Monte Carlo Simulation for Reliability Worth Assessment of Distribution System Considering Momentary Interruptions

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Abstract— **This paper deals with the reliability worth assessment of electric power distribution system considering momentary interruptions. Reliability worth study quantifies the interrupted energy and also monetary losses incurred by utility customers due to electric power failures. Sequential Monte Carlo (MC) simulation technique is applied for the assessment purpose. The advantage of using MC simulation over the analytical approach is that uncertainty of associated random variables can be taken into consideration in MC simulation. Case studies are conducted on the Roy Billinton Test System connected to bus 4 distribution system. The results of MC simulation technique are complementary to those calculated by the analytical method.**

Keywords— momentary interruption; Monte Carlo simulation; power distribution system; reliability worth evaluation

I. Introduction

The primary objective of an electric utility is to meet the customer load demand in an economical manner with minimal interruption. Reliability level of power system can be influenced by economic considerations in power systems design and planning. Adding protection system components and alternative supply in feeder design configurations may increase the level of system reliability which requires more investment. Some customers may be willing to pay more for increased reliability, while others may select a less reliable option [1]. The level of impact for varying reliability level depends on the characteristics of the users (e.g., type of user, size of operation, energy dependency, types of standby systems, etc.) and also on the characteristics of the interruptions (e.g., duration, frequency, and time of occurrence) [2].

Reliability worth is assessed for evaluating the interrupted energy and interrupted service cost/losses experienced by customers due to power outages considering a variety of system design configurations [3]. Expected Energy Not Supplied (EENS) and Expected Cost of Interruption (ECOST) are two important indices for the reliability worth assessment of distribution networks [3]. Evaluation of the monetary value of the unsupplied energy of a distribution system could be crucial in determining the best equity investment and also in identifying which regions or sectors of a distribution system should be cut off in the case of a power outage.

Due to the random nature of interruption frequency and length, EENS and ECOST are unexpected attributes as well [4]. The frequency and duration of interruptions are the important factors in calculating the reliability indices. On the other hand, Sector Customer Damage Function (SCDF) [5, 6] reveals the cost of interruption based on the distribution of interruption length for a specific type of customer sector. Reliability indices can be evaluated using both analytical and simulation approaches [1]. An analytical approach might be augmented by a simulation solution that could generate a more trustworthy result of the EENS and ECOST calculations by taking random variables into account [7, 8].

Monte Carlo (MC) simulation is widely used for the distribution system reliability evaluation [9-14]. It can be simulated in either a sequential or non-sequential mode [15]. In non-sequential mode, all component states are sampled and a non-chronological system state is obtained [16]. In the sequential MC, the operating and restoration states of the components are sequentially sampled by considering their probability distribution [17, 18]. Therefore, sequential MC is typically preferred over non-sequential MC method since it considers the chronological issues.

Sustained and momentary interruptions are typically two types of interruptions associated with an outage on the distribution network [19]. The frequency of occurring momentary interruptions is more than the sustained interruption. However, the impact of the momentary interruption can be varied depending on the type of customer sector. In this paper, we concentrate to evaluate the EENS and ECOST indices based on MC simulation considering only the momentary interruptions in the power distribution system.

This paper is organized as follows. Section II describes the modelling of EENS and ECOST. Section III describes the methodology. Section IV presents the test system. Section V describes the test system results. Impacts of different network configurations, failure rate variation of components are investigated in this section. Simulation results obtained from MC method are compared with those from analytical method. Finally, Section VI provides the concluding remarks.

II. Modelling of EENS and ECOST

In this study, the component model is represented by the two-state model i.e. up and down states as shown in Fig. 1. The up and down states indicate the operating and restoration

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mode of the component, respectively. Fig. 2 shows an example of operating and restoration cycles of a component. Time-to-failure (TTF) and Time-to-repair (TTR) are both random variables [1].

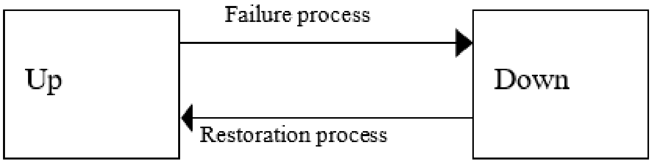

Fig. 1. State space diagram of component

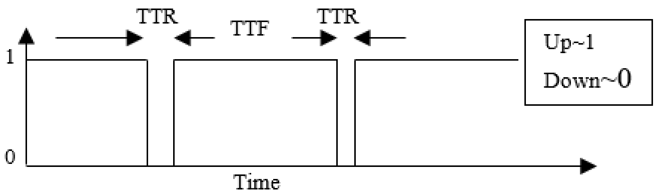

Fig. 2. Component operating and restoration cycles

The artificial operating and restoration histories for each outage event are generated using the exponential probability distribution function as (1) and (2), respectively.

$$T_{ui} = -1/\lambda_i \times ln(U) \quad (1)$$

$$T_{di} = -r_i \times ln(V) \quad (2)$$

T_{ui} and T_{di} indicate the operating and restoration histories of a component i, respectively. λ_i is the mean failure rate (failure/year) for a momentary event and r_i is the mean TTR (hour/failure) of the momentary outage event i. U, V are uniformly distributed random variables between [0, 1]. λ_i and r_i can be modelled using stochastic differential equations.

The SCDF calculates the cost of customer interruption based on the duration of the interruption [6]. The cost data is interpreted linearly in this study if there is any interruption lasting between 0.5 and 15 seconds. Based on average cost model (C_{avg}) from SCDF, the interruption cost related to a load point P failure for a duration r_p can be expressed as:

$$C_p = C_{avg}(r_p), \text{ (\$/kW)} \quad (3)$$

where C_p is the customer momentary interruption cost related to a load point P.

For a component failure i, the value of average outage rate A_i could be calculated using the following expression [20]:

$$A_i = \frac{Q}{\sum_{n=1}^{N} T_{ui}} \text{ (f/yr)} \quad (4)$$

where Q is the number of times component i fails during whole simulation period and N is the desired number of simulated periods. The value of component annual unavailability, B_i due to event i could be calculated using the following expression:

$$B_i = \frac{\sum_{n=1}^{N} T_{di(n)}}{\sum_{n=1}^{N} T_{ui(n)} + \sum_{n=1}^{N} T_{di(n)}/_{8760}} \text{ (hr/yr)} \quad (5)$$

For load point P, average outage rate F_p is evaluated as follows by accumulating the outage rate of all the momentary failure events associated to this load point [20].

$$F_p = \sum_{i=1}^{n_i} A_i \text{ (f/yr)} \quad (6)$$

where n_i denotes the number of momentary outage events interrupting the service of the load point P.

For load point P, annual unavailability U_p is evaluated by accumulating the unavailability of all the failure events connected to the load point as follows.

$$U_p = \sum_{i=1}^{n_i} B_i \text{ (hr/yr)} \quad (7)$$

System EENS and ECOST can be calculated using (8) and (9), respectively.

$$EENS = \sum_{p=1}^{n_p} U_p L_p \text{ (MWh/yr)} \quad (8)$$

$$ECOST = \sum_{p=1}^{n_p} F_p L_p C_p \text{ (k\$/yr)} \quad (9)$$

where n_p is the total number of supply points and L_P is the average load level per load point.

III. SIMULATION PROCESS

The proposed MC simulation method is a simple way to forecast assumptions emerging from stochastic simulation by averaging across a large number of samples on a single fine grid level [21]. Let X be the reliability index for this study either EENS or ECOST and $E[X]$ is the expectation or quantity of interest. Also, let $E[X_A]$ be the approximation to $E[X]$. If $X_A^{(i)}$ is the ith sample of X_A and N_{MC} is the number of independent MC samples. Then, an unbiased MC estimator for $E[X_A]$ is

$$\hat{Z}_{MC} = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} X_A^{(i)} \quad (10)$$

where $E[\hat{Z}_{MC}] = E[X_A]$, $N_{MC}^{-1} V[X_A]$ is the variance of this estimate and the rms error is $O(1/\sqrt{N_{MC}})$. To achieve an accuracy of ε, it requires $N_{MC} = O(\varepsilon^{-2})$ samples to be simulated.

Following simulation steps are followed to estimate EENS and ECOST for the current study.

Step 1) For each component of the distribution system, the failure rate, repair time and switching time as well as load, cost data and desired accuracy are initially defined.

Step 2) Generate two random numbers between [0, 1] using random number generator. Convert these random numbers into operating and restoration history of each failure event. The exponential probability distribution is used to create the operational history of each component.

Step 3) Determine the average outage rate and annual unavailability of the failure event using equations (4) and (5), respectively. Similarly, steps (2) – (3) are repeated for each event in the distribution system.

Step 4) Find all the load points affected by this outage event.

Step 5) Calculate average failure rate and annual unavailability of load point using (6) and (7). Steps (2)–(5) are then repeated for each load point in the distribution system.

Step 6) Compute the indices EENS and ECOST using equations (8) and (9), respectively. The whole process from steps (2) – (6) is repeated using (10) until desired accuracy is reached.

IV. TEST SYSTEM

A distribution system connected to bus 4 of the benchmark Roy Billinton Test System (RBTS) [22] as shown in Fig. 3 is considered to as the test system to conduct this study. Feeder and load data are found in [22]. Table 1 shows the momentary failure rate and repair time of components [23]. Table II presents customer sector-wise interruption cost data with interruption duration due to the momentary interruptions [23].

TABLE I. MOMENTARY FAILURE RATE AND REPAIR TIME

Component	Failure rate (f/yr)	Repair/Switching time (hr)
Line	0.16/km	3.0
Transformer (assume)	0.10	10.0
Switch		0.5

TABLE II. CUSTOMER INTERRUPTION COST WITH DURATION

Customer Type	Cost (k$/yr)	
	0.5 sec	15 sec
Residential	0.00068	0.0052
Small industrial	0.05412	0.4055
Commercial	0.02932	0.2198

V. TEST RESULTS AND ANALYSIS

In this section, test results are analyzed considering four different aspects (a) impact of feeder design configurations (b) impact of the variation of failure rate of line (c) impact of the variation of failure rate of transformer and (d) impact of customer types. Considering momentary interruption, EENS and ECOST are evaluated in four different cases as shown in Table III for each of the aspect. The results between analytical method and MC simulation are compared.

A. *Effect of Feeder Design Configurations*

Over 80% of the customer interruptions are occurred due to the failures in the distribution system. The effect of momentary interruption can't be avoidable since it happens more frequently than sustained interruption. The adoption of various protection and switching devices could reduce the occurrence and duration of such interruptions while also can improve network reliability. In other words, additional service investment could reduce the cost of interruption. Four case studies are considered as shown in Table III to assess the impact of feeder design/operating configurations on EENS and ECOST values due to momentary interruptions. Transformer action is restored through repairing for all the cases.

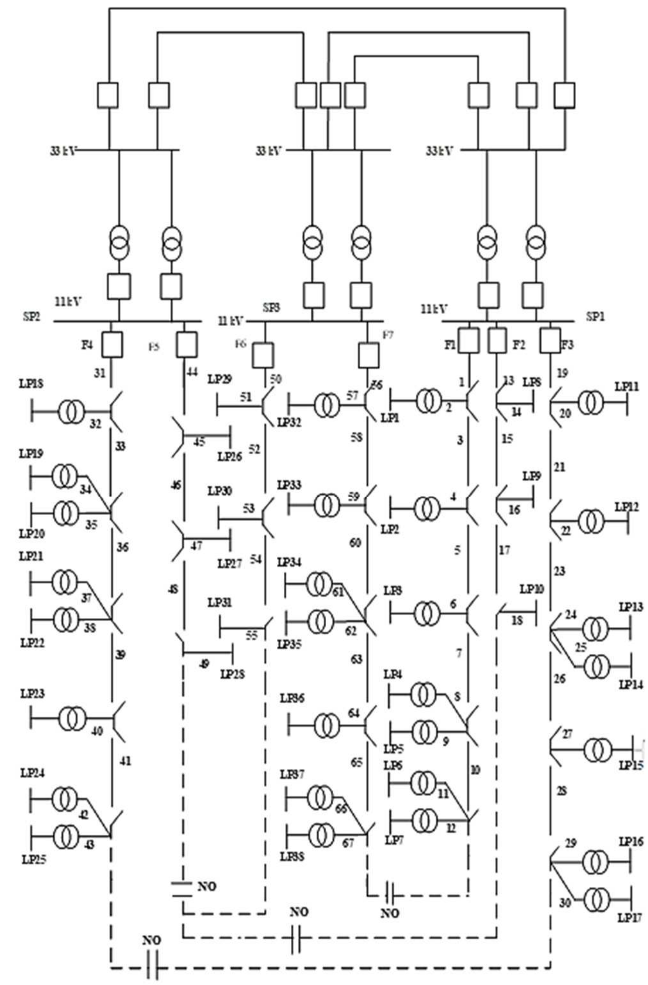

Fig. 3. Single line diagram of RBTS Bus 4

TABLE III. CASES FOR FEEDER DESIGN/OPERATING CONFIGURATIONS

Case	Disconnecting Switches	Fuses	Alternative Supply
A	Yes	Yes	Yes
B	No	No	No
C	No	Yes	No
D	Yes	No	No

Table IV presents the analytical and simulation values of the EENS and ECOST indices for all cases considering momentary interruptions. It is seen that the maximum EENS value is found in case B where disconnecting switches, fuses and alternative supply are not considered in feeder design. On the other hand, lowest EENS value is found in case A where the protective devices and alternative supply are considered. Similarly, EENS values in cases C and D varies with availability of protective devices. This is true for the variation ECOST values as well. In case B, ECOST value is the maximum due to less investment for the protective equipment compared to other feeder configurations. Indeed, the greater the investment in protection system components, the lower the effect of interruption and therefore the value of ENS and ECOST are also reduced. While the values are compared, the percentage of difference between the analytical and simulation results is less than 5% which is acceptable in reliability studies.

TABLE IV. EENS AND ECOST VARIATION FOR FEEDER CONFIGURATIONS

Case	**EENS (kWh/yr)**		**ECOST (k$/yr)**	
	Analytical	**MC**	**Analytical**	**MC**
A	28.95	28.92	0.4523	0.4371
B	188.59	188.57	1.4739	1.4213
C	60.56	59.38	0.7192	0.6971
D	122.18	121.18	1.3231	1.2718

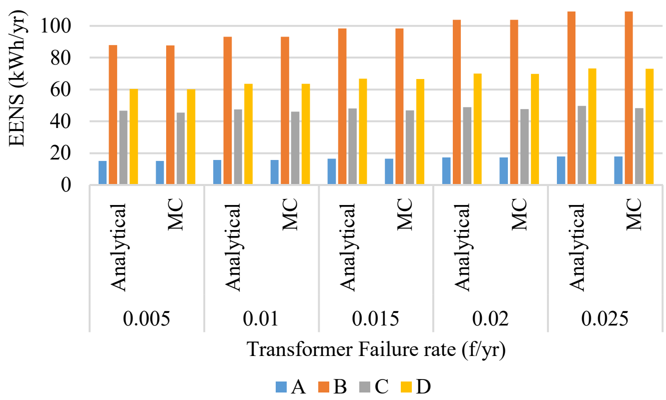

Fig. 4. Variation of EENS with the transformer failure rate

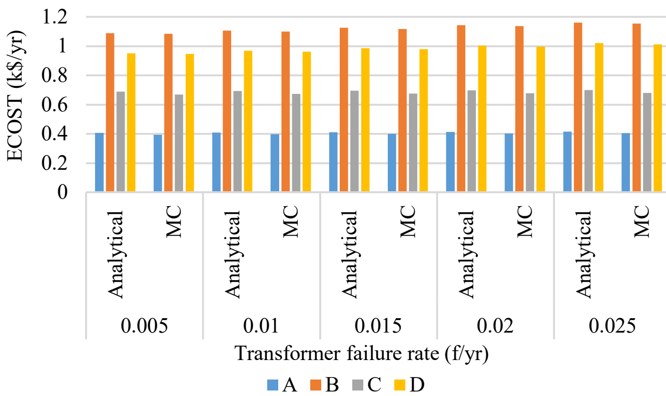

Fig. 5. Variation of ECOST with the transformer failure rate

B. *Effect of Transformer Failure Rate*

Figs. 4 and 5 show the impact of transformer failure rate on EENS and ECOST considering momentary interruptions for all cases, respectively. Transformer failure rates are varied from 0.005 f/yr to 0.025 f/yr with a 0.005 f/yr increment. It can be seen that the values of EENS for increasing failure rates are therefore increased about 5%, 10%, 15% and 19% for case A in which disconnecting switches, fuses and alternative supply are available. Similarly, if the failure rate of transformers are reduced, then the reliability of the distribution network for other cases would be significantly improved. The maximum EENS is found in case B for failure rate 0.025 f/yr and the minimum in case A for the failure rate 0.005 by taking the consideration of feeder design configurations. On the other hand, in case of ECOST, the values for increasing failure rates are increased about 0.70%, 1%, 2% and 2.5% for case A. The maximum ECOST is seen in case B for failure rate 0.025 f/yr and the minimum in case A for the failure rate 0.005 f/yr by taking consideration of feeder design configurations. In comparison, the MC approach has a respectable precision rate.

C. *Effect of Line Failure Rate*

The distribution system reliability is mainly affected by the failure rate of line. Figs. 6 and 7 show the impact of line failure rate on EENS and ECOST estimation considering momentary interruptions for all cases.

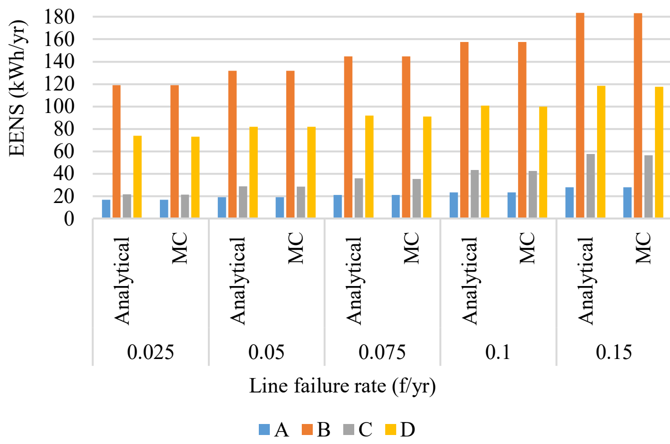

Fig. 6. Variation of EENS with the line failure rate

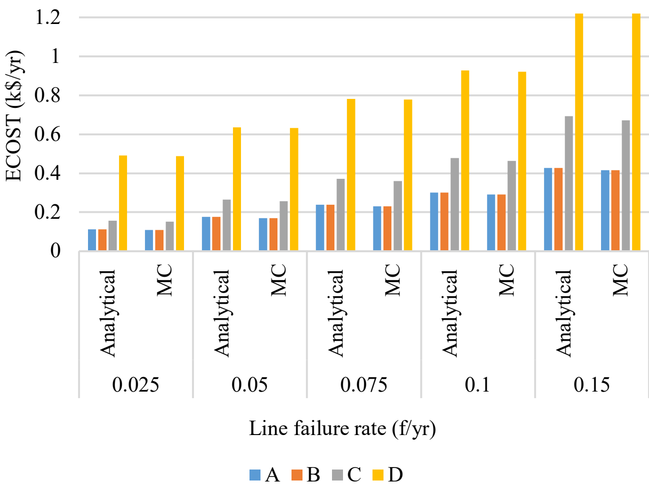

Fig. 7. Variation of ECOST with the line failure rate

The overhead line is an extremely important part of a feeder. The line failure rate has a greater impact on the entire network. To find the impact on EENS and ECOST estimation, a sensitivity analysis is performed with line failure rates ranging from 0.025 f/yr to 0.15 f/yr. As in Figs. 6 and 7, the system ENS and ECOST are increasing at a faster rate as the line failure rate rises. EENS values for increasing failure rates of line are therefore increased about 13%, 27%, 40% and 67% for case A. The maximum EENS is found in case B for failure rate 0.15 f/yr and the minimum in case A for the failure rate 0.025 by taking consideration of feeder design configurations. On the other hand, in case of ECOST, the values are increased about several times for case A for increasing failure rates. The maximum ECOST is found in case B for failure rate 0.15 f/yr and the minimum in case A for the failure rate 0.025 by taking consideration of feeder design configurations. The proposed MC technique can accurately quantify both EENS and ECOST compared to analytical method. Similarly, the length of a transmission line has a major impact on EENS and ECOST analysis, because a long line has a greater impact on the amount of failure than a short line.

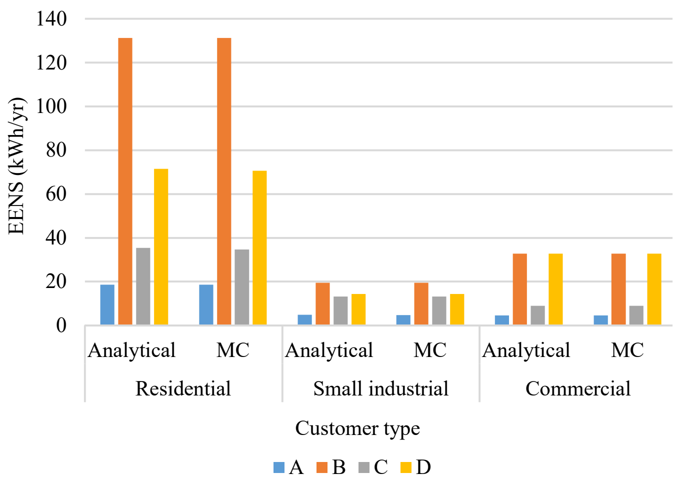

Fig. 8. Variation of EENS with the customer type

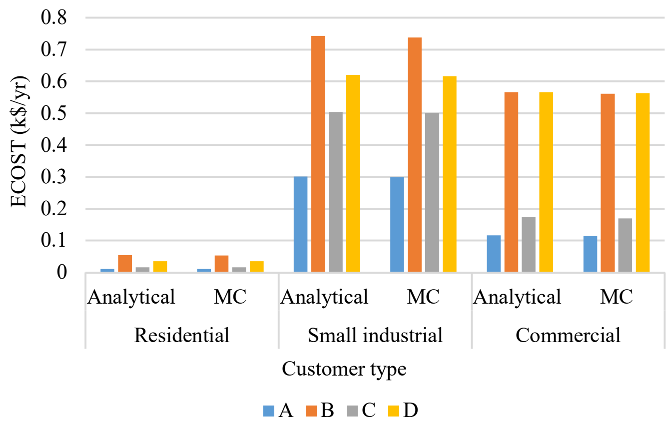

Fig. 9. Variation of ECOST with the customer type

D. Effect of Customer Type

The Bus 4 network has three categories of loads i.e. residential, small industrial user and commercial with a total load capacity of 24.58 MW across all 38 load points [22, 24]. Out of 38 customer points, the number of residential, small industrial user and commercial load points are 22, 9 and 7, respectively. Figs. 8 and 9 depict the impact of customer type on EENS and ECOST. For a specific customer type, both the number of load points and load level have impact to vary the customer EENS. Therefore, residential customers have a larger EENS than commercial customers. Similarly commercial customers have a higher EENS than small user customers in most circumstances. ECOST is greatly influenced by the service cost, failure rate and interruption duration incurred by customers. The ECOST of residential customers is lower than the ECOST of the other two customer segments. Also, if protective components and alternative supply are considered in feeder design, then expenditure will be higher, but the cost of interruption as well as ECOST will be lower. The results reveal that the values for EENS and ECOST obtained using the MC approach are very close to those obtained using the analytical method.

VI. CONCLUSION

The results of Monte Carlo simulation based reliability worth assessment of power distribution system considering momentary interruptions are presented in this paper. EENS and ECOST are calculated as the reliability worth indices. Four cases are considered to investigate the impact of the reliability worth on a RBTS model considering momentary interruptions. The effect of network configurations, line failure rate, transformer failure rate and customer type are also investigated. The results of the MC method are compared with those obtained by the analytical method which show that the results of MC simulation technique are complementary to those calculated by the analytical method. The results presented also indicate that the reliability worth indices are significantly affected by the feeder design configurations, failure rate of components and user type.

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