Reliability Assessment of Radial Distribution Systems with Distributed Generation

Imran Mohmmed[#1], Ch.Bharghav[*2].

[1] *M. Tech Student, Electrical and Electronics Engineering, SNIST, Hyderabad, India*[1]

mohmmedimran.eee@gmail.com

*[2]*Associate Professor, Dept. of Electrical and Electronics Engineering, SNIST, Hyderabad, India*[2]

bhargav_3417@yahoo.com

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. 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 impact of adding one DG to each feeder of the system, as well as the impact of placing DG at various distance plus the amount of DG installed are presented.**

This paper also explains the importance of understanding of power system reliability from an investment view for distribution companies in order to enhance the DG installation to costumers.

Keywords— **Reliability, Distributed Generations, Optimal placement, Cost/worth indices**

1. INTRODUCTION

The Reliability concepts can be applied to virtually any engineering systems. In its broadest sense, reliability is a measure of performance of the given system. This measure can be used to help systems meet performance criteria, to help quantify comparisons between various options, and to help make economic decisions. [1].

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 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, photovoltaic, 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. The results showed that SAIDI, SAIFI, CAIDI and ASAI were the most used indices. This paper also discussed outage factors and their roles in reliability calculation.

The location for DG placements is of key importance. Ref [8] describes the effects of DG on system reliability on an RBTS Distribution system. The analysis showed that reliability indices were highly sensitive to location. In [5], it describes the DG impacts on reliability, and showed that reliability indices could be improved by properly allocating DG.

In this paper, a technique based on [9] is used to calculate reliability indices (SAIDI, CAIDI and ENS). A RBTS residential distribution network is used as a case study. Reliability indices when a DG is installed as a backup generator are quantified. Different DG penetration levels, locations and the impacts of installing a large-scale DG vs. several small-scale randomly distributed DGs are explored.

A number of system indices such as SAIFI, SAIDI, CAIDI and AENS are computed for a real radial distribution system .A sensitivity analysis is performed to examine the impact of DG units, their location, and their number, on reliability indices. Finally the business plan is derived for distribution system.

II. RELIABILITY ASSESSMENT OF DISTRIBUTION SYSTEM

Reliability assessment has become important for utility planners in recent years. Improved service reliability might be motivated by government regulation or by market competition, but providing superior service at an attractive price is in the interest of both utilities and customers.

A. *Definitions*

Zone A circuit downstream of a protective device (breaker, recloser or fuse).For instance Zone Z1, Z2 & Z3in **Figure 1.**

Sub-Zone A circuit within a Zone, and downstream of a sectionalizing device (switch or sectionalizer).For instance Zone Z1 contains 4 sub-zonesZ1.0, Z1.1, Z1.2, and Z1.3 in **Figure 1**.

Restoration Time The time required to restore service to a load after the zone protective device opens to clear a permanent fault. The restoration time for loads at the fault location is the time required to repair/replace the faulted component. However, appropriate switching action might restore other loads faster by first isolating the fault and then re-connecting the loads to the original (or to an alternate) source. The restoration time for loads not actually located at the fault is smaller than that required to make repairs (r) or to manoeuvre the switching devices (t).

B .Example:

Figure 1 shows a radial distribution system with 3 zones.

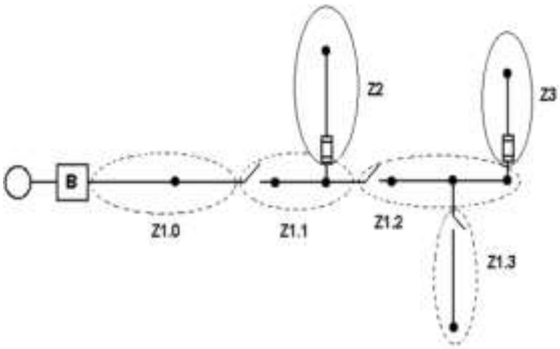

Figure 1: A radial distribution system

C. Reliability Indices Computation:

Customer oriented indices are the interruption frequency and the outage duration experienced at a load point. These indices are referred to as load-point indices and are computed for each “sub-zone” in the feeder. All customers’ loads within a sub-zone experience the “same” interruption frequency and outage duration.

Since interruption frequency and outage duration are known at every load point on the feeder, system indices such as SAIFI, SAIDI, CAIDI and AENS are obtained.

III MODELLING AND EVALUATION TECHNIQUE

The following algorithm is for assessing restoration time of sub-zones when distribution system contains DG units.

First, all sub-zones in the network should be determined. Once a fault occurs in one of the sections of a sub-zone, it causes main breaker of the substation to be automatically opened.

<u>*The following steps must be performed:*</u>

1) Find location of the fault.

2) Isolate the faulted sub-zone.

I. First of all, open the switch that is relating to the faulted sub-zone (upstream of the fault).

II. Open switches corresponding to adjacent sub-zones of the faulted sub-zone (downstream of the fault).

3) Close the main breaker.

4) Develop several islands by opening some switches of sub-zones and then utilize available DG units for restoring these islands.

The restoration time of these islands is equal to switching time plus time for starting DG units if they are available, else the restoration time is equal to the repair time of the faulted section.

The restoration time for some sub-zones that are downstream of the faulted sub-zone and are not in the island with DG units is equal to repair time of the faulted section.

Consequently, after isolating the fault five groups of sub-zones can be categorized as sorted below

a) Faulted sub-zone, its restoration time is equal to the repair time of the section.

b) Upstream sub-zone that can be restored through the main supply.

c) Downstream sub-zone without DG that cannot be restored until the repair time of the section.

d) Downstream sub-zone with available DG units that can be restored by starting DG units.

e) Downstream sub-zone with unavailable DG units thus the restoration time is equal to repair time of the section.

For assessing restoration time of downstream sub-zone after isolation of the fault the uncertainty associated with the availability of DG units must be considered. Therefore, a capacity outage probability table (COPT) for all DG units should be formed in each location. It is a simple array of capacity levels and the associated probabilities of existence. If all DG units in each location are identical, the capacity outage probability table can be easily obtained using **binomial distribution.** If not, the COPT can be created by recursive technique in which units are added sequentially to create the final model. For each level of capacity, operator should decide which switches must be opened to produce an island and restore healthy sub-zones. The decision is based on the fact that for each level, available capacity should be greater than all load points in the island. Now the restoration time of each sub-zone can be assessed for each contingency (short circuit fault) by weighting the restoration time with the probability of existence of that level and sum these weighted terms **[8].**

For each sub-zone, all the contingencies should be considered. For instance, when a fault occurs in section A, The main breaker is opened. Once the location of the fault is determined, the fault should be isolated and then switchS1 will be opened and thereupon the main breaker is closed. Now, a COPT for DG units should be developed. It is shown in Table I. Availability and unavailability of each unit are assumed to be A and U=1-A respectively.

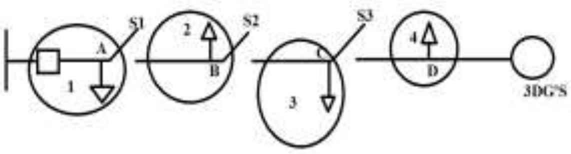

Figure 2: A radial distribution network

TABLE 1
COPT ONCE A FAULT OCCURS IN SECTION A

Capacity in	**Probability**	**Switches should be opened**	**Time**	**Restored sub-zones by DG**
3XC	A^3	**-**	T_{ST}	**2,3,4**
2XC	$3A^2U$	**S2**	$T_{ST}+SWT$	**3,4**
1XC	$3AU^2$	**S2,S3**	$T_{ST}+SWT$	**4**
0XC	U^3		**-(DG OFF)**	**-**

For illustration purpose the restoration time for each sub-zone due to contingency B (fault in section B) is calculated using conditional probability method. Subzone1will be restored through the main supply.

$$T_{res\_subzone1} = FLT + SWT$$

$$T_{res_{sub\_zone2}} = FLT + SWT + T_{rp}$$

$$T_{res\_subzone3} = FLT + SWT + A^3 T_{st} + (1 - A^3) T_{rp}$$

$$T_{res\_subzone4} = FLT + SWT + A^3 T_{st} + (3A^2U + 3AU^2)(T_{st} + swt) + (1 - A^3) T_{rp}$$

$$T_{res\_subzone5} = FLT + SWT + A^3 T_{st} + (3A^2U)(T_{st} + swt) + (3AU^2 + U^3) T_{rp}$$

T_{rp} = repair time

T_{st} = statrt time of DG unit

T_{res} = restoration time

FLT = fault location time

SWT = switching time

IV.STUDY RESULTS

The application of the proposed technique to a multi load point distribution system is clarified using the distribution system shown in **Figure 3**. The test system is a Roy Billinton test system of bus-2 feeder-1.The network has 7 load points and 652 customers.

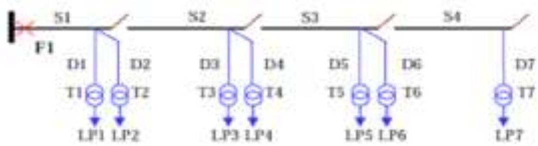

Figure 3: Test feeder

Data of the RBTS

The reliability parameters are as follows

1. Average failure rate for each section and distributor = 0.065 failures/yr-km
2. Average repair time for each section and distributor = 5 hours
3. Average failure rate for a transformer = 0.015 failures/year
4. Average replacement time for a transformer= 10 hours
5. Average switching time = 30 mins and Starting time of a DG Unit is assumed to be 30mins.

The circuit breakers and fuses are assumed to be 100% reliable.

In this network there are five locations for possible installation of DG units that is shown in **Figure 3** (these points are defined by the utility considering various factors). The purpose is to determine the best location and optimum number of DG units in order to maintain the predefined reliability level. The capacity of each DG unit is assumed to be 1000 KVA.

TABLE 2

TEST FEEDER DATA

Section Number	Length (Km)	Load Point Number	Average load (KVA)	Number customers
1	1.35	1	535	210
1	1.55	2	535	210
2	2.30	3	535	210
2	2.10	4	566	1
3	3.05	5	566	1
3	3.00	6	750	10
4	3.65	7	750	10

An analytical calculations are computed in order to obtain failure rate(λ), restoration time(r), and annual outage time(u) for each load point then calculated system indices such as SAIFI, SAIDI, CAIDI and AENS. Three different case studies are considered. For each case it is assumed that 0, 1, 2 or 3DG units can be established in each location and then system indices are calculated.

Because DG units are assumed as standby units they only affect on outage time and doesn't affect on interruption frequency, hence SAIFI will be constant in each case and is equal to0.247993 int/customer-yr.

A.CASE1

The effect of location of DG units on system indices are investigated in this case. The results are shown in **Table 3 to 5.**

These Figures show the system reliability indices (SAIDI, CAIDI, and AENS) of the test system for the comparative studies. In these Figures, each column pattern is associated with a special mode (No DG, 1 DG unit, 2 DG units and 3 DG units).Results show that indices such as CAIDI, SAIDI and AENS are strongly sensitive to the location of DG units consequently the location of DG units in a distribution system is very important and the best location for the certain number of DG units can be chosen from the results.

TABLE 3: DISTANCE VS SAIDI

S.No	Location	Base Case	1DG	2DG	3DG
1	0	1.236308	1.236308	1.236308	1.236308
2	0	1.236308	1.236308	1.236308	1.23631
3	0.75	1.236308	1.110694	0.98179	0.88459
4	1.5	1.236308	1.047588	0.87149	0.770999
5	2.25	1.236308	1.08509	0.89398	0.770999
6	2.85	1.236308	1.08203	0.89358	0.768367

TABLE 4: DISTANCE VS. CAIDI

S.No	Location	Base Case	1DG	2DG	3DG
1	0	4.98525	4.98525	4.98525	4.98525
2	0	4.98525	4.98525	4.98525	4.98525
3	0.75	4.98525	4.47873	3.958943	3.566993
4	1.5	4.98525	4.224263	3.514171	3.108954
5	2.25	4.98525	4.375496	3.604862	3.108954
6	2.85	4.98525	4.365644	3.604413	3.09773

TABLE .5: DISTANCE VS. ENS

S.No	Location	Base Case	1DG	2DG	3DG
1	0	18.171	18.17	18.1712	18.1712
2	0	18.171	18.1712	18.1712	18.1712
3	0.75	18.171	16.3249	14.4303	13.0016
4	1.5	18.171	15.3974	12.8091	11.3321
5	2.25	18.171	15.9486	13.1397	11.3321
6	2.85	18.171	15.9127	13.1380	11.2912

The effect of location of DG units on system indices are investigated in this case. The results are shown in **Figure 4 to 6.**

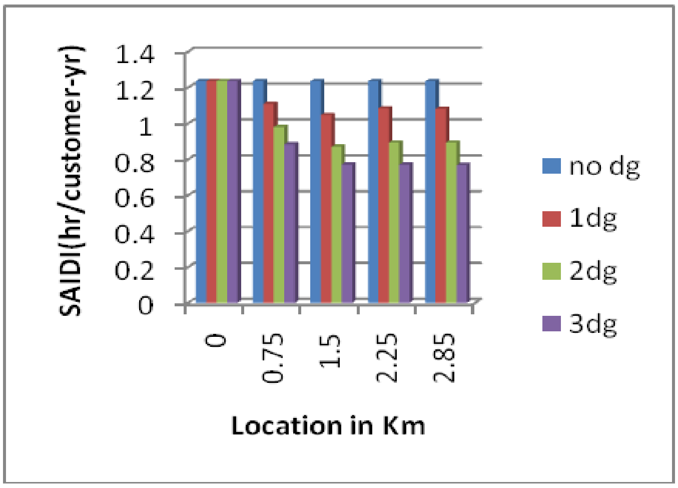

Figure 4: SAIDI by placing DG's at Various Locations

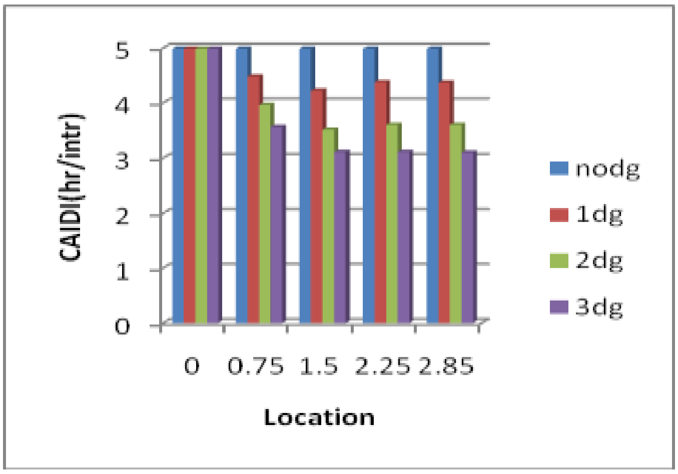

Figure 5: CAIDI by placing DG's at Various Locations

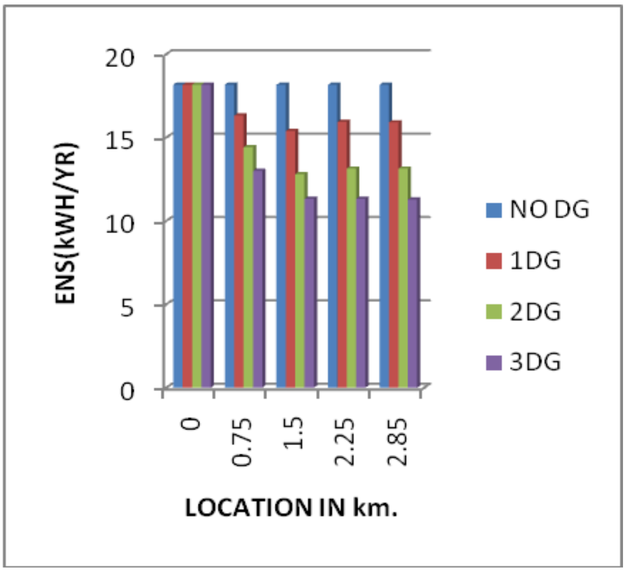

Figure 6: Energy not supplied by placing DG's at Various Locations

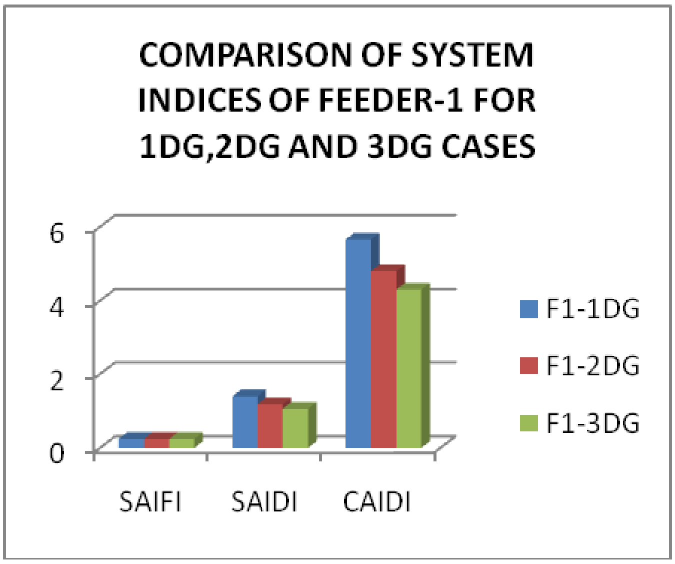

Figure 7: comparisons of system indices for Reliability vs. Number of DG units in feeder-1

B.CASE 2

The effect of number of DG units at the end of the feeder on system indices and cost-worth indices are investigated in this case. The optimum number of DG units can be found for each location by considering financial factors and suitable level of indices [6].

In this case the effect of DG units in each location studied for overall system of RBTS BUS-2, first we studied the overall system by placing 1DG at the end of the feeder then 1more additional DG is added to the system. Finally the system studied using 3DG's at the end of the feeder. The results are shown in the **Tables 6** and **Figure 7.**

TABLE 6

SYSTEM INDICES FOR RELIABILITY vs. NUMBER OF DG UNITS IN FEEDER-1

	SAIDI (hr/yr)	SAIDI(hr/yr)	CAIDI(hr/intr)
1DG	0.247993	1.402354	5.654809
2DG	0.247993	1.187653	4.789055
3DG	0.247993	1.067387	4.304098

C.CASE-3(Reliability vs. Distance)

This case study proposes is to quantify the value of adding DG at different points of the radial distribution systems, **Figure 8** shows main feeder1, with five suggested locations for placing DG. DG location at the supply point (A); 0.75 kilometres from SP (B); 1.5 kilometres from SP (C); 2.25 kilometres from SP (D) and 2.85 kilometres from SP (E).

For each case the system reliability indices SAIFI, CAIDI, SAIDI, ENNS and ECOST are calculated and compared with base case (BC) scenario, shown in **Table 7.**

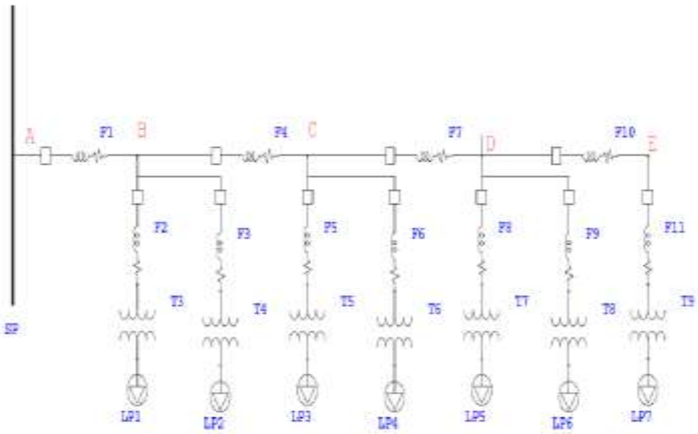

Figure 8: Main feeder1

TABLE 7

SYSTEM INDICES FOR DG AT DIFFERENT DISTANCE FROM SP

	DG SCENARIO					
	BC	A	B	C	D	E
Distance		0	0.75	1.5	2.25	2.85
SAIFI	0.2479	0.2263	0.2430	0.2431	0.2440	0.2440
SAIDI	1.2363	1.1351	1.0991	1.0423	1.0807	1.0781
CAIDI	4.9852	5.0144	4.5223	4.2875	4.4274	4.4184
ECOST	**11.073**	**10.797**	**10.247**	**9.9419**	**9.9664**	**9.3136**
EENS	3.9136	3.7358	3.5185	3.4525	3.4582	3.2473
IEAR	2.8293	2.8903	2.9125	2.8795	2.8819	2.8680

It can be seen from **Table 7** that the DG unit installed at the beginning of the feeder barely improve the reliability indices, this is because the circuit will not be mitigated as the DG unit just acts as an additional source to the supply bus as the power grid. However, the DG would be used when there is failure of the grid that is why reliability indices are slightly better.

There are clearly significant improvements when the DG is placed at any other point distant from the supply point. SAIFI and SAIDI are reduced while DG is further from SP. On the other hand CAIDI tends to be slightly higher when distance from SP increases.

ECOST index presents the cost due to outages, for this project used as reference to choose the best scenario. Table 8.6 shows that lower ECOST is at location E, **Figure 9** present another point of view of ECOST index, it can be seen the difference of ECOST between the base case and each location, this result as the annual worth of placing a DG unit at the different locations. IEAR values and the annual worth increase when the DG is placed close to load point 6 and 7 which have a higher IEAR, because the probability of failure at these points is highly reduced when DG is close to them.

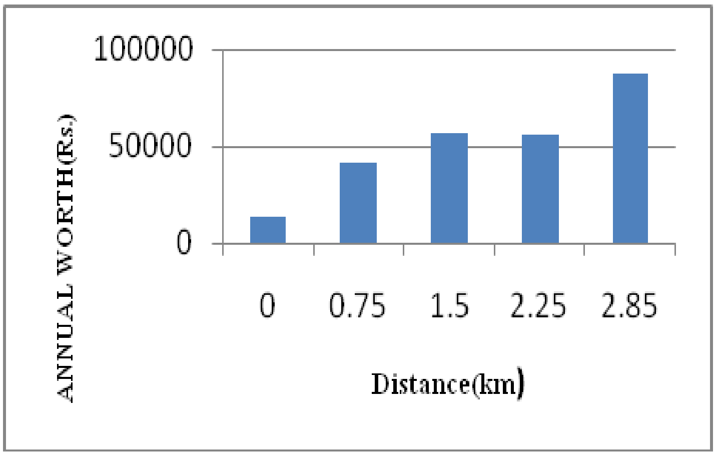

Figure 9: Annual worth vs. Distance

D.CASE-4(Reliability while increasing dg units)

This case study proposes to evaluate the value of placing more than a DG at on e location. Five locations and up to three DG units are considered, so 15 reliability analysis are performed. It is concluded that increasing the number of DG at the same locations does not have a positive effect to the system reliability. F or the test system of this project locating more than one DG at some point have an inverted effect on reliability, the protections needed to isolate the faults have also a failure rate. Placing more than one unit at one location is equivalent of having DG in parallel, then if any of the protections that isolate each DG fail would make the rest fail to, because all are connected to the same busbar.

Figure 10 shows the ECOST while increasing number of DG's in each location. It is concluded that increasing the number of DG at the same locations does not have a positive effect to the system reliability. For the test system of this project locating more than one DG at some point have an inverted effect on reliability, the protections needed to isolate the faults have also a failure rate. Placing more than one unit at one location is equivalent of having DG in parallel, then if any of the protections that isolate each DG fail would make the rest fail to, because all are connected to the same busbar.

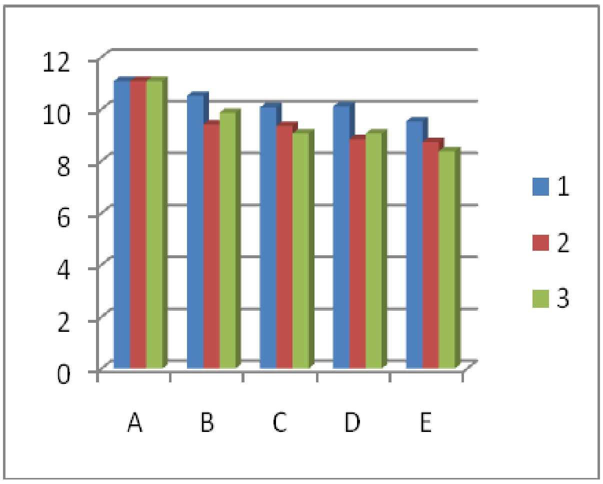

Figure 10: ECOST index for each location and DG

E.CASE-5(Reliability worth Assessment):

From the all previous studies it is concluded that the best location to place a DG is E. Moreover, even that is not profitable to used more DG at the same location, other location should be studied and see if there is still change to increase the reliability and how profitable would it be.

1. Distributed generation cost:

The distributed generation units used for the study case are a diesel generation of 500kW rated power. The diesel generator chosen is the "150 kW Kirloskar BLISS Diesel Generator" [3] the total cost is Rs.7, 10, 000 including installation cost. In addition, there are others costs associated with operation and maintenance; these are considered per KWh, however, fuel cost is not consider the cost because it is assumed to be the same the cost that the energy that is not being delivered by the power grid would have, while the diesel generator is on. Non-fuel O&M costs for diesel generation are considered $0.04 kWh [8]. i.e. (=50*0.04) Rs.2KWh.

Distributed generation optimal placing:

This section focuses on value the best positions to place for more than one DG. Previously, it have been concluded that more than one DG is not reliable if it is at the same place of an existing one. However, trying other location may still increase the system reliability.

The path to achieve this is to start with the first DG at E, and see improvements of placing an extra DG at any of the 4 points, if there is a increase in reliability worth another unit will be suggested to be placed at any other of the 3 locations left. It will be continued until all 5 locations are with DG or the reliability of the systems stops increasing. It is not considered again a location that has already a DG, because as seen at CASE-4 does not increase reliability.

Figure 11 presents a summary of the path of the study performed, each box is one scenario where inside has the location of the DG and the ECOST index. It starts from the base case, where ECOST is 553650Rs/year i.e. (11073$/year) and is followed by all the possible options of placing a DG. Firstly, all locations are available, where as discussed before the best is E where there is a revenue of 87800Rs/year i.e.1756$/year which makes ECOST be 465850Rs/year i.e. (9317$/year). While placing a second DG, it is seen that there is now much difference between where is placed. In addition is shown at load point indices **Appendix B** and at **Figure 11**, that there is no much revenue while placing a second DG, the best location is C with an increase of Rs.46950 i.e. (939$). Finally, there is not benefit when placing a third DG. Therefore there are 3 scenarios to compare.

Figure 11: ECOST ($/year) diagram of the different steps while placing DG

Figure 12 presents the EENS values for following the same structure as **Figure 11**, EENS data is important in order to calculate the cost of DG. It is considered that the reduction of EENS shown on top of the diagram arrows is entirely supplied by the DG.

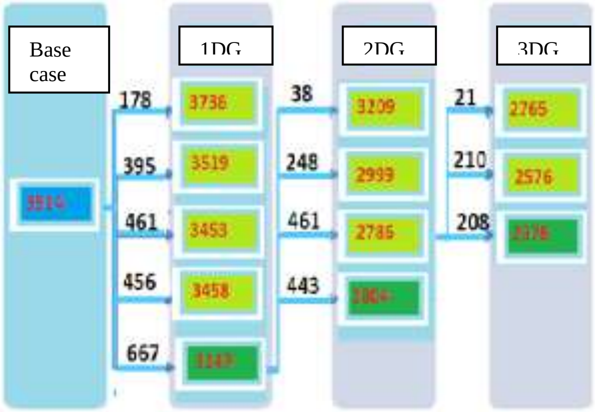

Figure 12: EENS (KWh/year) diagram of the different steps while placing DG

F.CASE-6(Business Plan):

This section discusses the profitability of the placing DG taking into account the costs discussed on **CASE-5.** The annual interest rate is taken to be a 5%.

1. ***First distributed generation at E:***

Table 7 presents the profitability indices when first distributed generation is placed at location E.

TABLE 8
PROFITABILITY INDICES AND PAY BACK FOR FIRST DG

Capital Cost	Rs.7,10,000/-
O&M cost per year	Rs.1334/-
Reliability revenue per year	Rs.87,800/-
Payback	9years
Internal rate of return	11.08%

2. ***Second distributed generation at D:***

This section studies the profitability indices when a second distributed generation is placed at location D. **Table 8** shows the extra profitability of adding this second DG in taking as base case the first DG. The reliability revenue is very low to make this scenario profitable.

TABLE 9
PROFITABILITY INDICES AND PAY BACK FOR SECOND DG

Capital Cost	Rs.7,10,000/-
O&M cost per year	Rs.922/-
Reliability revenue per year	Rs.46,950/-
Payback	N/A
Internal rate of return	N/A

However looking the overall and taking into account both units at a time, it is seen that the payback is at 16 years and the internal rate of return is just 0.57 point above our interest rate which make this scenario very risky. A profit, which comes from the first unit. Therefore the best assessment for our test system is to place a DG at location E.

TABLE 10
OVERALL PROFITABILITY INDICES AND PAY BACK

Capital Cost	Rs.14,20,000/-
O&M cost per year	Rs.2256/-
Reliability revenue per year	Rs.1,34,750/-
Payback	16years
Internal rate of return	5.57%

V. CONCLUSION

This paper proposed an analytical approach to study the DG impacts on distribution system reliability indices. The method assumes DG units as backup generation and considers availability and unavailability of DG units. The method is then applied to a RBTS BUS-2 and system indices such as SAIFI, SAIDI, CAIDI and AENS has been computed for 3 cases with the developed computer program. The results show when DG units are applied as standby units, only affect on outage duration and don't affect on interruption frequency so SAIFI will be constant. In addition, the results show that indices are too sensitive to location, number and availability of DG units. Hence, the optimum number of DG units for the best location in distribution system can be obtained using the proposed method and also obtained best location for placement of DG. Finally derived Business plan for installing DG's on the Test feeder.

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