Reliability Analysis of A Radial Distributed Generation Distribution System

Peyman Mazidi ,G.N. Sreenivas
Department of EEE, College of Engineering, JNTUH, Hyderabad, India

Abstract— **Distributed Generation (DG) plays an important role in current power systems with high demand growth. DG provides an alternative to the traditional electricity sources like oil, gas, coal, water, etc. and can also be used to enhance the current electrical system. DG distribution is likely to improve the reliability of a power distribution system by at least partially minimizing unplanned power interruptions to customers due to loss of utility generators or due to faults in transmission and distribution lines/equipments. In this paper, a typical distribution system is considered and to show the reliability enhancement of the system, different components (fuses, disconnects, DGs) are step by step taken into account and added to the system in five cases. Analytical methodology is used for the analysis. The results demonstrate that DG does improve the reliability of the distribution system.**

Keywords—Distributed Generation; Reliability assessment; Distribution System; Reliability Indices

I. INTRODUCTION

Reliability is an abstract term meaning durability, steadiness, and good performance. For engineering systems, however, it is more than an abstract term; it is something that can be computed, measured, evaluated, planned, and designed into a piece of equipment or a system. Reliability means the capability of a system to accomplish the function it is designed for under the operating conditions stumbled upon during its anticipated lifetime. Traditionally, a power system has been divided into three almost independent areas of operation as follows: 1.Generation System: facilities for the electricity generation from economical energy sources. 2.Transmission System: transportation system to move bulk energy from generation section to specific geographical regions. 3.Distribution System: distribute the energy to individual consumers (e.g., residential, commercial, industrial, etc.) within a specific geographical area. Ideally, reliability of a power system from consumer's viewpoint means uninterrupted supply of power from the generation to the consumer. In action, the important elements of a power system's reliability for consumers are frequency and duration of interruptions at consumption point (i.e., load point). From an engineering point of view, the question is how you mathematically determine the frequency and length of load point interruptions.

To fulfill the growing customer load requirements, electric utilities were constantly adding more facilities to their systems in the past. As load increases, the distribution system must be extended to please increasing customer load requirements. For instance, due to the increased load growth in a particular area in a distribution system, the local area distribution network is considered insufficient and requires extension.

At present, deregulation is obliging electric utilities into unexplored areas. Failure to distinguish customer demands has caused many business failures industries. The electric industries' drive in the direction of a competitive market makes all associated businesses to evaluate their focus, strengths, weaknesses, and strategies. One of the main encounters for electric utilities is to increase the price of their services and reliability and to lower their costs of operation, maintenance, and construction in order to provide customers with lower electricity rates. For power systems delivering power to different kinds of customers, there is an optimal value of reliability that would result in lowest costs.

II. DG AND ITS IMPACTS ON DISTRIBUTION SYSTEM AND RELIABILITY

Electric utility companies are looking for methods to decrease costs and still provide the satisfactory level of reliability essential for the customers. One solution is to add DG that can now be built. DG are small generators usually ranging in capacity from 15 to 10,000kW connected to the electric distribution system. DG can be installed at the utility or at the customer site. DG technologies include conventional and nonconventional energy solutions such as diesel engine driven generators, wind turbines, fuel cells, and micro turbines.

Smaller-sized generators continue to improve in cost and efficiency, moving closer to the performance of large power plants. Utilities or end users can install flexible distributed generation quickly. This local generation lessens the need for large-scale utility projects. Distributed generation can allow utilities to defer transmission and distribution upgrades. Also, DG decreases losses and improves voltage. With the right configuration, distributed generation can also improve customer reliability and power quality.

Generation is not always easy to integrate into existing distribution systems. Distribution systems were not designed to include generation; they were designed for one-way power flow, from the utility substation to the end users. Generators can disorder distribution operations if they are not carefully applied. One of the most critical situations islanding. Islanding raises safety hazards, and islanded generators can cause over voltages on the circuit. In addition to islanding, generators can interrupt protection, upset voltage regulation, and cause other power quality problems.

The utility supply has the benefit of tethering thousands of generators together, providing reliability and matching load. Microgrids tie generators together on a localized scale to gain reliability and load matching advantages of the traditional utility grid. Several research literature have summarized positive and negative impacts of DGs on power system operation, stability and security as listed in Table1 below:

Table1 IMPACTS OF DG ON POWER SYSTEM OPERATION

Negative Impacts	**Positive Impacts**
Increase in short circuit current	Voltage and reactive power support
Drop of sensitivity to faults	Voltage control
Voltage rise and fluctuations	Reduction of losses and transmission blocking
Changes in losses and voltage profile	Generation growth and better utilization of assets
Frequency and voltage instability	Improvement of reliability by ensuring continuity of supply

III. EVALUATION TECHNIQUE

The techniques required to analyze a distribution system depend on the type of system and the depth of analysis. The author has considered a radial distribution network for reliability modeling and evaluation. A radial distribution system is made up of a set of series components, including lines, cables, disconnects (or isolators), busbars, etc. A customer connected to any load point of such a system requires all components between himself and the supply point to be operating. Three basic reliability parameters of average failure rate, λ_s, average outage time, r_s, and average annual outage time, U_s, are given by:

$$\lambda_s = \sum_i \lambda_i \tag{1}$$

$$U_s = \sum_i \lambda_i . r_i \tag{2}$$

$$r_s = \frac{U_s}{\lambda_s} = \frac{\sum_i \lambda_i . r_i}{\sum_i \lambda_i} \tag{3}$$

Equations (1), (2) and (3) are used to evaluate the load point indices.

Although the three primary indices are fundamentally important, they do not always give a thorough demonstration of the system performance and response. For instance, the same indices would be evaluated irrespective of whether one customer or 100 customers were connected to the load point or whether the average load at a load point was 10 kW or 100 MW. In order to reflect the harshness of a system outage, additional reliability indices frequently are evaluated.

The most widely used reliability indices are averages that weight each customer equally. Customer-based indices are popular with regulating authorities since a small residential customer has just as much importance as a large industrial customer.

A. Customer-Orientated Indices

1) System Average Interruption Frequency Index, SAIFI

$$\text{SAIFI}=\frac{\text{total number of customer interruptions}}{\text{total number of customers served}} = \frac{\sum_i \lambda_i . N_i}{\sum_i N_i}; \quad \frac{\text{interruptions}}{\text{customer}}.\text{yr} \tag{4}$$

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

SAIFI is a measure of how many sustained interruptions an average customer will experience over the course of a year. For a fixed number of customers, the only way to improve SAIFI is to reduce the number of sustained interruptions experienced by customers.

2) System average interruption duration index, SAIDI

$$SAIDI = \frac{\text{Sum of customer interruption durations}}{\text{total number of customers served}} = \frac{\sum_i U_i . N_i}{\sum_i N_i}; \quad \frac{hr}{customer}.yr \tag{5}$$

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

SAIDI is a measure of how many interruption hours an average customer will experience over the course of a year. For a fixed number of customers, SAIDI can be improved by decreasing the number of interruptions or by decreasing the duration of these interruptions. Since both of these reflect reliability improvements, a reduction in SAIDI means an improvement in reliability.

3) Customer average interruption duration index, CAIDI

$$CAIDI = \frac{\text{Sum of customer interruption durations}}{\text{total number of customer Interruptions}} = \frac{\sum_i U_i . N_i}{\sum_i \lambda_i . N_i}; \quad \frac{hr}{customer\ interruption} \tag{6}$$

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

CAIDI is a measure of how long an average interruption lasts, and is used as a measure of utility response time to system incidents. CAIDI can be improved by decreasing the length of interruptions, but can also be decreased by increasing the number of short interruptions. As a result, a decrease in CAIDI does not necessarily mean an improvement in reliability.

4) *Average service availability (unavailability) index, ASAI (ASUI)*

(7)

(8)

where 8760 (365*24) is the number of hours in a calendar year.

ASAI is the customer-weighted availability of the system and provides the same information as SAIDI. Higher ASAI values mean higher levels of system reliability, with most US utilities having ASAI greater than 0.999.

B. Load- and energy-orientated indices

One of the important parameters required in the evaluation of load- and energy-orientated indices is the average load at each load-point busbar.

The average load is given by

(9)

where = peak load demand, and = load factor.

(10)

where t is normally one calendar year.

a) Energy not supplied index, ENS

ENS = total energy not supplied by the system =

(11)

where is the average load connected to load point *i*.

b) Average energy not supplied, AENS

(12)

IV. DESCRIPTION OF THE TEST SYSTEM

Considered distribution system in this paper is BUS2 of Roy Billinton Test System known as RBTS with some changes in the configuration of the system Fig.8. BUS2 has 4 feeders with voltage level of 11KV. It is assumed that 11KV source breaker operates successfully when required, disconnects are opened whenever possible to isolate a fault and the supply restored to as many load points as possible using appropriate disconnects and the alternative supply if available. The change is that the 2 Normally Open switches are replaced with 4 DGs each at the end of a feeder. In this study, there is no restriction in the load transfer, meaning that DGs play a role exactly similar to a power source. (DGs are considered 100% of the capacity of all of the loads). Fig.8.

Peak Loads and Feeders types and lengths are shown in Table2 and Table3 respectively.

Table2 Peak Loads

Customer Type	Peak Loads, MW
Residential	7.25
Small User	3.5
Government/Institutions	5.55
Commercial	3.7
TOTAL	20

Table3 Feeder Types and Lengths

Feeder Type	Length, km	Feeder Section Numbers
1	0.60	2,6,10,14,17,21,25,28,30,34
2	0.75	1,4,7,9,12,16,19,22,24,27,29,32,35
3	0.80	3,5,8,11,13,15,18,20,23,26,31,33,36

V. CUSTOMER AND LOADING DATA

The number of customers of each type and individual load levels are shown in Table4 for each load point.

The defined average load assumes that this will be the average value seen by the load point due to diversity between customers and normal load variations through the day and through the year. This customer data can be appropriately combined to give the feeder loading data shown in Table5.

Table4 Customer Data

Number of Load Points	Load Points	Customer Type	Load level per average	Load Point, MW peak	Number of Customers
5	1-3, 10, 11	residential	0.535	0.8668	210
4	12, 17-19	residential	0.45	0.7291	200
1	8	small user	1	1.6279	1
1	9	small user	1.15	1.8721	1
6	4, 5, 13, 14, 20, 21	govt/inst	0.566	0.9167	1
5	6, 7, 15, 16, 22	commercial	0.454	0.75	10
TOTALS			12.291	20	1908

Table5 Loading Data

Feeder Number	Load Points	Feeder Average	Load, MW Peak	Number of Customers
F1	1--7	3.645	5.934	652
F2	8--9	2.15	3.5	2
F3	10--15	3.106	5.057	632
F4	16--22	3.39	5.509	622
BUS 2	TOTALS	12.291	20	1908

The failure rate for all of the lines is 0.065 (f/yr/km) and for the transformers is 0.015 (f/yr). The repair time of all of the components is 5 hrs, and for transformers, the repair time is 200hrs. Switching time is 1 hr.

VI. SYSTEM SURVEYS

A range of reliability indices were calculated for a number of studies.

Load point indices: These are average failure rate (λ), average outage time (r), average annual unavailability (U), load disconnected (L) and energy not supplied (E). These can be calculated at each specified load point.

System indices: These are SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS and AENS. They are fully specified and can be evaluated from the load point indices for a group of load points or the whole system.

VII. CASE STUDIES

Five case studies are performed on the system. These center on inclusion or not of fuses in each lateral, disconnects in the main feeders and a DG at the end of each feeder. System is shown in Fig.8.

A. *Case 1*

Case 1 assumes the system with no disconnect, no fuse and no DG. The individual load point indices (λ, r, U) are shown in Table6.

Since the average demand and number of customers at each load point is known, the primary indices can be extended to give the customer- and load-oriented indices and they are shown in Table7.

Table6 Case1, Load Point Reliability Indices

Load Point	λ (f/yr)	r (hr)	U (h/yr)
1	0.535	10.467	5.600
2	0.535	10.467	5.600
3	0.535	10.467	5.600
4	0.535	10.467	5.600
5	0.535	10.467	5.600
6	0.535	10.467	5.600
7	0.535	10.467	5.600
8	0.192	5.000	0.959
9	0.192	5.000	0.959
10	0.483	11.056	5.340
11	0.483	11.056	5.340
12	0.483	11.056	5.340
13	0.483	11.056	5.340
14	0.483	11.056	5.340
15	0.483	11.056	5.340
16	0.535	10.467	5.600
17	0.535	10.467	5.600
18	0.535	10.467	5.600
19	0.535	10.467	5.600
20	0.535	10.467	5.600
21	0.535	10.467	5.600
22	0.535	10.467	5.600

Table7 Case1, System Indices

System Indices	Feeder 1	Feeder 2	Feeder 3	Feeder 4
SAIFI	0.535	0.192	0.483	0.535
SAIDI	5.6	0.959	5.34	5.6
CAIDI	10.467	4.995	11.056	10.467
ASAI	0.999361	0.999891	0.99939	0.999361
ASUI	0.000639	0.000109	0.00061	0.000639
ENS	20412	2062	16586	18984
AENS	31.13	1031	26.244	30.521

B. *Case 2*

Case 2 assumes the system with disconnects, with fuses and no DG. This case shows the effect of main and lateral distributor protection on the system.

Additional protection is frequently used in practical distribution systems. One possibility is to install fusegear at the tee-point in each lateral distributor. In this case a short circuit on a lateral distributor causes its appropriate fuse to blow; this causes the disconnection of its load point until the failure is repaired but does not affect or cause the disconnection of any other load point. In this condition, only installing the fuses, the reliability indices are improved for all load points although the amount of improvement is different for each one. The most unreliable load point is the furthest one because of the dominant effect of failure on its lateral distributor.

A second or alternative reinforcement or improvement scheme is the provision of disconnects or isolators at sensible points along the main feeder. These are generally not fault breaking switches and therefore any short circuit on a feeder still causes the main breaker to operate. After the fault has been detected, however, the relevant disconnect can be opened and the breaker reclosed. This procedure allows restoration of all load points between the supply point and the point of isolation before the repair process has been completed. After adding disconnects, the reliability of load points other than the last furthest ones are improved, the amount of improvement being greater for those near to the supply point or less for those further from it. The indices of the furthest load points will remain unchanged because isolation cannot remove the effect of any failure on these loads. Finally, all of the load points reliability indices will increase after adding fusegears and disconnects.

C. *Case 3*

Case 3 assumes the system with disconnects, with fuses operate with a probability of 0.9 and no DG.

The reliability indices for each load point in previous cases were evaluated assuming that the fuses in the lateral distributor operated whenever a failure occurred on the distributor they were supposed to protect. Irregularly, however, the primary protection system fails to operate. In these cases, the back-up protection functions. Assume that the fusegear operates with the probability of 0.9, i.e. the fuses operate successfully 9 times out of 10 when required. In this case the reliability indices shown in previous case tables are modified because, for example, failures on distributors 3, 5, 6, 8, 9 and 11 also contribute to the failure of load point LP1. Similarly this happens for the other load points. The contribution to the failure rate can be evaluated using the concept of expectation:

Failure rate = (failure rate | fuse operates) × P(fuse operates) + (failure rate | fuse fails) × P(fuse fails) (14)

Therefore the contribution to the failure rate of load point LP1 by distributor 3 is:

Failure rate = 0 × 0.9 + 0.052 × 0.1 = 0.0052 (15)

The results show that the reliability of each load point reduces as expected, the amount of reduction being dependent on the probability that the fusegear operates successfully and the relative effect of the additional failure events compared with those that occur even if the fuses are 100% reliable in operation.

D. Case 4

Case 4 assumes the system with disconnects, with fuses operate with a probability of 0.9 and with DGs.

And finally,

E. Case 5

Case 5 assumes the system with disconnects, with fuses and with DGs.

The results indicate that the greatest effect occurs for the load points furthest from the supply point and nearest to the DG.

VIII. CONCLUSION

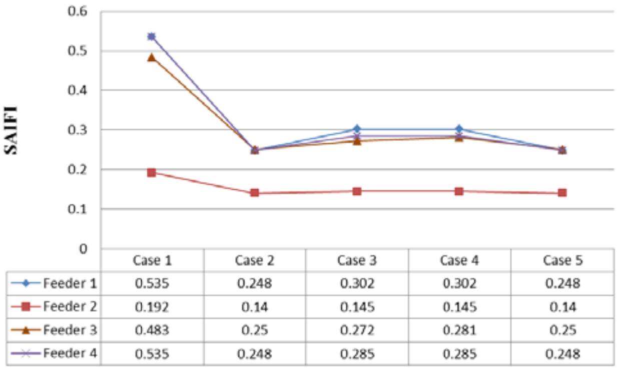
As expected, Case 1 produces the worst set of indices because this system is the most basic and least capital intensive. All the other studies provide facilities for improving load point reliability.

It is shown that by adding fuses, disconnects and DGs the reliability increases more and more and the best condition is when the system includes all of these components together.

To sum up, we know that a reduction in SAIDI indicates an improvement in reliability; meanwhile, higher ASAI values mean higher levels of system reliability.

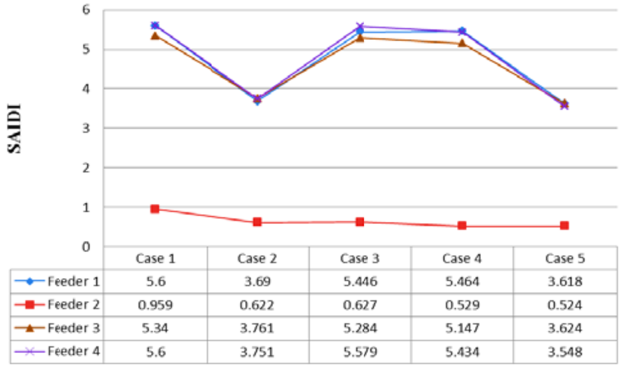
Figures are also drawn here to simplify the comparison between these cases.

As it was supposed, Case 5 has the best reliability and Case 1 has the worst system reliability.



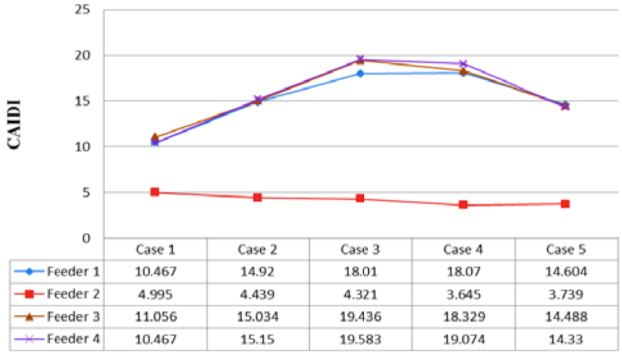
	Case 1	Case 2	Case 3	Case 4	Case 5
Feeder 1	0.535	0.248	0.302	0.302	0.248
Feeder 2	0.192	0.14	0.145	0.145	0.14
Feeder 3	0.483	0.25	0.272	0.281	0.25
Feeder 4	0.535	0.248	0.285	0.285	0.248

Figure1 System Average Interruption Frequency Index (int/cust.yr)



	Case 1	Case 2	Case 3	Case 4	Case 5
Feeder 1	5.6	3.69	5.446	5.464	3.618
Feeder 2	0.959	0.622	0.627	0.529	0.524
Feeder 3	5.34	3.761	5.284	5.147	3.624
Feeder 4	5.6	3.751	5.579	5.434	3.548

Figure2 System Average Interruption Duration Index (hr/cust.yr)



	Case 1	Case 2	Case 3	Case 4	Case 5
Feeder 1	10.467	14.92	18.01	18.07	14.604
Feeder 2	4.995	4.439	4.321	3.645	3.739
Feeder 3	11.056	15.034	19.436	18.329	14.488
Feeder 4	10.467	15.15	19.583	19.074	14.33

Figure3 Customer Average Interruption Duration Index (hr/cust.int)

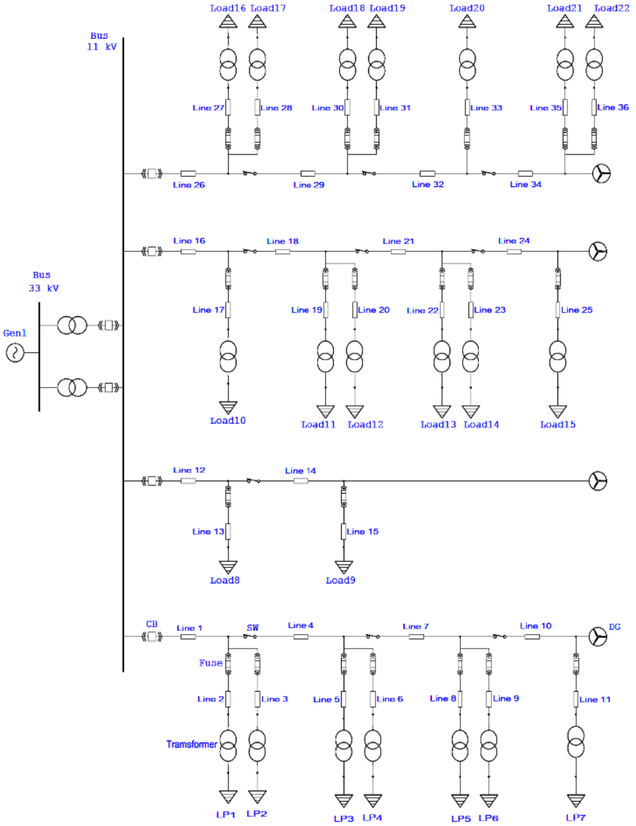
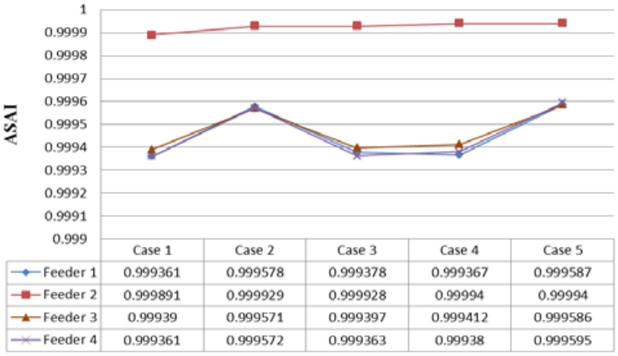
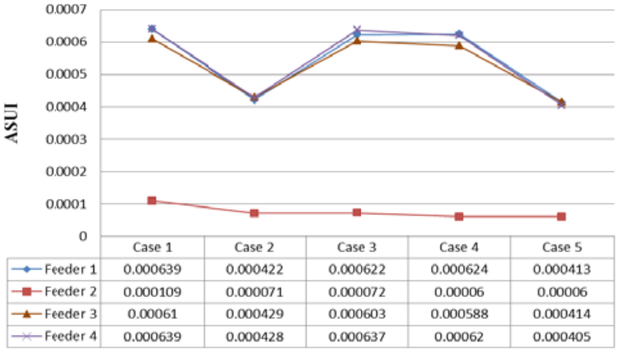


Figure8 Case Study Distribution System with Fuses, with Disconnects and with DGs



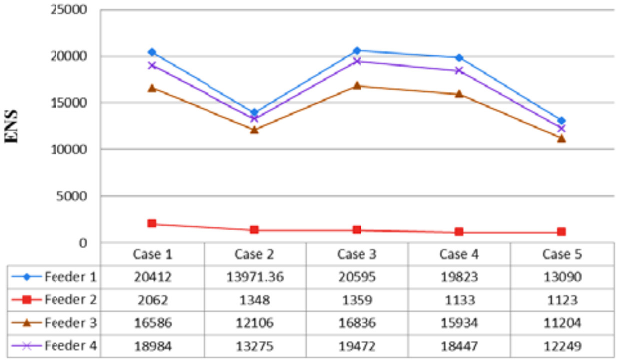
	Case 1	Case 2	Case 3	Case 4	Case 5
◆ Feeder 1	0.999361	0.999578	0.999378	0.999367	0.999587
■ Feeder 2	0.999891	0.999929	0.999928	0.99994	0.99994
▲ Feeder 3	0.99939	0.999571	0.999397	0.999412	0.999586
✕ Feeder 4	0.999361	0.999572	0.999363	0.99938	0.999595

Figure4 Average Service Availability Index



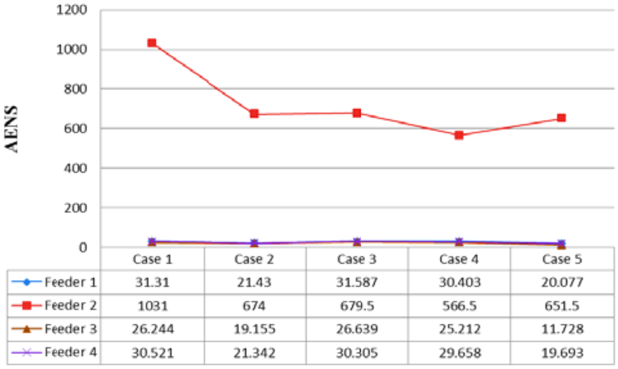
	Case 1	Case 2	Case 3	Case 4	Case 5
◆ Feeder 1	0.000639	0.000422	0.000622	0.000624	0.000413
■ Feeder 2	0.000109	0.000071	0.000072	0.00006	0.00006
▲ Feeder 3	0.00061	0.000429	0.000603	0.000588	0.000414
✕ Feeder 4	0.000639	0.000428	0.000637	0.00062	0.000405

Figure5 Average Service Unavailability Index



	Case 1	Case 2	Case 3	Case 4	Case 5
◆ Feeder 1	20412	13971.36	20595	19823	13090
■ Feeder 2	2062	1348	1359	1133	1123
▲ Feeder 3	16586	12106	16836	15934	11204
✕ Feeder 4	18984	13275	19472	18447	12249

Figure6 Energy Not Supplied (kWhr/yr)



	Case 1	Case 2	Case 3	Case 4	Case 5
◆ Feeder 1	31.31	21.43	31.587	30.403	20.077
■ Feeder 2	1031	674	679.5	566.5	651.5
▲ Feeder 3	26.244	19.155	26.639	25.212	11.728
✕ Feeder 4	30.521	21.342	30.305	29.658	19.693

Figure7 Average Energy Not Supplied (kWhr/cust.yr)

IX. REFERENCES

[1] R.E. Brown, *Electrical Power Distribution Reliability*, Mareel Dekker, 2002.

[2] R. Billinton, *Reliability Evaluation of Engineering Systems*, Plenum Press, New York, 1996.

[3] R. Billinton, S. Jonnavithula, *A Test System for Teaching Overall Reliability Assessment*, IEEE Transactions on Power Systems, Vol. II, No. 4, November 1996.

[4] R. N. Allan, R Billinton, I. Sjarief, L Goel, and K.S. So, *A Reliability Test System for Education Purposes - Basic Distribution System Data and Results*, IEEE Transactions on Power Systems, VoL 6, May 1991.

[5] Billinton R., Kumar S . , Chowdhury N., Chu K., Debnath K., Goel L., Khan E., Kos P., Nourbakhsh G. and Oteng-Adjei J., *A Reliability Test System for Educational Purposes - Basic Data*, IEEE Trans on Power Systems, PWRS-4, 1989, pp 1238-1244.

[6] R. Billinton; R. N. Allan, *Reliability Evaluation of Power Systems, Seconnd Editon*, Plenum Press, 1996.

[7] Barker, P.P.; De Mello, R.W., *Determining the impact of distributed generation on power systems. I. Radial distribution systems*, Power Engineering Society Summer Meeting, 2000. IEEE , vol.3, no., pp.1645-1656 vol. 3, 2000

[8] R. Billinton, *Reliability Evaluation of Electrical Power Systems*, University of Saskatchewan Saskatoon, Canada, October 2004.

[9] I. Waseem, M. Pipattanasomporn, M. Pipattanasomporn, *Reliability Benefits of Distributed Generation as a Backup Source*, IEEE Power & Energy Society General Meeting, PES '09, 2009.

[10] Richard E. Brown, *Electric Power Distribution Reliability, Second Edition*, CRC Press, 2008.

[11] Leonard L. Grigsby, *Electric Power Engineering Handbook-Power Systems,* CRC Press, 2007.

[12] Ali A. Chowdhury, Don O. Koval , *Power Distribution System Reliability: Practical Methods and Applications,* WILEY- IEEE Press Series on Power Engineering, 2009.