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Reliability evaluation of distribution system integrated with distributed generation

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ABSTRACT

Distributed generation (DG) improves the reliability of the system by providing a means of alternate power supply to the load points. DG is integrated to meet the system load along with the utility. In this work roy billinton test system (RBTS) bus 4 is considered for evaluating the effect of DG integration on system reliability. Reliability is evaluated using failure modes and effect analysis (FMEA) technique and the results are validated using Monte Carlo simulation technique. A MATLAB program is developed for both the techniques to evaluate the reliability. The failure rate of DG and the islanding capability of the DG are considered to resemble the practical operating conditions of DG. When DG is operating in islanded mode, if DG fails it affects the outage time of the load points. DG failure rate is also considered as the second order failure event overlapping with the feeder section failures. All the practical operating conditions of DG considered and their effect on the reliability of the system is evaluated.

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1. INTRODUCTION

The reliability of the distribution system is becoming a major concern in the changing scenario of socio and economic conditions of the consumers. To improve the reliability of the system utilities are adopting different procedures like, changing the existing system form overhead lines to underground cable, providing backup devices, reconfiguring the system, and implementing distribution automation [1], [2]. The reliability of the system can also be improved by adopting reliability centred maintenance [3], [4], incorporating smart grid technologies [5], [6] and integrating DG to the grid [7], [8]. The improvement in the system reliability when an existing overhead line system is changed to underground cable system is presented by Guldbrand [9]. Etemadi and Firuzabad [10] discussed about the optimal capacitor placement for reliability improvement. Bertling *et al.* [11] proved that the reliability centred maintenance can considerably affect the reliability of the system. In [12], [13] discussed the effect of reconfiguration of the distribution system on the reliability of the system. In [14], [15] evaluated the improvement in the system relaibiliy considering distribution automation. The effect of implementing the smart grid technologies into the system on distribution system reliability is evaluated in [16]. Installing DG at the load points can also improve the reliability of the system considerably. Javadian and Massaeli [17] have studied the effect of DG on distribution system reliability by considering the mis-operation of fuse and recloser. Yuan *et al.* [18] has considered the effect of DG location on the distribution system reliability. Ngaopitakkul *et al.* [19] have evaluated the effect of size and location of DG on distribution system reliability and calculated the cost of interruption.

The improvement in the reliability when DG is integrated needs to be quantified for assessing the benefits of reliability. In the earlier works on DG integration reliability assessment have considered systems containing breakers to isolate the fault. In practice a distribution feeder will have breaker at the starting, reclosures and/or isolators along the length of the feeder. The system considered in this work considers this aspect that one breaker at the starting point of the feeder and has isolators to isolate the faulted section. This changes the method of reliability evaluation and alters the outage time of the load points. When DG is operating islanded mode if a failure in DG occurs, the load points experience a second order failure. For the power output of DG is dependent on the availability of renewable energy sources particularly in the case of Solar and Wind based technologies. In this work all the above points are considered for the system evaluation of reliability indices.

2. RELIABILITY INDICES EVALUATION METHODS

2.1. Failure modes and effects analysis

Failure modes and effects analysis (FMEA) is an inductive technique that seeks to identify all possible equipment failure modes and their associated impact on system reliability [20]. Possible failure events of each component in the distribution system are identified and analysed to determine their effects on the surrounding load points. Failure modes represent component outages that must overlap to cause system outage. Each of these overlapping outages will cause system failure; therefor all the overlapping outages are effectively considered in series from reliability point of view.

A MATLAB program is developed to evaluate the reliability indices of the system using FMEA technique. The developed program reads the failure data of the sections, laterals and bus bars. The corresponding feeder section and lateral are identified for all the load points. There is a breaker at the beginning of the feeder and for any faults on the feeder sections; breaker operates interrupting the supply to the load points. The faulted section can be isolated with the help of isolators. Supply can be restored to the load points on the upstream of the fault and the downstream load points remain disconnected untill the fault is cleared. Figure 1 shows the flow chart of the developed program.

a. Monte Carlo simulation

Components in the power system do not follow a particular pattern in their failure rates and the nature of failure is random in nature. This can be considered in relaibiliy evaluation using Monte Carlo simulation method [21]. The Monte Carlo method is the general designation for stochastic simulation using random numbers.

Algorithm for Monte Carlo simulation
Step 1: Read the system data.
Step 2: Set the number of simulations.
Step 3: For all the components generate a random number and convert that number into its time to failure considering the failure rate of the components.
Step 4: Compare the time to failure obtained in step 3 with the mission time (1 year). If the component is transformer or lateral go to step 10 if it is less go to step 5.
Step 5: Identify the effected load points depending on the section number.
Step 6: Generate a random number for DG and convert it into time to fail (TTFL)
Step 7: If the failed section is less than the DG section number calculate the islanded load.
Step 8: If the load is less than or equal to DG capacity and the TTFL of DG is greater than the mission time, considers repair time for the failed section and switching time for all other sections.
Step 9: If the load is more than DG capacity or the TTFL of DG is less than the mission time that is 8760 hr consider repair time for downstream sections of load point as the repair time and upstream of the load point as switching time.
Step 10: Increment the number of failures and calculate outage time, energy not supplied
Step 11: Find the average failure rate, annual outage time of all the load points.
Step 12: Calculate the reliability Indices, system average interuption frequency index (SAIFI), system average duration index (SAIDI), expected energy not served (EENS) and average energy not served (AENS)
Step 13: End.

2.2. Test system and data

To quantify the effect of DG integration on distribution system reliability bus 4 of Roy Billinton test system (RBTS) is considered and is shown in Figure 2. It has 7 feeders with three supply points. Feeder 1, feeder 2 and feeder 3 are supplied by supply point 1 through two 16 mega volt ampere (MVA) transformers. Feeder 4 and feeder 5 are supplied by supply point 2through two 10 MVA transformers. Feeder 6 and feeder 7 are supplied by supply point 3 with two 10 MVA transformers. It has a peak load of 40 megawatt (MW) and an average load of 24.58 MW. There are 29 distribution transformers, 38 load points, 29 feeder sections and 38 laterals.

The normally open switches are ignored and the system is considered to be fully radial without any tie line switches. The data required for the system reliability indices is shown in Tables 1 and 2. To calculate the energy-oriented indices of the system, the details of the load points in terms of type of customers, number of customers and their average, peak load are required. Details of number, type of customers connected, average and peak loads of load points are given in Table 3.

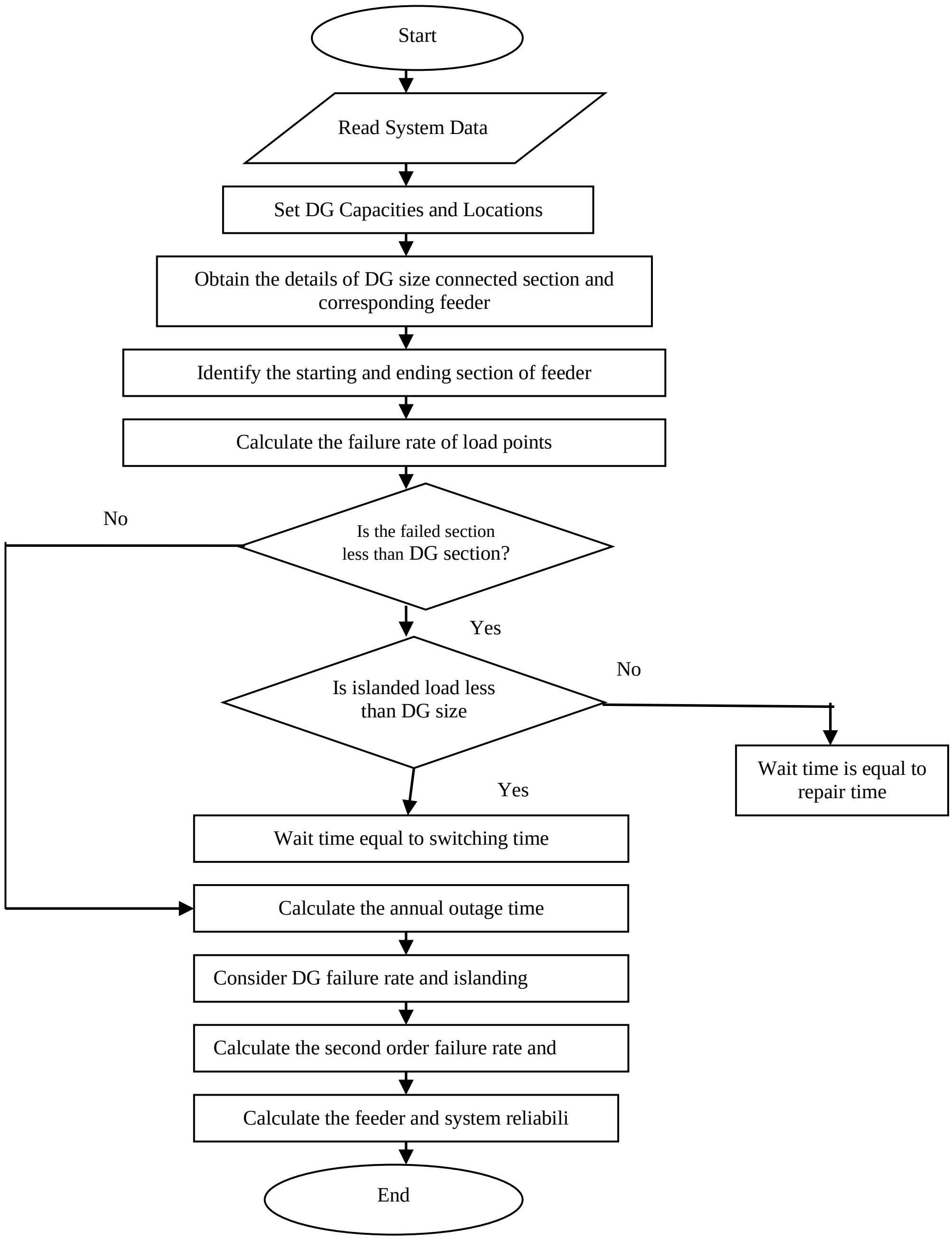

Figure 1. Flow chart for FMEA technique

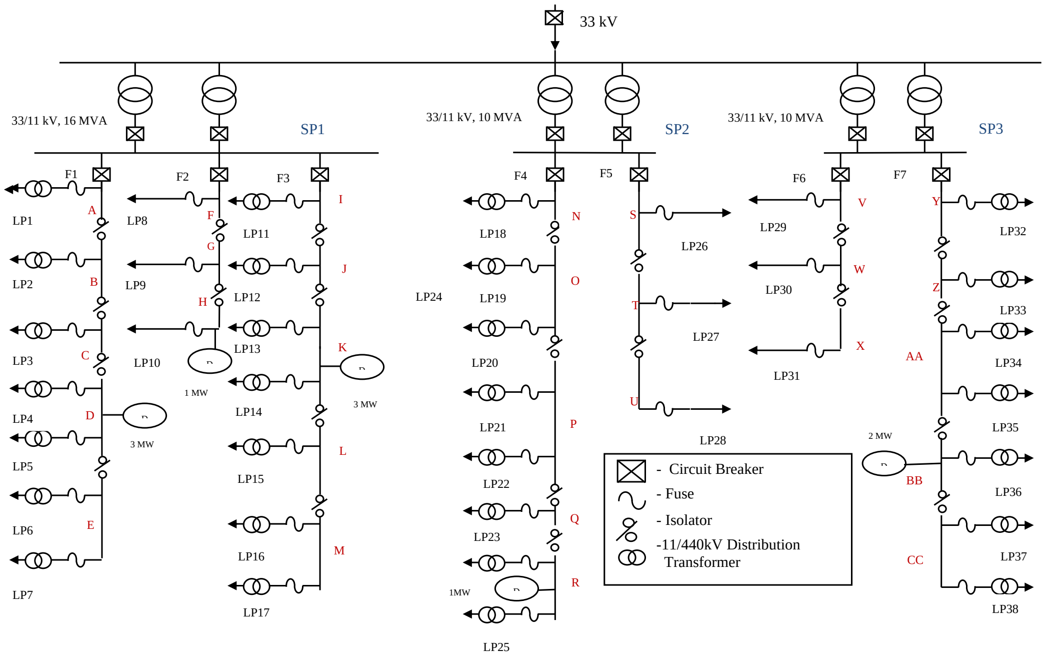

Figure 2. RBTS bus 4 with DG integrated at optimal location

Table 1. Component outage data

S. No.	Component	Failure rate (f/yr)	Repair time (hr)
1	Over headlines	0.065	5
2	11/0.415 kV transformer	0.015	200
3	33 kV bus bar	0.001	2
4	11 kV bus bar	0.001	2
5	33/11 kV transformer	0.015	15

*failures per year (f/yr), hour (hr)

Table 2. Failure data of the lines-RBTS bus 4

S. No	Line number	Failure rate (f/yr)
1	2,6,10,14,17,21,25,28,30,34,38,41,43,46,49,51,55,58,61,64,67	0.039
2	1,4,7,9,12,16,19,22,24,27,29,32,35,37,40,42,45,48,50,53,56,60,63,65	0.049
3	3,5,8,11,13,15,18,20,23,26,31,33,36,39,44,47,52,54,57,59,62,66	0.052

*failures per year (f/yr)

Table 3. Load point data-RBTS bus 4

Load point	Type of customer	Peak load (MW)	Avg. load (MW)	No. of customers	Load point	Type of customer	Peak load (MW)	Avg. load (MW)	No. of customers
LP 1	Residential	0.8869	0.545	220	LP 20	Residential	0.8869	0.545	220
LP 2	Residential	0.8869	0.545	220	LP 21	Residential	0.8869	0.545	220
LP 3	Residential	0.8869	0.545	220	LP 22	Residential	0.8137	0.500	200
LP 4	Residential	0.8869	0.545	220	LP 23	Residential	0.8137	0.500	200
LP 5	Residential	0.8137	0.500	200	LP 24	Commercial	0.6714	0.415	10
LP 6	Commercial	0.6714	0.415	10	LP 25	Commercial	0.6714	0.415	10
LP 7	Commercial	0.6714	0.415	10	LP 26	Small user	1.63	1.00	1
LP 8	Small user	1.63	1.00	1	LP 27	Small user	1.63	1.00	1
LP 9	Small user	2.445	1.50	1	LP 28	Small user	1.63	1.00	1
LP 10	Small user	1.63	1.00	1	LP 29	Small user	1.63	1.00	1
LP 11	Residential	0.8869	0.545	220	LP 30	Small user	1.63	1.00	1
LP 12	Residential	0.8869	0.545	220	LP 31	Small user	2.445	1.50	1
LP 13	Residential	0.8869	0.545	220	LP 32	Residential	0.8869	0.545	220
LP 14	Residential	0.8137	0.500	200	LP 33	Residential	0.8869	0.545	220
LP 15	Residential	0.8137	0.500	200	LP 34	Residential	0.8869	0.545	220
LP 16	Commercial	0.6714	0.415	10	LP 35	Residential	0.8869	0.545	220
LP 17	Commercial	0.6714	0.415	10	LP 36	Residential	0.8137	0.500	200
LP 18	Residential	0.8869	0.545	220	LP 37	Residential	0.8137	0.500	200
LP 19	Residential	0.8869	0.545	220	LP 38	Commercial	0.6714	0.415	10

Using the above data reliability indices are evaluated without DG integration and is considered as base case. The indices for the system are determined using analytical and simulation methods under the specified operating conditions. The following operating conditions are assumed for evaluation, i) 33 kV and 11 kV feeders, laterals are considered as over-head lines, ii) first order permanent faults due to random outages are considered, iii) 3 kV and 11 kV source breakers operate successfully when required, iv) disconnects in the main feeder sections and fuses in the laterals operate with 100% efficiency whenever a fault occurs, iv) the supply is restored to possible load points using appropriate disconnects, v) single weather conditions are considered, vi) failure events are independent event, vii) there is no alternate supply, and viii) the presence of Tie lines is ignored. Maintenance delay time is added to the component repair time.

2.3. DG modeling for reliability evaluation

When DG is integrated, load is collectively met by both utility and DG. In the event of any failure on utility DG alone supplies the load (islanding). In earlier works of reliability evaluation with DG integration, there were breakers to isolate each feeder section independently [22], [23]. When breakers are present in the feeder sections only the faulted section is isolated as the breakers near to the fault will trip. Either utility or DG will be supplying the load points depending on the location of fault. Thus, a particular load point is interrupted if both DG and utility are disconnected. Thus, the modeling equations for evaluating the DG impact on reliability correspond to the parallel systems.

In the system considered, there is only one breaker at the beginning of the feeder and isolators in feeder sections. Isolators are not fault detecting devices and for any fault on the feeder sections feeder breaker near the bus bar trips. For faults on the lateral the fuse blows. Whenever fault occurs on feeder section, both utility and DG gets disconnected. If the faulted section is between utility & DG islanding occurs as shown in Figure 3. Depending on the DG capacity, DG may supply islanded load partially or completely.

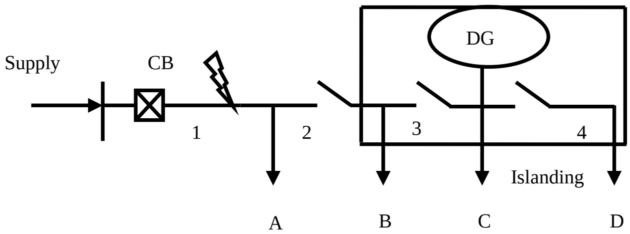

Figure 3. DG supplying islanded load

In Figure 1 if a failure on feeder section 1 occurs CB trips disconnecting the supply. The isolator in the section 2 is opened and DG can supply the load points B, C and D. Thus, integration of DG cannot change the failure rate of the system, but it can affect the outage time of the load points. When islanding occurs, following three conditions are to be considered for the evaluation of system reliability indices.

a. Condition 1: if failure of DG occurs in the event of islanding, load points get disconnected from DG. This creates an overlapping failure for the load points.
b. Condition 2: when DG is supplying the power during islanding condition, if the islanded load is more than capacity then it is assumed that DG cannot supply the loads.
c. Condition 3: depending on the power generated by the DG, DG may supply or may not supply the islanded load. This is considered in terms of islanding probability (IPLP).

Modeling of the conditions 1 and 3 in the evaluation of reliability indices for the system shown in Figure 1 for load point 5 is explained in the following sections

2.4. Determination of load point indices of LP5

Supply is interrupted to load point 5, if there is a failure on 33 kV bus bar, two 33/11 kV transformers, 11 kV bus bar and the sections 1, 4, 7, 10, 8 and the distribution transformer. When a failure on 33 kV bus bar, 33/11 kV transformer, 11 kV bus bar and section 1 and 10 occurs the outage time for the load point 5 is equal to the switching time as these failures can be isolated and load point can be supplied through DG. When a failure on section 7 occurs the load point cannot be connected to either utility or DG section. Thus, the outage time is equal to repair time of the section. In (1), (2), and (3) illustrate the evaluation of the failure rate of the load point, annual outage time and the outage time

$$\lambda_{LP5} = \lambda_{33\,kVbb} + \lambda_{33tran} + \lambda_{11\,kV\,bb} + \lambda_1 + \lambda_4 + \lambda_7 + \lambda_{10} + \lambda_{tr} + \lambda_9 \tag{1}$$

$$U_{LP5} = \lambda_{33\,kVbb} \times s_{33\,kVbb} + \lambda_{33\,tran} \times s_{33\,tran} + \lambda_{11\,kV\,bb} \times s_{11\,kVbb} + \lambda_1 \times s_1 + \lambda_4 \times s_4 + \lambda_7 \times s_7 + \lambda_{10} \times s_{10} + \lambda_{tr} \times r_{tr} + \lambda_9 \times r_9 \quad (2)$$

$$r_{LP5} = \frac{U_{LP5}}{\lambda_{LP5}} \quad (3)$$

During this outage time r_{LP5} of the load (5), if failure of DG occurs, load point cannot be supplied, and this results in overlapping failure. Failure rate, annual outage time and the outage time of the load points are calculated using (4), (5), and (6).

$$\lambda^*_{LP5} = \frac{\lambda_{LP5} \times \lambda_{DG} \times (r_{LP5} + r_{DG})}{1 + \lambda_{LP5} \times r_{LP5} \times \lambda_{DG} \times r_{DG}} \quad (4)$$

$$U^*_{LP5} = \lambda_{LP5} \times \lambda_{DG} \times r_{LP5} \times \frac{(r_{LP5} \times r_{DG})}{(r_{LP5} + r_{DG})} + \lambda_{LP5} \times \lambda_{DG} \times r_{DG} \times \frac{(r_{LP5} \times r_{DG})}{(r_{LP5} + r_{DG})} \quad (5)$$

$$r^*_{LP5} = \frac{U^*_{LP5}}{\lambda^*_{LP5}} \quad (6)$$

There are now two contributions for load point failure, the first being component failures and the second being DG failure overlapping the component failure. There is a set of indices associated with each contribution. Since either contribution will cause the system failure, they are combined using the principles associated with the series system and these are given in (7), (8), and (9).

$$\lambda_{LP5T} = \lambda_{LP5} + \lambda^*_{LP5} \quad (7)$$

$$r_{LP5T} = (\lambda_{LP5} \times r_{LP5} + \lambda^*_{LP5} \times r^*_{LP5}) / \lambda_{LP5T} \quad (8)$$

$$U_{LP5T} = \lambda_{LP5T} \times r_{LP5T} \quad (9)$$

2.5. Islanding probability of DG

Islanding phenomenon (or power islands) is an electrical condition exists in power distribution networks containing distributed generation (DG). When a zone or an area of distribution network supplied by both powergrid and the DG gets isolated from grid supply due to some reason, DG units continue to energize a portion or the entire load present within the isolated section. The power output of conventional generation units can be adjusted to meet the load requirements. The power output from renewable energy sources (solar and wind) is dependent on an unpredictable input (irradiance and wind speed). The load in the islanded area may be less than the DG rated capacity but the capability of DG supplying the power depends on ability of DG to produce the required output. If the power output from DG can meet the load, the wait time for the load points is switching time else wait time is repair time. This nature of DG is modeled in terms of IPLP [24] and the ability of the system to produce the required output.

In this work the effect of irradiance is considered for evaluating the IPLP. The values of Monthly averaged daily solar insolation data are available from the MNRE website [25], [26] for Indian locations. Taking these solar irradiance values and assuming conversion efficiency as 10% [27], [28]. The energy output of a solar cell for a year is calculated using (10).

$$Solar\ Energy\ Output = Solar\ array\ area(m^2) \times Conversion\ Efficiency \times Solar\ irradiation(/m^2) \quad (10)$$

Mean and variance of these values are obtained and fitted in a normal probability distribution curve to determine the probability of delivering the average output. This value is taken as the IPLP of DG and is obtained as 0.54. The failure rate and the corresponding associated outage time are calculated applying conditional probability. If DG can supply the load, failure rate is taken as in (7) otherwise taken as given in (1).

$$\lambda_{LP5N} = IPLP \times \lambda_{LP5T} + (1 - IPLP) \times \lambda_{LP5T} \quad (11)$$

$$r_{LP5N} = IPLP \times r_{LP5T} + (1 - IPLP) \times r_{LP5T} \quad (12)$$

where λ_{LP5N} and r_{LP5N} are the new failure rate and new outage time of load point considering the IPLP of DG.

3. RESULTS AND DISCUSSION

RBTS bus 4 with optimal DGs connected in the feeders is shown in Figure 2. The optimal location and size of the DGs that can be connected in the system satisfying the voltage profile, protection coordination and yielding minimum losses, obtained as explained in [29] are considered for reliability evaluation. The optimal DG size obtained for feeder 5 and feeder 6 is 0.5 MW and 0.25 MW respectively. This DG size cannot meet any single load point load in the event of islanding. Thus, the presence of DG is ignored in these feeders. The load point indices and the system indices [30] are evaluated for RBTS bus 4 using FMEA technique. The results of system indices are tabulated in Table 4.

Monte Carlo simulation is applied to evaluate the load point and reliability indices of the RBTS bus 4 and the feeder and system indices are given in Table 5. The variation of the system indices SAIDI, average service unavailability index (ASUI) and EENS with number of trials in are shown in Figures 4-6 respectively. Comparison of the results obtained using FMEA technique and MCS are presented in Table 6.

Table 4. Reliability indices with optimum DG at the optimal location using FMEA–RBTS bus 4

Feeder/system	SAIFI (int./cust.yr)	SAIDI (hr/cust.yr)	CAIDI (hr/cust.Int.)	ASUI ($\times 10^{-4}$)	EENS (MWh/yr)	AENS (kWh/cust.yr)
Feeder 1	0.3030	4.0598	13.3970	4.6345	14.4184	13.1
Feeder 2	0.1916	0.8519	4.4466	0.9725	3.0317	1010.6
Feeder 3	0.2953	3.9338	13.2228	4.4907	13.8736	12.8
Feeder 4	0.3095	4.1863	13.5241	4.7788	16.5308	12.7
Feeder 5	0.1883	0.8294	4.4037	0.9467	2.4881	829.3
Feeder 6	0.1970	0.9192	4.6658	1.0493	3.3115	1103.8
Feeder 7	0.2987	4.1871	14.0186	4.7797	15.1348	11.7
System	0.3017	4.0941	13.5715	4.6736	68.7890	14.3

*customer average interruption duration index (CAIDI), hour (hr)

Table 5. Reliability indices with optimal DG size and location using MCS-RBTS bus 4

Feeder/system	SAIFI (int./cust.yr)	SAIDI (hr/cust.yr)	CAIDI (hr/cust.Int.)	ASUI ($\times 10^{-4}$)	EENS (MWh/yr)	AENS (kWh/cust.yr)
Feeder 1	0.3039	3.6874	12.1342	4.2093	13.8681	12.6
Feeder 2	0.1841	0.8976	4.8753	1.0247	3.1518	1050.6
Feeder 3	0.2958	3.9939	13.5003	4.5593	14.1952	13.1
Feeder 4	0.3014	4.0485	13.4334	4.6216	16.4407	12.6
Feeder 5	0.1832	0.8751	4.7761	0.9896	2.6253	875.1
Feeder 6	0.1915	0.8889	4.6416	1.0148	3.2073	1069.1
Feeder 7	0.2968	4.2892	14.4527	4.8963	15.6339	12.1
System	0.2992	4.0121	13.407	4.5800	69.1223	14.5

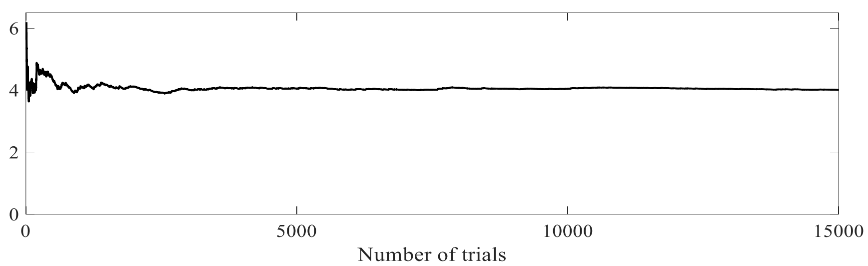

Figure 4. Variation of SAIDI with number of trials-RBTS bus 4

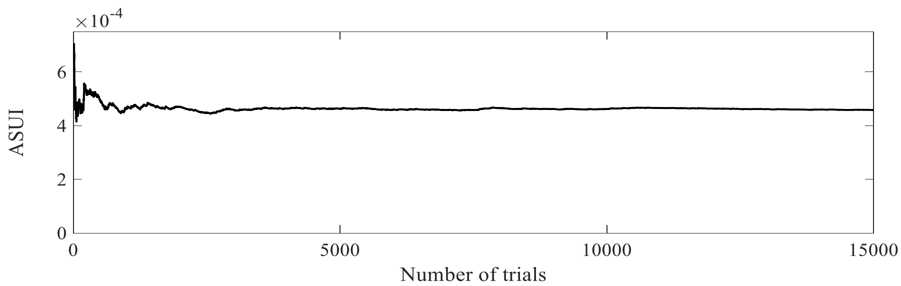

Figure 5. Variation of ASUI with number of trials-RBTS bus 4

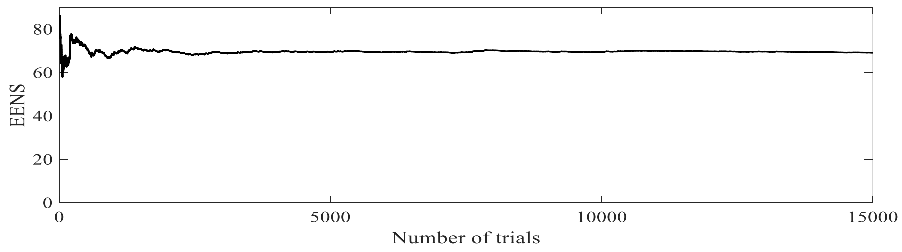

Figure 6. Variation of EENS with number of trials-RBTS bus 4

Table 6. Reliability indices analytical vs simulation-RBTS bus 4

Index	Analytical	Simulation	Difference (%)
SAIFI	0.3017	0.2992	0.83
SAIDI	4.0941	4.0121	2.00
EENS	68.7890	69.1223	0.48

3.1. Reliability evaluation with and without DG

DG improves the reliability of the system by providing alternate means of supply. The system configuration considered in this paper has only one breaker at the start of the feeder and isolators in the rest of the feeder. As the isolators are not fault detecting devices, feeder breaker will trip. When the system is integrated with DG, DG also contributes to fault thus DG cannot supply the islanded load till the fault is cleared. DG when considered as a substation it can take the total islanded load and the outage time for all the feeder sections except for the failed section will be switching time. In this work the capacity of the DG is taken into consideration for the reliability evaluation and the islanded load is compared with the DG capacity. When renewable energy-based DG technologies are integrated the output of the DG depends on the availability of the resources (like wind and solar) and this is taken care of in terms of IPLP. During islanding condition if the DG fails then the load cannot be supplied and this overlapping failure is considered for reliability evaluation. Thus, the improvement in the reliability of the system will not be same as the improvement in the reliability of the system when DG is considered as substation. Table 7 shows the improvement in the SAIDI and the improvement in the EENS for RBTS bus 4 obtained through analytical method when DG is integrated in the system. The improvement in the EENS index is shown Figure 7.

Table 7. Variation of SAIDI and EENS with and without DG–RBTS bus 4

Feeder/system	SAIDI without DG	SAIDI with DG	Improvement (%)	EENS without DG	EENS with DG	Improvement (%)
Feeder 1	4.2650	4.0598	4.81	15.3012	13.6679	4.81
Feeder 2	0.9208	0.8519	7.48	3.2376	2.5096	7.48
Feeder 3	4.1800	3.9338	5.77	14.8085	13.4194	5.77
Feeder 4	4.2301	4.1863	1.03	17.3216	16.3192	1.03
Feeder 7	4.2454	4.1871	1.37	15.3974	14.0639	1.37
System	4.2247	4.0941	3.09	72.0516	65.9652	3.09

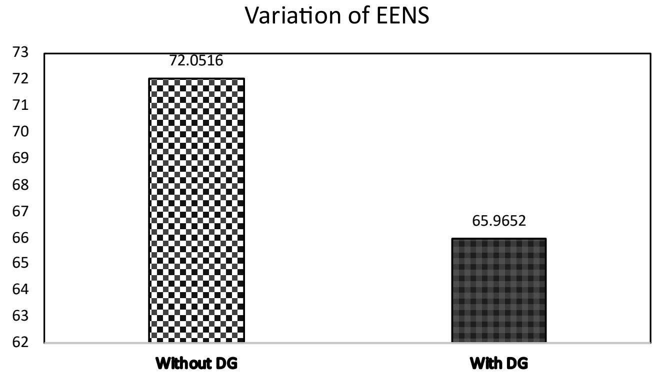

Figure 7. EENS index with and without DG-RBTS bus 4

4. CONCLUSION

The effect of integrating DG on the reliability indices of RBTS bus 4 is evaluated using FMEA technique and the results are validated using Monte Carlo simulation technique. Effect of DG failure rate is taken as the overlapping failure on component failure in evaluation of indices. The capability of DG to supply the islanded load is considered and modeled as IPLP. All possible practical operating conditions of DG are considered in the reliability indices evaluation. Reliability evaluation using Monte Carlo simulation technique considers the random behaviour of the failure of the components. Results obtained in this study provide a base for quanitifying the reliability improvement in distribution system planning studies.

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