International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-8 Issue-6, August, 2019

Distribution System Reliability Assessment for Improved Feeder Configurations

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Abstract: ***This Paper enlightens the significance of the reliability evaluation for an electrical power distribution network using the analytical technique FMEA. The power distribution system is subject to interruptions frequently as a lot of devices are responsible for its effective operation. All the possible failures of each component are considered and the reliability is evaluated in terms of system reliability indices like SAIFI, SAIDI, ENS, and ASAI. FMEA method observes the failure modes of a procedure and reduces it by ranking over its impacts. In this paper, RBTS bus2 distribution network is used for the analysis. The influences of various feeder reconfigurations are considered and the system reliability indices are obtained. The obtained results show that the reliability of the distribution system is enriched with various feeder reconfigurations. Reliability Evaluation helps to design the future Distribution system and its expansion.***

Keywords: ***Distribution system, ENS, Reliability, Reliability Indices, SAIDI, SAIFI.***

I. INTRODUCTION

A lot of researches on generation system modeling are carried out in the past compared with distribution system modeling to provide uninterrupted service to the consumers. However, researches on customer interruption data illustrate that the distribution system failures are responsible for 80% of the consumer outage [1]. Therefore to enhance the continuity of supply to the customer, efforts should be taken based on the distribution behavior. Distribution system (DS) adequacy assessment and system performance indices are well-defined in [2]. Customer failure data collection methods for the analysis of the reliability of the distribution system are specified in [3]. Reliability of distribution system extensively varies with integrating DG as an alternate supply and it is evaluated with a fluctuating load in [4, 5].

Reliability indices are acquired from the mathematical model in Analytical technique while in Simulation technique arbitrary performance of the system is simulated to observe the reliability indices. Momentary interruption indices and the interruption cost are evaluated using the analytic and probabilistic method in [6]. In recent times, Distributed Generation (DG) turns out to be the dynamic alternative supply resource. Improvement in the reliability when incorporating DG with the distribution system is presented in [7].

Revised Manuscript Received on October 30, 2019.
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In addition, DG has an impact on voltage control, positive environmsental impact, reactive power support and reduction of losses if they are appropriately synchronized with the distribution system. In contrast, voltage and frequency instability, the rise in short circuit current occurs due to the inclusion of DG [8]. Probabilistic analysis of reliability indices is explained in [11].

Monte Carlo (MC) simulation technique is applied to evaluate the reliability of the distribution system using random parameters distributions. Monte Carlo simulation technique is employed in a complex distribution network to predict the reliability using random failure events is given in [12, 13, 14]. Reliability can be enhanced by placing reclosers. Impact of Recloser along with DG on reliability is analyzed in [15]. Another way of enhancing the power system reliability through optimal capacitor placement is given in [16].

Failures in the distribution networks have major influence on the continuity of supply to the customer. Therefore, it is essential to know the type of failure and restoration of supply in the system. Appropriate mathematical model development is needed in the reliability evaluation.

RBTS test system is taken in this paper to understand the distribution system model and for the evaluation of reliability [1]. It comprises of the main components found in the real-time distribution system and with adequately less number of components to ease the analysis. All the possible failures of each component in this system are considered for the reliability evaluation. This paper comprehends various alternative operating configurations and their influences on the reliability of the DS.

Nomenclature	
AENS- Average Energy not supplied	RBTS -Roy Billinton test system
ASAI - Average system availability index	SAIDI -System average interruption duration index
ASUI -Average system unavailability index	SAIFI- System average interruption frequency index
CAIDI -Customer average interruption duration index	λ- frequency of failure rate
ENS- Energy not supplied	r - repair time
FMEA-Failure Mode and Effect Analysis	U- Unavailability

II. DISTRIBUTION SYSTEM RELIABILITY

Radial distribution systems consist of main feeder, lateral distributors, fuse, disconnects (isolators), breakers, bus bars, etc. All these components are required to connect between the supply point and any load point of a system [9]. Distribution system faults are categorized as momentary and long-lasting faults based on the cause and interval of failure [9]. In practical networks, faults are cleared by auto recloser and protection switches. The analytical procedure required for the reliability assessment is an inductive method and is based on Failure Mode and Effect Analysis (FMEA) which [10]. This method states all the possible failures for every single component and finds their subsequent effects on the system. Each and every failure of all the components in the system are acknowledged and assessed to analyze the consequence on every load points. Load point indices are obtained for these failures. FMEA method cannot be directly used due to its complex configurations with multiple components and operating models. Hence, the system is reduced into a simple system and the reliability equivalents are calculated as follows. Position, Failure rate and repair time, feeder arrangement of a component define its reliability. Reliability indices of a distribution network are classified as load point reliability indices and the system reliability indices [10].

A. Load Point Reliability Indices

Powers supply is delivered to each customer load points starting from a substation through distribution network. The average failure rate (λ), average outage time (r) and the average annual unavailability (U) are the elementary reliability indices used to express the reliability of the distribution system [13]. Average failure rate indicates the number of failures happens at individual load point for the specific time duration. Average failure time interval at the load point is denoted by average outage time. Average supply inaccessibility at the load point for a period of one year is stated as average annual outage time. The average supply inaccessibility is attained from the product of average failure occurrence and the average outage time. These elementary indices are the expected reliability values and denote the average values.

Based on the component failure rate, repair time and the feeder configuration the basic reliability parameters such as average failure rate λ_s, average outage time r_s, and average annual outage time U_s are expressed by the following equations [9].

$$\lambda_s = \Sigma\lambda_i \quad \text{(fr/yr)} \tag{1}$$

$$U_s = \Sigma\lambda_i r_i \quad \text{(hr/yr)} \tag{2}$$

$$r_s = \frac{U_s}{\lambda_s} = \frac{\Sigma\lambda_i r_i}{\Sigma\lambda_i}(hr) \tag{3}$$

Where, λ_i and r_i are the failure rate and the average repair time of component i, and U_i is the annual unavailability at the load point i.

B. System Reliability Indices

To represent the overall system reliability additional system reliability indices such as SAIFI, SAIDI, CAIFI, CAIDI, ASAI, and ASUI are required to be calculated [9]. These system reliability indices are determined from the basic load point indices. These indices are beneficial to evaluate the reliability, severity of the fault and consequences of the entire system and also to an individual feeder, and a segment of the system. Reliability cost worth indices such as ECOST, IEAR can also be calculated using the basic reliability indices.

B. Customer-oriented reliability indices

System Average Interruption Frequency Index (SAIFI)

SAIFI = Total Number of Customer Interruptions/ Total Number of customers served

$$SAIFI = \frac{\sum \lambda_{sys,i} N_i}{\sum N_i} \text{int/ } cust.yr \tag{4}$$

System Average Interruption Duration Index (SAIDI)

$$SAIDI = \frac{\sum U_{sys,i} N_i}{\sum N_i} hr/cust.yr \tag{5}$$

Customer Average Interruption Duration Index (CAIDI)

$$CAIDI = \frac{\sum U_{sys,i} N_i}{\sum \lambda_{sys,i} N_i} hr/cust.\text{int} \tag{6}$$

Average Service Availability Index (ASAI)

$$ASAI = \frac{\sum 8760 N_i - \sum U_i N_i}{\sum 8760 N_i} \tag{7}$$

Load and Energy oriented reliability indices

Energy Not Supplied (ENS)

$$ENS = \sum L_i U_{sys,i} KWhr/yr \tag{8}$$

Average Energy Not Supplied (AENS)

$$AENS = \frac{\sum L_i U_{sys,i}}{\sum N_i} KWhr.yr/customer \tag{9}$$

Where L_i – Average load connected to i^{th} load point
N_i – Number of customers at load point i
$U_{sys,\,i}$ - Annual outage duration at i th load point

Table- I: Main feeder section and Lateral distributor lengths

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

Table- II: Component data

Component	Failure rate λ	Repair time r(hr)
Transformer(11/.415KV)	0.015 (f/yr)	200
Lines (11KV)	0.0650(f/yr*km)	5
Bus bars(11KV)	0.0010 (f/yr)	2

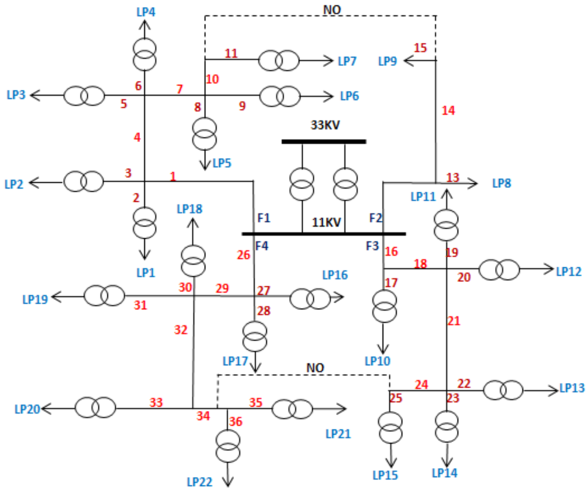

Fig.1 RBTS bus system 2

III. TEST SYSTEM DESCRIPTION

Roy Billinton Test System (RBTS) has 5 bus bars (Bus2 to Bus6) [1]. RBTS bus2 system shown in Fig.1 is considered in this paper for the reliability evaluation analysis. It consists of 4 feeders and 22 load points with the voltage level of 11KV. A Breaker is located at the source of the 11KV main feeder. It is assumed that the operation of the breaker is 100% available and is opened up if any fault occurs in the system and isolate the faulty load point and service is continued for the remaining customers of the healthy load points. Table I provides the length of the main feeder section and the lateral distributor [1]. Table II shows the component failure rate and repair time data [1]. The following assumptions are made for the calculation reliability evaluation.

- The fuses and circuit breakers are assumed to be 100% reliable
- A defected transformer is substituted by another as an alternative of repairing it.
- Repair time is taken as 5.0 hrs. for the main and lateral line sections and
- Switching time is taken as 1.0 hr.

IV. RELIABILITY EVALUATION OF THE TEST SYSTEM USING ANALYTICAL METHODS

A radial distribution feeder comprises of main feeder sections and lateral sections. Load points are attached with the main feeder through lateral distributors. A circuit breaker is attached at the source side of the feeder to protect the components during the fault. Fuses are installed in distributors to isolate failures on the lateral section from the main feeder. Main feeder section is providing with disconnects or isolators to isolate faulted sections. An alternate supply is provided to supply the load points to continue the service to the healthy load points during failure.

In this method, the possible failure of each component is considered and the consequence of failure on every single component is calculated using the load point indices. System reliability indices for all the four Feeders are calculated by means of this basic reliability indices

4.1 Load Point Reliability Indices Calculation

The elementary load point reliability indices Average failure frequency λ_{LP}, average repair length $r_{LP,}$ and average annual outage period U_{LP} of the Feeders F1, F2, F3, and F4 are calculated for every components failure using the equations (1) to (3). In this paper, we consider four different alternative feeder reconfigurations and the system reliability indices for each case is evaluated to analyze the impact of feeder reconfiguration in reliability of a distribution system.

The failure frequency and average outage period of the load point LP1 is calculated using the equations (1) to (3) as follows. The components incorporated for the calculation of load point LP1 from Feeder1 are the main line segments 1,4,7,10 and the lateral section2. Calculation of load point reliability indices of LP1 for case 2 is specified as follows.

(i) Failure rate $\lambda_1 = (\lambda_{line}$*length of the line)$+\lambda_{trfr}+\lambda_{BB}$ = (0.065*3.45)+0.015+0.001=0.24f/yr

(ii) Annual unavailability $U_1 = (\lambda_{line}*length*r_{line}) + \lambda_{trfr}*r_{BB} + \lambda_{BB}r_{BB}$ = (0.065*0.75*5)+(0.065*0.6*5)+ (0.065*0.75*1) +(0.065*0.75*1)+(0.065*0.6*1)+(0.015*200)+(0.001*2)= 3.58hr/yr

(iii) Outage time of the load point $r_1 = U_1/\lambda_1$=14.91yr

Table III: Load point reliability indices (case2)

Feeder Number	Load Point	Failure rate λ(f/yr)	Average outage time r(hrs)	Annual outage Time U (h/yr)
F1	1	0.240	14.91	3.58
	2	0.253	14.40	3.64
	3	0.253	14.40	3.64
	4	0.240	14.91	3.58
	5	0.253	14.40	3.64
	6	0.250	14.51	3.63
	7	0.253	14.24	3.60
F2	8	0.140	3.89	0.54
	9	0.140	3.60	0.50
F3	10	0.243	14.73	3.58
	11	0.253	14.40	3.64
	12	0.256	14.29	3.66
	13	0.253	14.19	3.59
	14	0.256	14.08	3.61
	15	0.243	14.73	3.58
F4	16	0.253	14.40	3.64
	17	0.243	14.78	3.59
	18	0.243	14.73	3.58
	19	0.256	14.24	3.65
	20	0.256	14.24	3.65
	21	0.253	14.19	3.59
	22	0.256	14.08	3.61

Result from Table III shows that, system reliability indices are enhanced in definite percentage in all the load point of the feeder with the installation of lateral protection (fuse at tee point). The quantity of enhancement varies for each load point.

Table IV: Customer data

Feeder Number	Load Points	Number of customers in each Load point	Peak Load Level per Load Point(MW)
F1	1,2,3	210	0.8668
	4,5	1	0.9167
	6,7	10	0.7500
F2	8	1	1.6279
	9	1	1.8721
F3	10,11	210	0.8668
	12	200	0.7291
	13,14	1	0.9167
	15	10	0.7500
F4	16	10	0.7500
	17,18,19	200	0.7291
	20,21	1	0.9167
	22	10	0.7500

4.2 System Reliability Indices Calculation

The required customer data and data of customer load point to evaluate the system reliability indices are tabulated in Table IV and Table V in turn [1]. Load point reliability indices only give the average values of the unavailability of the load points. Therefore, it is required to evaluate the system reliability indices for further distribution system control and operations. System reliability Indices of each feeder is calculated from the elementary load point reliability indices using the equations (4) to (9).

Table V: Loading Data

Feeder Number	Load Points	Number of customers	Average Load (MW)	Peak Load (MW)
F1	1- 7	652	3.645	5.934
F2	8,9	2	2.15	3.5
F3	10-15	632	3.106	5.057
F4	16-22	622	3.390	5.509
Total	22	1908	12.291	20.0

Case1: Base Case: No disconnects, No Fuse, No alternate supply, repair of transformers

Basic radial distribution system feeder without any protection devices such as fuse gears and disconnects is considered in this case. Any fault occurs in the main feeder causes the load points of lateral feeders with interrupted power supply. In this case, incorporating DG into the main feeder does not supply the healthy load points of lateral due to the incapability to cut off the faulted section of the main feeder and hence the reliability cannot be enhanced. This is the worst case scenario with no isolating elements to isolate the faulted segments.

In this case, basic load point indices include the failure rate of all the components in each and every load point of the feeder. As a result, every load point in a feeder has the identical value of failure rate, annual outage duration and the repair time. Hence the elementary load point reliability indices of all the load points in a feeder. System indices are tabulated in Table VI.

Case2: Effect of lateral distributor protection

In this case, lateral distributor is protected with a fuse gear. If any fault occurs on the lateral element makes its appropriate fuse to blow. This detaches the defective load point from the main feeder until the fault is repaired but continues to supply the other healthy load points. However, there are no disconnects on the main line segments. If any fault occurs on the main line segments all the lateral distributors would get interrupted. Hence, the DG installation will not enhance the reliability of the system. The system indices are tabulated in Table VII.

Case3: Effect of fuse and main feeder disconnects

In this improvement scheme Isolators or disconnects are incorporated at suitable points in the main feeder. If any fault occurs on the feeder initially the main breaker opens up to locate the faulted section. Now the faulted section is detached from the feeder by opening the appropriate disconnect. Afterward the breaker is reclosed and lets the restoration of all the healthy load points in the middle of the source and the point of isolation before the repair procedure is carried out.

Insertion of disconnects, enhance the reliability of the load points. The enhancement is more particularly in the load points near to the source and only a smaller amount is obtained in the far away load points due to the inability to disconnect the faulty segment. Hence, installing disconnects on the main distribution line significantly improves the reliability of the system and the results are tabulated in Table VIII.

Case4: Effect of lateral protection (fuse) with 0.9 probabilities

The fuse gear installed at the lateral feeder operates with the probability of 0.9 if there is any failure on the distributor. The reliability indices in previous cases are evaluated by assuming that the fuses in the lateral distributor operated with the probability of 1.If the fuse gear operate with the probability of 0.9, i.e. the fuses operate successfully 9 times out of 10 when required. The impact to the failure rate can be evaluated as follows [9].

Failure rate = (failure rate/fuse operate)*probability (fuse operates) +(failure rate/fuse fail)*probability(fuse fails). Therefore, the failure rate, in this case, can be calculated as follows and the system indices are set out in Table IX.

System reliability Indices of each feeder is calculated from the basic load point reliability indices using the equations (4) to (9). The obtained values are tabulated for four different cases from Table VI to Table IX.

Table VI: Base case: No disconnects-No Fuses-No Alternate Supply

Feeder Number	SAIFI (int/cu st.yr)	SAIDI (hrs/cus t.yr)	CAIDI (int/cu st.yr)	ASAI	ENS (KWh /yr)	AENS (KWh /yr)
F1	0.626	23.61	37.71	0.9973 05	86040	131.9
F2	0.192	0.96	5.00	0.9998 90	2064	103.2
F3	0.559	20.35	36.40	0.9976 78	63192	99.99
F4	0.626	23.61	37.71	0.9973 05	80021	128.65

Table VII: Lateral fuse with No disconnects and No Alternate supply

FEEDER	SAIFI (int/cu st.yr)	SAIDI (hrs/cus t.yr)	CAIDI (int/cus t.yr)	ASAI	ENS (KW h/yr)	AENS (KWh/ yr)
F1	0.2487	4.17	16.76	0.99952	15194	23.20
F2	0.1400	0.70	5.0	0.99992	1505	752.5
F3	0.2509	4.18	16.68	0.99952	12980	20.54
F4	0.2478	4.16	16.81	0.99952	14181	22.80

Table VIII: Lateral fuse with Main feeder disconnects and Alternate supply

FEEDER	SAIFI (int/cu st.yr)	SAIDI (hrs/cu st.yr)	CAIDI (int/cu st.yr)	ASAI	ENS (KW h/yr)	AENS (KWh/ yr)
F1	0.248	3.623	14.59	0.999578	13172	20.20
F2	0.140	0.522	3.74	0.999939	1122	561
F3	0.250	3.62	14.50	0.999579	11203	17.73
F4	0.247	3.61	14.59	0.999579	12248	19.69

Table IX: Lateral fuse with a Probability of 0.9 and Disconnects and No Alternate supply

FEEDER	SAIFI (int/cu st.yr)	SAIDI (hrs/cu st.yr)	CAIDI (int/cu st.yr)	ASAI	ENS (KW h/yr)	AENS (KWh/ yr)
F1	0.3022	5.446	18.01	0.999378	20595	31.587
F2	0.1454	0.627	4.321	0.999928	1359	679.5
F3	0.2724	5.284	19.436	0.999397	16836	26.639
F4	0.2855	5.579	19.583	0.999363	19472	30.305

V. RESULTS AND DISCUSSIONS

It is observed from Fig. 2 that the failure occurrence frequency is more in the base case in all the feeders. Any fault occurs in the main feeder or lateral disconnect will result in unsupplied energy for the customers in all the load points. Installing fuse into the lateral distributor isolate the faulty load point and the remaining load points are supplied with the source. However, if there is any fault in the main line of the feeder the customers of every load point are left with unsupplied energy. After installing disconnects in the main feeder the faulty load points can be detached and other load points are reconnected with the source or alternate supply. Thus the average failure frequency is reduced substantially in every feeder. The reduction in SAIFI is less in feeder 2 due to less number of customers in this load point.

Similarly, the failure duration is also reduced significantly in every feeder due to the inclusion of protection devices and the values of SAIDI is compared in all the feeders for four different cases and it is shown in Fig. 3.

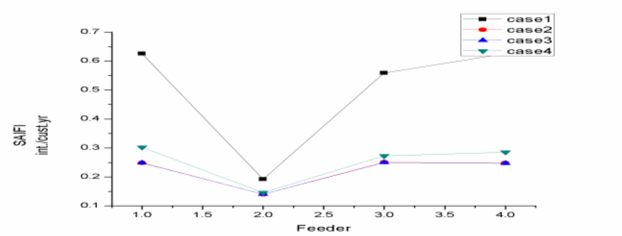

Fig. 2 (SAIFI) System Average Interruption Frequency Index

Fig. 4 shows the energy not delivered to the customers in the feeder. In every feeder the unsupplied energy in reduced noticeably regardless of the amount of reduction. Further, the reliability can be enhanced in the required load point using this basic scrutiny.

Average service availability index presented in Fig. 5 conveys that the inclusion of disconnects and lateral distributor protection in the main feeder increases the available power service to the customers in all the load points.

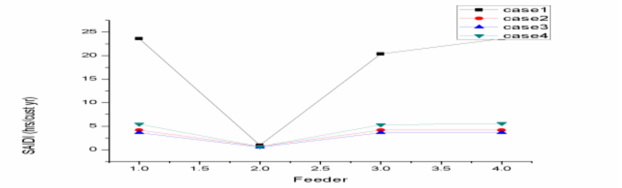

Fig. 3 (SAIDI) System Average Interruption Duration Index

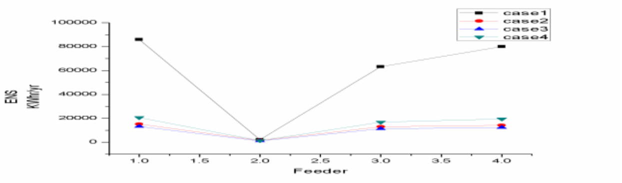

Fig. 4 Energy not supplied

VI. CONCLUSION

Four different test cases are considered for the RBTS system and the customer and energy reliability indices are obtained. The consequences of reliability indices of distribution system reconfiguration with various settings have been analyzed. Comparing the results of all the three cases with the base case shows that the reliability indices SAIFI, SAIDI, and ENS have been improved for all the load points as a result of the inclusion of various protection devices such as fuse at tee point, disconnects or isolators at the main feeder line and DG. The failure rate, repair time and the Energy not supplied to the customer are reduced significantly and ensuring the betterment of reliability. The system reliability indices are acquired by allowing simply the first-order occasions. This analysis of reliability provides a framework for the assessment of reliability worth evaluation and for the reliability enhancement assessment of radial distribution system.

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