency of the distribution system. The best DG locations for SAIDI and CAIDI maximum improvement varied with the patterns of customer scattering. The ENS and AENS depended only on the locations of DG and not on the patterns of customer scattering.

The results obtained by considering restoration time calculation of the impact of customer scattering on distribution system reliability and reliability indices based on analytical method and the simulation method is same.

This method 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 customer scattering.

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