Distribution System Reliability Evaluation using Time Sequential Monte Carlo Simulation

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Abstract-Reliability assessment is an important tool for distribution system planning and operation. Distribution system reliability assessment is able to predict the interruption profile of a distribution system at the customer end based on system topology and component reliability data. The reliability indices can be evaluated using analytical method or Monte Carlo simulation method. The main objective of reliability analysis is to quantify, predict, and compare reliability indexes for various reliability improvement initiatives/network configurations. By understanding the distribution system reliability indices using analytical method, this paper further implements a reliability models to evaluate the distribution system reliability using Monte-Carlo simulation method and describes a algorithm for computer program to implement these techniques in VC++. General distribution system elements, operating models and radial configurations are considered in the program. Overall system and load point reliability indices and expected energy unserved are computed using these techniques. Reliability assessment estimates the performance at customer load points considering the stochastic nature of failure occurrences and outage duration. The basic indices associated with load points are: failure rate, average outage duration and annual unavailability. Furthermore, these models can predict other indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Frequency Index (CAIFI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability /Unavailability Index (ASAI), Energy Not Supplied (ENS) and Average Energy Not Supplied (AENS). This information helps utility engineers and managers at electric utility organizations to decide how to spend the money to improve reliability of the system by identifying the most effective actions/ reconfigurations.

Index Terms: Distribution system, Reliability evaluation, Load point indices, Reliability indices, Random failures, Time sequential Monte-Carlo simulation and Roy Billinton Test System.

I. INTRODUCTION

The basic function of the power distribution system is to provide an adequate electrical supply to its customers as economically as possible with reasonable level of reliability and quality. The distribution system is a portion of an electric system that delivers electric energy from transformation points on the transmission system to the customer point. Reliability of a power distribution system is defined as "the ability to deliver uninterrupted service to the end customers". The techniques used in distribution system reliability evaluation can be divided into two basic categories - analytical and simulation methods. The difference between these methods is in the way the methodology uses the input data in which the reliability indices are evaluated. Analytical techniques represent the system by simplified mathematical models derived from mathematical equations and evaluate the reliability indices using direct mathematical solutions.

Simulation techniques, estimate the reliability indices by simulating the actual process and stochastic behavior of the system. Therefore, the method treats the problem as a series of real experiments conducted in simulated time. It estimates probability of the events and other indices by counting the number of times an event occurs. Earlier day's reliability assessment was based on deterministic criteria for system failures like thumb rules like fixed values based on their experience in system operation. Nowadays, probabilistic methods are used to analyze the more complex distribution system.

Reliability assessment of distribution system is usually concerned with the system performance at the customer end, i.e. at the load points. The basic indices used to predict the reliability of a distribution system are: average load point failure rate, average load point outage duration and average annual load point outage time or annual unavailability. The basic indices are important from an individual customer's point of view and also utility point of view. However they do not provide an overall performance of the system. An additional set of indices can be calculated using these three basic indices and the number of customers/load connected at each load point in the system. Most of these additional indices are weighted averages of the basic load point indices. The most common additional or system indices are; SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS and AENS. These indices are also calculated by a large number of utilities from system interruption data and provide valuable indications of historic system performance. By considering the basic system indices to measure past performance can also used to calculate the same basic indices for future performance.

Reliability indices of a distribution system are functions of component failures, repairs and restoration times which are random by nature. The calculated indices are therefore random variables and can be described by probability distributions. The main objective of reliability analysis is to quantify, predict, and compare reliability indexes for various reliability improvement initiatives/network configurations. This information helps engineers and managers at electric utility organizations to decide how to spend reliability improvement dollars by identifying the most effective actions/ reconfigurations for improving reliability of distribution feeders. There are many types of system design and maintenance tasks that fall under the reliability improvement umbrella.

Basic distribution system data, Roy Billinton Test System (RBTS) is presented in [1] and is used in reliability test system for educational purposes. This test system includes all the main practical elements like circuit breaker, switches, distribution transformers, main and lateral sections. This data has been used to understand reliability models and evaluation techniques and reliability indices like SAIFI, SAIDI are evaluated in [1] using analytical method. The way of gaining confidence in a reliability model is developed by a validation method in [2], it automatically determines appropriate default component reliability data so that predicted reliability indices results match historical values. Reliability can be improved by reconfiguring the feeder in [3], [4] and [5] and predictive reliability model is used to compute reliability indices for the distribution systems and a novel algorithm are used to adjust switch positions until an optimal solution is identified in [3].

The conventional FMEA technique is applied to complex radial networks to develop a digital computer program using general technique for two small practical test systems in [6]. By using the feeder branches and load branches technique in [7] computer program is developed and numerical results show that, the proposed technique is effective for the reliability evaluation and design of distribution systems. In [8] recursive search is used in the algorithm, which reduces the amount of programming and improves its efficiency. An algorithm for Monte-Carlo Simulation technique is used in evaluation of complex distribution system in [9]. In [10] the simulation program is tested on Feeder 1 of Bus – 2 of Roy Billiton Test System (RBTS) and set of system related indices are presented. In [11] reliability indices of expected values such as System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) are calculated and results are compared for two distribution systems by using both analytical and simulation methods.

This paper attempts to develop the sequential Monte-Carlo simulation technique for distribution system reliability analysis. The first section of this paper briefly illustrates the basic concepts of analytical method and second section illustrates the basic concepts of the time sequential Monte-Carlo simulation. The development of the algorithm and flowchart using Monte-Carlo simulation technique for distribution system reliability evaluation is described in third section. Developed simulation programs are applied on a RBTS test system and validated the same with published results using analytical method. The presented methodology can be used directly by utility system to observe the reliability performance of the system at customer and utility end and also can be used to improve reliability of the system further by reconfiguration of network.

II. ANALYTICAL APPROACH

The analytical method looks at how the load points would be affected if a particular component fails. The three basic indices are used to predict the load-point reliability of a distribution system are (failure rate (λ), outage time (r) and annual unavailability (U) can be calculated using the “(1) to (3)”.

$$\lambda p = \sum_{i=1}^{N} \lambda_i \left(\frac{f}{y\,r}\right) \tag{1}$$

$$Up = \sum_{i=1}^{N} \lambda i\ ri \left(\frac{hr}{yr}\right) \tag{2}$$

$$rp = \frac{Up}{\lambda p}(hr) \tag{3}$$

Reliability indices such as SAIFI, SAIDI, CAIFI, CAIDI, ASAI, ASUI, ENS, AENS and ACCI can be calculated using “(4) to (10)”.

A. Methodology of Monte-Carlo Simulation Technique

A power system is stochastic in nature and therefore Monte-Carlo simulation technique can be applied for reliability evaluation of a power system for more precise results. There are primarily two types of Monte-Carlo simulation: state sampling and time sequential techniques. In this paper time sequential simulation method is used for development.

B. Time sequential Monte Carlo simulation technique

The time-sequential Monte-Carlo simulation technique can be used on any system that is stochastic in nature. This time sequential simulation process can be used to examine and predict real behavior patterns in simulated time, to obtain the probability distributions of the various reliability parameters and to estimate the expected or average value of these indices. In a time sequential simulation, an artificial history that shows the up and down times of the system elements is generated in chronological order using random number generators and the probability distributions of the element failure and restoration parameters. The system reliability indices and their probability distributions are obtained from the artificial history of the system.

Distribution system elements include basic equipment such as distribution lines/cables and transformers, and protection elements such as disconnect switches, fuses, breakers, and alternate supplies. Line sections and transformers can generally be represented by the two-state model as shown in Figure 1 where the up state indicates that the element is in the operating state and the down state implies that the element is inoperable due to failure.

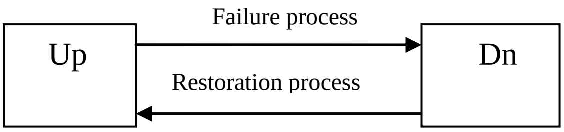

Figure 1: State Space diagram of element

The time during which the element remains in the up state is called the time to failure (TTF) or failure time (FT). The time during which the element is in the down state is called restoration time that can be either the time to repair (TTR) or the time to replace. The process of transiting from the up state to down state is the failure process. Transition from up state to down state can be caused by the failure of an element or by the removal of elements for maintenance. Figure 2 shows the simulated element operating/restoration history.

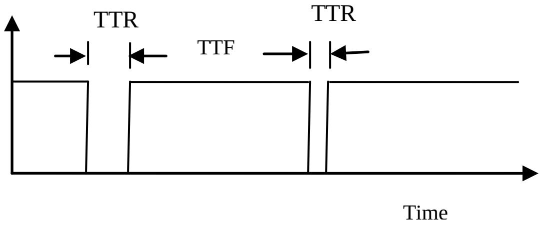

Figure 2: Element operating/repair history

The parameters like TTF, TTR are random variables and may have different probability distributions. The uniform distribution can be generated directly by a uniform random number generator and this generated random numbers are converted into TTF or TTR using this equation.

$$\mathrm{TTF} = \left(-\log\frac{\mathrm{U}}{\lambda}\right) * 8760 \qquad (11)$$

Where, U is uniformly distributed random variable in the interval [0, 1] and T is exponentially distributed.

C. Determination of Load Point Failures

The most difficult problem in the simulation is to find the load points affected by the failure of an element. A complex radial distribution system can be divided into the combination of main feeder and sub feeders. The procedure for determining the failed load points and their operating/restoration histories is as follows in [9]:

1) Determine the type and location of the failed element, the failed element number and the failed feeder number that the failed element is connected to.

2) Determine the affected load points connected to the failed feeder and the failure durations of these load points according to the configuration and protection scheme of the failed feeder.

3) Determine the sub feeders which are the downstream feeders connected to the failed feeder and the effects of the failed element on the load points connected to these sub feeders.

4) Repeat (2) and (3) for each failed sub feeder until all the sub feeders connected to the failed feeder are found and evaluated.

5) Determine the up feeder which is the upstream feeder to which the failed feeder is connected and the effects of the failed element on the load points in the up feeder

6) Repeat (2) to (5) until the main feeder is reached and evaluated.

D. System Analysis

The distribution system is represented as a mathematical model for analytical techniques to be applied. A failure in any component between the supply point and load point will result in outages. The Bus 6 of the RBTS is a distribution system containing of 4 main feeders, 3 sub feeders, 42 main sections, 22 lateral sections and 40 load points comprising agricultural, small industrial, commercial and residential customers shown in Figure 3. The total number of customers connected on feeders F1, F2, F3 and F4 are 764, 969, 22 and 1183 customers respectively.

Each system segments consists of a mixture of components. A main section can be a distribution line, a combination of line and disconnect switches which can be installed in each end or both ends of the line. A lateral section usually consists of a line, transformer, fuse or their combination. Some of the components that have not been taken into account are assumed to be 100% reliable. The basic data used in these studies is given in [1]. The failure rate of each element is assumed to be constant. The repair and switching times are assumed to be log normally distributed. It is assumed that the standard deviations of the distribution line repair time; transformer replace time and switching time of all elements are one hour, 10 hours and 0.4 hours respectively. The lines and cables have a failure rate which is approximately proportional to their length. Therefore, the main feeder sections (L1-L64) have a failure rate of 0.065 f/ km-yr.

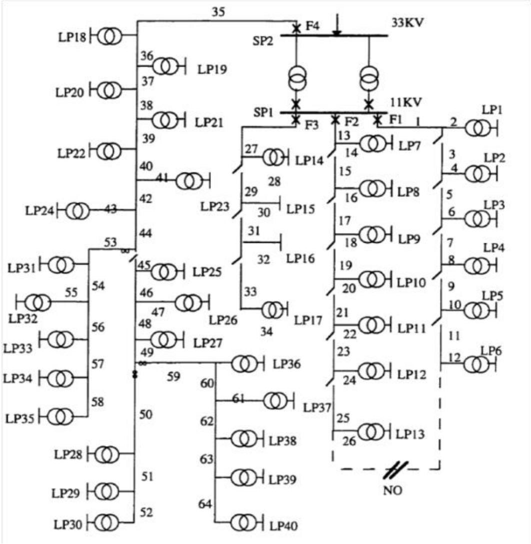

Figure 3: Distribution system of RBTS Bus 6 [7]

System indices are as follows:

i. System average interruption frequency index, SAIFI

$$\frac{\text{total number of customer interruptions}}{\text{total number of customers served}}$$

$$\mathrm{SAIFI}=\frac{\sum_{i=1}^{K}\lambda iNi}{\sum_{i=1}^{K}Ni} \qquad (4)$$

ii. System average interruption duration index, SAIDI

$$\frac{\text{sum of customer interruption durations}}{\text{total number of customer served}}$$

$$\mathrm{SAIDI}=\frac{\sum_{i=1}^{K}UiNi}{\sum_{i=1}^{K}Ni} \qquad (5)$$

iii. Customer average interruption duration index, CAIDI

$$\frac{\text{sum of customer interruption durations}}{\text{total number of customer interruptions}}$$

$$\mathrm{CAIDI}=\frac{\sum_{i=1}^{K}UiNi}{\sum_{i=1}^{K}\lambda iNi} \qquad (6)$$

iv. Average service availability index, ASAI

$$\frac{\text{customer hours of available service}}{\text{customer hours demanded}}$$

$$\mathrm{ASAI}=\frac{\sum_{i=1}^{K}8760Ni\ -\ \sum_{i=1}^{K}UiNi}{\sum_{i=1}^{K}8760Ni} \qquad (7)$$

v. Average service unavailability index, ASUI

$$\mathrm{ASUI}\ =\ 1-\ \mathrm{ASAI} \qquad (8)$$

vi. Energy not Supplied by the system,

$$\mathrm{ENS}=\sum_{i=1}^{K}UiLa(i) \qquad (9)$$

vii. Average energy not Supplied indices,

$$\frac{\text{total energy not supplied}}{\text{total number of customers served}}$$

$$\mathrm{AENS}=\frac{\sum_{i=1}^{K}UiLa(i)}{\sum_{i=1}^{K}Ni} \qquad (10)$$

Where λi is the failure rate, Ui is the annual outage time and Ni is the number of customers at load point i La(i) is the average load connected to load point i and 8760 is the number of hours in a calendar year.

E. Algorithm & flowchart

The algorithm is used to develop the computer program to determine the distribution system reliability indices using Time Sequential Monte Carlo simulation consists of following steps:

Step1: Define the system i.e. input data such as location of components, failure rate, failure duration, load connected etc. of the system.

Step 2: Input number of sample years ‘N’, simulation period ‘T’.

Step 3: Simulation starts, n = 1, t=0.

Step 4: Generate random number [0-1] for each element in the system and convert these random numbers into times to failure (TTF), based on the failure time distribution and the expected time to failure of each element. Using “(11)”, TTF can be calculated. TTF= (-log (U)/λ) x 8760, Where U is random number between 0 to 1.

Step 5: Find the element with minimum TTF.

Step 6: Generate random number and converted this into repair time (RT) for this element according to probability distribution chosen.

Step 7: Generate random number and converted this into switching time (ST) according to probability distribution if applicable. For this research work, switching time is a fixed value of 1 hour.

Step 8: Find the load points that are affected by the failure of this element considering the configuration and status of breakers, disconnects, fuses and alternate supply and record a failure for each of these load points.

Step 9: Determine the failure duration depending upon the configuration and status of breakers, disconnects, fuses and alternate supply and record the outage duration for each failed load point.

Step 10: Generate a random number and convert this into TTF for the failed element.

Step 11: Go back to Step 5 if the simulation time is less than the mission time. Otherwise, go to Step 12.

Step 12: Calculate the average value of the load point failure rate and failure duration for the sample years.

Step 14: Calculate the system indices for the sample years.

Step 15: Return to Step 4 if the simulation time is less that the total simulation period. Otherwise, output the results.

In the time sequential Monte Carlo simulation technique, the effect of the events of each component on the power system is chronologically analyzed. This technique has been applied in this paper to evaluate the reliability indices. The simulation program developed evaluates the reliability indices for a general radial distribution system.

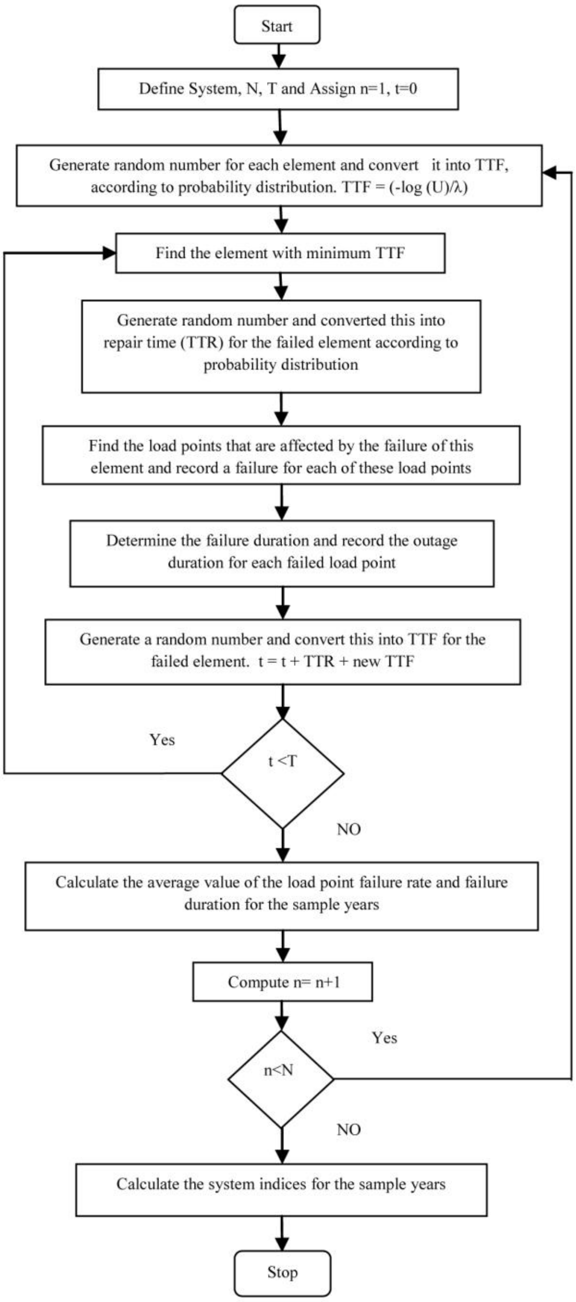

Figure 4: Flowchart for Monte Carlo Simulation.

The program in VC++ is developed to evaluate the reliability indices. Feeders from practical test system known as RBTS Bus 6 are considered for the sequential analysis. The random numbers generated do not appear in any table since they were inserted directly in the calculation formulas when necessary. Flowchart for above algorithm is given in Figure 4.

The following modeling assumptions are made to simplify the program:

1. Circuit breakers are assumed to work instantly and without any failures or delay.
2. Alternate supply is assumed to be available whenever needed and can supply all necessary power to the load. No transfer load restriction exists.
3. Fuses are assumed to work without failures.
4. No common mode failures occur.
5. No busbar failures occur.
6. The same probability distributions are assigned to the same type of components.

III. RESULTS

Comparison of load point indices and system indices for Bus 6 using both analytical (A) and Monte Carlo simulation (S) techniques are presented in “Table 1”.

A. Description

The test system is shown in Fig 3. The data is used from paper [1] by L. Goel et al. (1991). The lines and cables have a failure rate which is approximately proportional to their length. Therefore, the main feeder sections (L1-L64) have a failure rate of 0.065 f/ km-yr, transformer failure rate of 0.015 f/ km-yr, repair time should be 5 hours for main and lateral section and 200 hours for transformer section and switching time is 1 hour considered in this network. Some of the components that have not been taken into account are assumed to be 100% reliable.

B. Calculations for Feeder 1 and Feeder 2

To calculate the load point failure rate have to consider all the main section line failures and particular load point lateral and transformer section line failures using “(1)”. To calculate the load point unavailability has to consider all the main section line failures and particular lateral and transformer sections line failures that should multiplied with particular load point repair time, otherwise switching time has to multiply for all main sections using “(2)”. By using Equation 3 average repair time can be calculated. Feeder 1 and Feeder 2 is normally opened. To calculate the Feeder 1 and Feeder 2 indices have to consider number of customers, average load, peak load and calculated failure rate, unavailability and average repair time for each load point using “(4) to (10)”.

C. Calculation for Feeder 3

The failure mode and effect analysis (FMEA) method used in analytical techniques and is applied on Feeder 3. While calculating load point failure rate has to consider all the main sections line failure and particular lateral and transformer sections line failures. But in unavailability calculation has to consider particular lateral and transformer section line failure that should multiply with repair time. Then all the main sections has to consider and particular load point main section line failures from supply side should multiply with repair time; otherwise switching time has to multiply. Because there is no alternate supply connected to this feeder. Average repair time is calculated using “(3)”. To calculate the Feeder 3 indices have to consider number of customers, average load, peak load and calculated failure rate, unavailability and average repair time for each load point using “(4) to (10)”.

D. Calculation for Feeder 4

In feeder F4 there are three sub feeders namely F5, F6 and F7 are considered. To calculate the load point failure rate by using Equation 1 for the feeder F4 has to consider all the main section line failures and particular lateral and transformer sections line failures, and not necessary to consider the sub feeders. To calculate the Unavailability consider all the main section line failures should multiply with repair time before the disconnect switch. After the switch main section line failure should multiply with switching time. To calculate the sub feeder load point indices has to consider feeder F4 main, lateral and transformer failures and particular sub feeder failures using “(1) to (3)”. To calculate the Feeder 4 indices has to consider number of customers, average load, peak load and calculated failure rate, unavailability and average repair time for each load point using “(4) to (10)”. To calculate the System indices has to consider the entire load point Failure rates, Unavailability, Average repair time, Number of customers connected, Average load and Peak load using “(4) to (10)”.

TABLE.1: AVERAGE LOAD POINT FAILURE RATES

Load points	Failure rate (f/yr)		
	Published by Analytical method	Developed method by Analytical	Developed by Monte-Carlo method
LP1	0.3303	0.33025	0.3317
LP5	0.34	0.34	0.3349
LP10	0.3795	0.3595	0.3624
LP15	0.2373	0.23725	0.2311
LP20	1.6725	1.6725	1.6738
LP25	1.6725	1.6725	1.674
LP30	2.225	2.225	2.5975
LP35	2.537	2.537	2.5845
LP40	2.511	2.511	2.6258

TABLE.2: AVERAGE ANNUAL LOAD POINT OUTAGE TIME OR ANNUAL UNAVAILABILITY

Load points	Unavailability(hr/yr)		
	Published by Analytical method	Developed method by Analytical	Developed by Monte-Carlo method
LP1	3.67	3.666	3.6954
LP5	3.68	3.676	3.856
LP10	3.66	3.656	3.541
LP15	0.84	0.835	0.795
LP20	8.4	8.40	8.654
LP25	11.29	11.287	11.568
LP30	14.05	14.05	14.23
LP35	12.72	12.724	12.985
LP40	15.48	15.48	15.62

TABLE.3: AVERAGE LOAD POINT OUTAGE DURATION OR REPAIR TIME

Load points	Average Repair Time(hr/f)		
	Published by Analytical method	Developed method by Analytical	Developed by Monte-Carlo method
LP1	11.1	11.101	11.1409
LP5	10.81	10.811	11.015
LP10	10.17	10.171	9.7716
LP15	3.52	3.52054	3.442
LP20	5.02	5.0233	5.170
LP25	6.75	6.74887	6.910
LP30	6.31	6.31460	5.478
LP35	5.02	5.0153	5.0240
LP40	6.16	6.164	5.9484

TABLE.4: SYSTEM INDICES FOR BUS 6

Indices	Methods	Feeder 1	Feeder 2	Feeder 3	Feeder 4	System
SAIFI	(A)	0.33566	0.36739	0.242170	1.977813	1.00664
	(S)	0.33539	0.36916	0.233313	1.98777	1.0111
SAIDI	(A)	3.68285	3.713983	3.591034	1.043973	6.66878
	(S)	3.66304	3.605774	3.621233	11.35233	6.73997
CAIDI	(A)	10.971	10.10886	14.82853	0.527842	6.62473
	(S)	10.92167	9.767469	15.52088	5.711089	6.66595
ASAI	(A)	0.999579	0.999576	0.99959	0.998735	0.99923
	(S)	0.999581	0.999588	0.999586	0.998704	0.99923
ASUI	(A)	0.000420	0.000423	0.00041	0.001264	0.00076
	(S)	0.000418	0.000412	0.000413	0.001295	0.00076
ENS	(A)	4.23152	4.717013	5.902532	57.79038	72.6414
	(S)	4.225334	4.559431	5.904939	59.18776	73.8774
AENS	(A)	5.538650	4.8679191	268.2969	48.85070	24.72479
	(S)	5.530542	4.705295	492.0783	50.03192	25.14549

E. Average value of Load Point and System Indices

The published results by analytical method results and developed program results by analytical and Monte-Carlo method for average load point failure rates, average annual load point outage time or annual unavailability and average load point outage duration or repair time are shown in “Tables from 1 to 3”.

The system indices for Bus 6 were calculated using both analytical (A) and Monte Carlo simulation (S) techniques and are shown in “Table 4”.

F. Comparison of Analytical and Monte Carlo Simulation Method

“Tables from 1 to 3” shows results of the average load point failure rates indices, average annual load point outage time or annual unavailability and average load point outage duration or repair time for all feeders obtained using analytical (A) and simulation techniques (S). The results obtained by analytical method are compared by the results of simulation method. The systems indices results obtained by analytical method are compared by the results of simulation method and are shown in “Table 4”.

By understanding and development of distribution system reliability indices using analytical & Monte-Carlo simulation methods can be further extended to find the predictive reliability indices by changing the network configurations in smart grid environment.

IV. CONCLUSION

This paper introduces the methodology for calculation of distribution system reliability indices using both Analytical and Monte-Carlo simulation techniques. The failure mode and effect analysis (FMEA) method used in analytical techniques is applied on Feeder 3 of Bus 6 of the RBTS. To evaluate load point and system indices, the algorithm and flow chart are described and computer program is developed to implement time sequential Monte-Carlo simulation technique in VC++. A comparison of the load point and system indices for Bus 6 of the RBTS using both Analytical and Monte-Carlo simulation technique are also illustrated. The Monte-Carlo simulation results are very in line with Analytical method and hence the Monte-Carlo simulation technique can further used to model renewable energy sources where it is very difficult to model renewable in analytical methods.

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