EFFICIENT APPROACH FOR RELIABILITY EVALUATION OF DISTRIBUTION SYSTEM CONSIDERING MOMENTARY INTERRUPTION

By

Tanjil Ahmed

16121092

Rezuwan Hassan

16121073

Palash Chandra Ghosh

16121079

Mohammad Saiful Huq

14121027

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Department of Electrical and Electronic Engineering

Brac University

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Declaration

We hereby declare that

1. The thesis submitted is our own original work while completing degree at BRAC University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. We have acknowledged all main sources of help.

Student's Full Name & Signature:

Tanjil Ahmed	REZUWAN HASSAN
Tanjil Ahmed	**Rezuwan Hassan**
16121092	**16121073**
Palash Ghosh	Mohammad Saiful Huq
Palash Chandra Ghosh	**Mohammad Saiful Huq**
16121079	**14121027**

Approval

The thesis titled "Efficient Approach for Reliability Evaluation of Distribution System Considering Momentary Interruption" submitted by

Tanjil Ahmed	(ID: 16121092)
Rezuwan Hassan	(ID: 16121073)
Palash Chandra Ghosh	(ID: 16121079)
Mohammad Saiful Huq	(ID: 14121027)

of Spring, 2020 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Bachelor of Science in Electrical and Electronic Engineering on 27th June, 2020.

Examining Committee:

Supervisor:

(Member)

A. S. Nazmul Huda, PhD
Assistant Professor, Department of
Electrical and Electronic Engineering
Brac University

Thesis Coordinator:

(Member)

A. S. M. Mohsin, PhD
Assistant Professor, Department of
Electrical and Electronic Engineering
Brac University

Head of the Department:

(Chair)

Shahidul Islam Khan, PhD
Professor and Chairperson, Department of
Electrical and Electronic Engineering
Brac University

Abstract

The purpose of an electric power system is to provide electricity to its customers with acceptable levels of reliability at the lowest possible cost. In this thesis, we propose an efficient method for power distribution system reliability evaluation considering momentary interruption. The proposed method is based on sequential Monte Carlo (MC) simulation technique. The method is effectively used for evaluating cost of customer interruption and duration of interruption length in a complex distribution system. A comparative analysis between analytical and MC time sequential simulation based results is also presented. Satisfactory results are obtained from the analysis. Sensitivity analysis of different variables of distribution system reliability is also conducted.

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List of Abbreviations

MC	Monte Carlo
MLMC	Multi-Level Monte Carlo
ENS	Energy Not Supplied
ECOST	Expected Interruption Cost
SCDF	Sector Customer Damage Function
TTF	Time-to-Failure
SDE	Stochastic Differential Equation
RBTS	Roy Billinton Test System
SP	Supply Points

Chapter 1

Introduction

1.1 Importance of Reliability Analysis of Distribution System

The purpose of an electric power system is to provide electricity to its customers with best electrical distribution service at lowest cost possible with acceptable levels of reliability. Both economy and reliability aspects often clash with current power management, planning and operating systems with a broad spectrum of challenging issues. The service package a customer is subscribed to is directly related to the power disruption frequency & cost. If a user gets anything less than the service quality they are subscribed to, they may claim for being excessively charged. Not every user can afford the same quality. Some consumers may be happy to pay more to receive greater reliability and some may incline the package and purchase an alternative service package of lesser reliability [1].

Estimation of the Expected Interruption Costs (ECOST) and Energy Not Supplied (ENS) are critical aspects of distribution systems reliability assessment [2]. Identifying the monetary value of ENS of a distribution system could play a major role in making an optimal equity investment and in deciding which regions or sectors should be cut off in the event of electricity shortages. ECOST is a totally unpredictable attribute because of the influence of random frequency and interruption length, and this interruption period is nothing but the value of ENS [3]. The key element in ECOST calculation relies on the interruption frequency and duration of interruption. Likewise, the cost of interruption and the distribution of interruption length for a given type of customer found by analyzing the Customer Damage Function Sector (SCDF) [4,5] and These factors differ according to the length of the malfunction and start time. Analytical procedure focused on average duration, load and cost models of interruption may then be supplemented by a simulation solution that could produce the more reliable outcome of the ECOST and ENS calculation by considering random variables [6,7]. Via the simulation method, information could be obtained on the distribution of probability of ENS and ECOST which is necessary for the expansion of distribution systems and long term planning.

1.2 Proposed Approach

The simulation approach generally used in the reliability evaluation of distribution systems [8-13] such as the estimation of ENS and ECOST is based on the Monte Carlo (MC) standard simulation. MC approach produces the stochastic nature of the outages and repair times of components. It can either be simulated in sequential or non-sequential mode [14]. The states of all components are sampled in non-sequential mode, and a non-chronological system state is obtained [15]. But on the other hand, in the sequential approach the up and down cycles of all components are simulated, and the overall operating cycle of the system is obtained by combining all component cycles [15]. The sequential MC mode allows for the consideration of chronological problems [16]. Each state duration sampling approach is generally used to simulate chronological problems that provide different indices of reliability regarding interruption cost and duration of interruption of the load point [17].

1.3 Momentary Interruption

Sustained and Momentary interruptions are typically correlated elsewhere on a delivery network with a malfunction. If there is a flaw, the circuit breaker opens up to resolve the flaw and recloses immediately after a gap of time. Such reclosing activity can occur many times in an attempt to create a temporary fault with continuous operation. If the fault is temporary in nature, a reclosing operation on the breaker should be successful and the interruption will only be temporary, therefore the customer experiencing a momentary interruption with that faulty feeder. Even so, when it is the permanent fault, it should fail to reclose operations on the breaker and the reclosing device will be trapped-out, because of that, the customer experiences a sustained interruption with faulty feeder. In fact, the momentary interruptions are triggered by defensive mechanisms in reclosing behaviors. Dead time is the cause of momentary interruptions. [18].

1.4 Thesis Outline

Major contribution of this thesis comprises of five sections organized as follows.

- **Chapter 1** introduces the importance of ENS and ECOST in the distribution system along with the proposed approach and momentary interruption.
- **Chapter 2** describes approaches that we are going to use to evaluate the system ENS and ECOST.
- **Chapter 3**, ENS and ECOST methodologies have been listed in this section. This segment comprises five sub-sections: generation of operating history, modeling of load, modeling of per unit interruption cost, modeling of system ENS and ECOST and both ENS and ECOST simulation phases.
- In **Chapter 4**, definition of Bus 4 network and test device result is provided. The network overview portion of Bus 4 consists of two sub-sections: description of distribution network, system data and the result component consists of four sub-sections: Effect of network reinforcement, effect of transformer failure rate, effect of line failure rate, effect of network configuration and customer type.
- Finally, in **Chapter 5**, the thesis is concluded with summary and future work.

Chapter 2

Approaches for Evaluating Reliability Indices

2.1 Analytical Method

The basic procedure used in the generalized analytical method [1] of evaluating energy that is not supplied and cost indices of customer interruption can be summarized in the following steps:

Step 1: Find the average failure rate λ_j, the average repair time r_j and the average switching time s_j for a failed element j.

Step 2: Find the affected load points using a direct search technique according to the network configuration. Sum of all unavailability of a load point $U_{ij,}$ the failure rate λ_{ij} and the failure duration r_{ij} *for* an affected load point ***i*** can be calculated using Equations (2.1), (2.2) and (2.3).

$$\boldsymbol{\lambda_{ij} = \lambda_j \prod_{k=1}^{Npr}(1 - p_k)} \tag{2.1}$$

where p_k is the probability that fuse (or breaker) *k* operates successfully. N_{pr} is the total number of breakers and ruses between the load point ***i*** and the failed element *j*.

$$\boldsymbol{r_{ij} = p_a s_j + (1 - p_a)\, r_j} \tag{2.2}$$

where p_a is the probability of being able to transfer load for a load point that can be isolated from the failed element. p_a is zero for load points that cannot be isolated by disconnect switches from the failed element j.

$$\boldsymbol{U_{ij} = \sum (l_j\, \lambda_j\, r_j)} \tag{2.3}$$

where $\boldsymbol{l_j}$ is the length of the line for affected load point *i*.

Step 3: Using the outage time r_{ij} and the customer type at load point *i*. determine the per unit (kW) interruption cost c_{ij} using the corresponding sector customer damage function (SCDF).

$$c_{ij} = f\,(r_{ij}) \tag{2.4}$$

where $f\,(r_{ij})$ is the SCDF.

Step 4: Evaluate the energy not supplied ENS_{ij} and expected interruption cost $ECOST_{ij}$ of the load point *i* caused by failure element j.

$$ENS_{ij} = L_i U_{ij} \tag{2.5}$$

$$ECOST_{ij} = L_i\, c_{ij}\, \lambda_{ij} \tag{2.6}$$

where L_i is the average load point of i.

Step 5: Repeat 1-4 for all elements in order to calculate total load point ENS_i, $ECOST_i$ using the following equations:

$$ENS_i = L_i \sum_{j=1}^{Ne} U_{ij} \tag{2.7}$$

$$ECOST_i = L_i \sum_{j=1}^{Ne} c_{ij}\, \lambda_{ij} \tag{2.8}$$

where *Ne* is the total number of elements in the distribution system.

Step 6: Repeat 5 until the ENS_i, $ECOST_i$ of all the load points are evaluated.

Step 7: Evaluate the total system *ENS*, *ECOST* using the following equations.

$$ENS_i = \sum_{i=1}^{Np} L_i \sum_{j=1}^{Ne} U_{ij} \tag{2.9}$$

$$ECOST_i = \sum_{i=1}^{Np} L_i \sum_{j=1}^{Ne} c_{ij}\, \lambda_{ij} \tag{2.10}$$

where *Np* is the total number of load points in the system.

2.2 MC Method

Our proposed approach is, MC method, which is an easy way to predict assumptions resulting from stochastic simulation where ENS and ECOST are estimated by averaging over a large number of samples on a single fine grid level [19]. Let X be the factor for this study 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

$$\boldsymbol{\hat{Z}_{MC}} = \frac{\boldsymbol{1}}{\boldsymbol{N_{MC}}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{N_{MC}}} \boldsymbol{X_A^{(i)}} \tag{2.11}$$

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 $\mathcal{O}(1/\sqrt{N_{MC}})$.

To achieve an accuracy of ε, it requires $N_{MC} = \mathcal{O}(\varepsilon^{-2})$ samples to be simulated. The number of measurements often decreases with a growing degree of precision. Since the samples are running at the finest level, the accuracy in the MC method is sufficiently accurate.

Chapter 3

Methodology

3.1 Generation of Operating History

For generating the operating history of any component, the stochastic model of component Time-to-Failure (TTF) is first developed. Consider λ_i and r_i are the failure rate and repair time of a component i, respectively. Also, consider the SDE of TTF is driven by the Brownian motion [20]. If $S_{\lambda i(t)}$ is the TTF of an event i at a time t, then SDE of TTF with defined drift μ, volatility σ and initial TTF can be modelled using the Brownian motion W on the whole time interval $[0, T]$ [21] as follows:

$$\boldsymbol{dS_{\lambda i(t)} = \mu[S_{\lambda i(t)}, t]dt + \sigma[S_{\lambda i(t)}, t]dW} \tag{3.1}$$

In this paper, the SDE is solved by the Milstein discretisation scheme [22]. The discretization scheme with n time-steps, step size $h = T/n$ and Brownian increments ΔW_m could be written as:

$$\boldsymbol{S_{\lambda i(m+1)} = S_{\lambda i(m)} + \mu[S_{\lambda i(m)}, t_m]h + \sigma[S_{\lambda i(m)}, t_m]\Delta W_m + \frac{1}{2}\sigma^2[S_{\lambda i(m)}, t_m](\Delta W_m^2 - h)} \tag{3.2}$$

where ΔW_m are the normally distributed independent random variables. $\Delta W_m = W_{m+1} - W_m$ $[m = 0, \dots \dots, n-1]$ and $t_m = kh$ $[k = 0, \dots \dots, n]$. Using Equation (10), the operating history of component i, T_{ui} could be generated as follows:

$$\boldsymbol{T_{ui} = -S_{\lambda i(m+1)} \ln(U)} \tag{3.3}$$

where U is a uniformly distributed random variable between [0, 1].

3.2 Modelling of Per Unit Interruption Cost

The cost of interruption of a load point is found from SCDF [5] for any duration Load point per unit interruption depends on the type of the customer connected at that point. The SCDF describes the expense of consumer disruption as a result of the length of the disruption. It can be shown that the costs per unit of interruption are specific across various consumer segments based on the length of the interruption [25]. For example, when a momentary interruption continues for 15sec, the highest and minimal per unit expense is greater than the 0.5sec interruption. For ECOST, all data and calculations are given in section 4. In this study, a linear interpretation of the cost data is used, where the interruption duration is between 0.5sec and 15sec.

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:

$$\boldsymbol{C_p = C_{avg}(r_p)}, \text{ (\$/kW)} \tag{3.5}$$

Here C_p is the customer interruption cost related to a load point P. From SCDF, only the average monetary losses of customer interruptions are found.

3.3 Modelling of ENS and ECOST

For a component failure i, the value of average outage rate B_i could be calculated using the following expression [25]:

$$\boldsymbol{B_i = \frac{M}{\sum_{n=1}^{N} T_{ui}}}, \text{ (f/yr)} \tag{3.6}$$

where M is the number of times component i fails during whole simulation period and N is the desired number of simulated periods.

For load point P, average outage rate F_p is evaluated as follows by accumulating the outage rate of all the failure events connected to this load point [25].

$$F_p = \sum_{i=1}^{n_i} B_i, \text{ (f/yr)} \tag{3.7}$$

where n_i denotes the number of outage events interrupting the service of the load point P. We can determine the overall ENS of the systems by means of equations (3.4) and (3.7). The overall distribution system ECOST can also be evaluated as follows by using equations (3.4), (3.5) and (3.7).

$$ENS = \sum_{p=1}^{n_p} F_p L_p, \quad \text{(kWh/yr)} \tag{3.8}$$

$$ECOST = \sum_{p=1}^{n_p} F_p L_p C_p, \text{ (k\$/yr)} \tag{3.9}$$

where n_p is the total number of supply points in the system.

3.4 Simulation Process

The stochastic model of ENS and ECOST is established at both coarse and fine levels during the simulation. Initially, the failure rate, repair / switching time are defined for each component of the distribution system [25]. In addition, sample size values for convergence test (N), initial sample size on each level (N_{in}), drift, volatility and target accuracy level are defined. Up-down statuses reflect the pattern of a variable [25]. Every component 's operational history is developed using equation (3.3) according to the exponential probability distribution. Based on peak load, hourly, regular and weekly load diversity variables of increasing load point during the failure cycle is defined using equation (3.4). Following this, the average fault rate of each component is calculated using equation (3.6). By following equation (3.7), the value of each load point total failure rate is determined by averaging the individual value of the variable linked to the related load point. System ENS is evaluated using equation (3.8) and then ECOST is determined using equation (3.9).

A flowchart [25] on coarse and fine levels of the ENS and ECOST calculation is shown in Figure. (3.1)

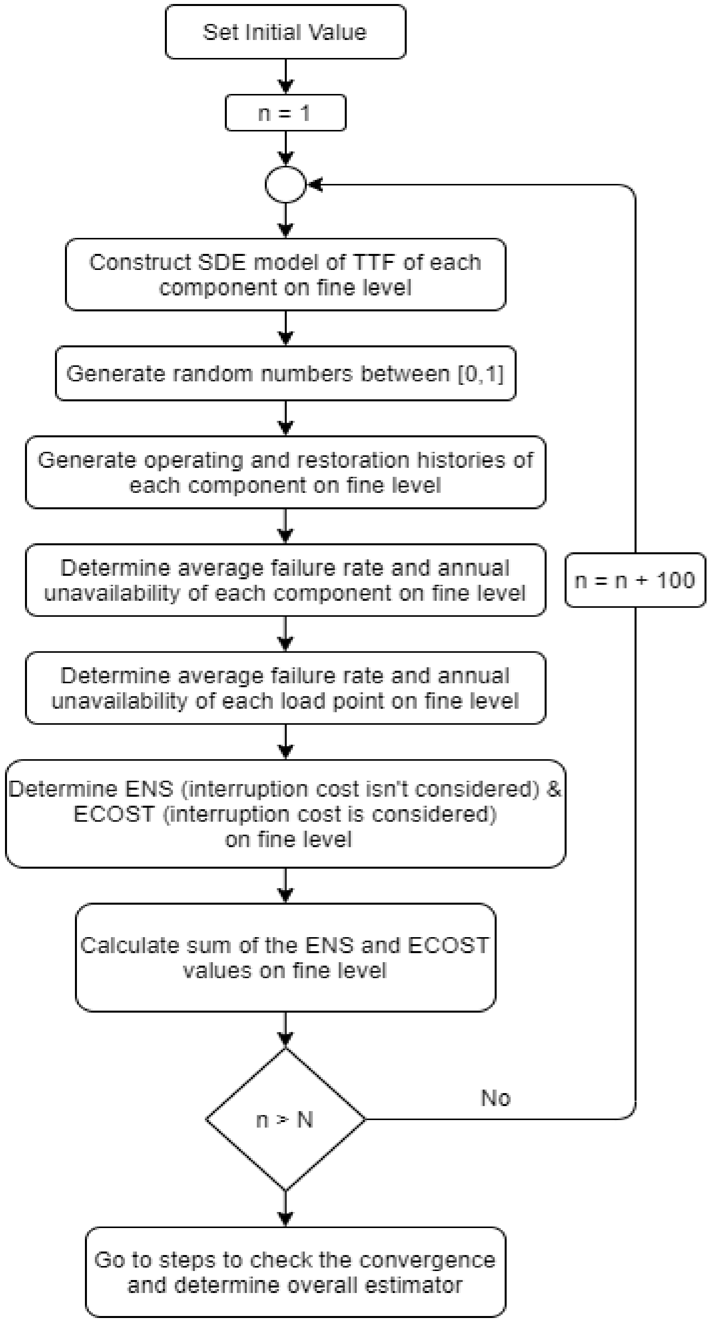

Figure 3.1: Flowchart of ENS and ECOST estimation

Chapter 4

Result and Analysis

4.1 Definition of Bus 4 Network

4.1.1 Peak Load and Length Data

RBTS comprises 5 load bus bars: BUS2-BUS6. We picked BUS4 and developed a distribution network for that bus bar. Table 4.1 shows the peak loads defined in the RBTS for the different types of customers, Table 4.2 presents feeder types and lengths in the RBTS [26] and Figure 4.1 displays a single line diagram of Bus 4 distribution system in the RBTS [25].

Table 4.1 Peak loads in the RBTS

Customer Type	BUS4 (MW)
Residential (R)	19.00
Small User (SU)	16.30
Commercial (C)	4.70
Total	40.00

Table 4.2 Feeder types and lengths

Feeder Type	Length (km)	Feeder Section Numbers
1	0.60	2 6 10 14 17 21 25 28 30 34 38 41 43 46 49 51 57 61 64 67
2	0.75	1 4 7 9 12 16 19 22 24 27 29 32 35 37 40 42 45 48 50 53 56 60 63 65
3	0.80	3 5 8 11 13 15 18 20 23 26 31 33 36 39 44 47 52 54 59 62 66

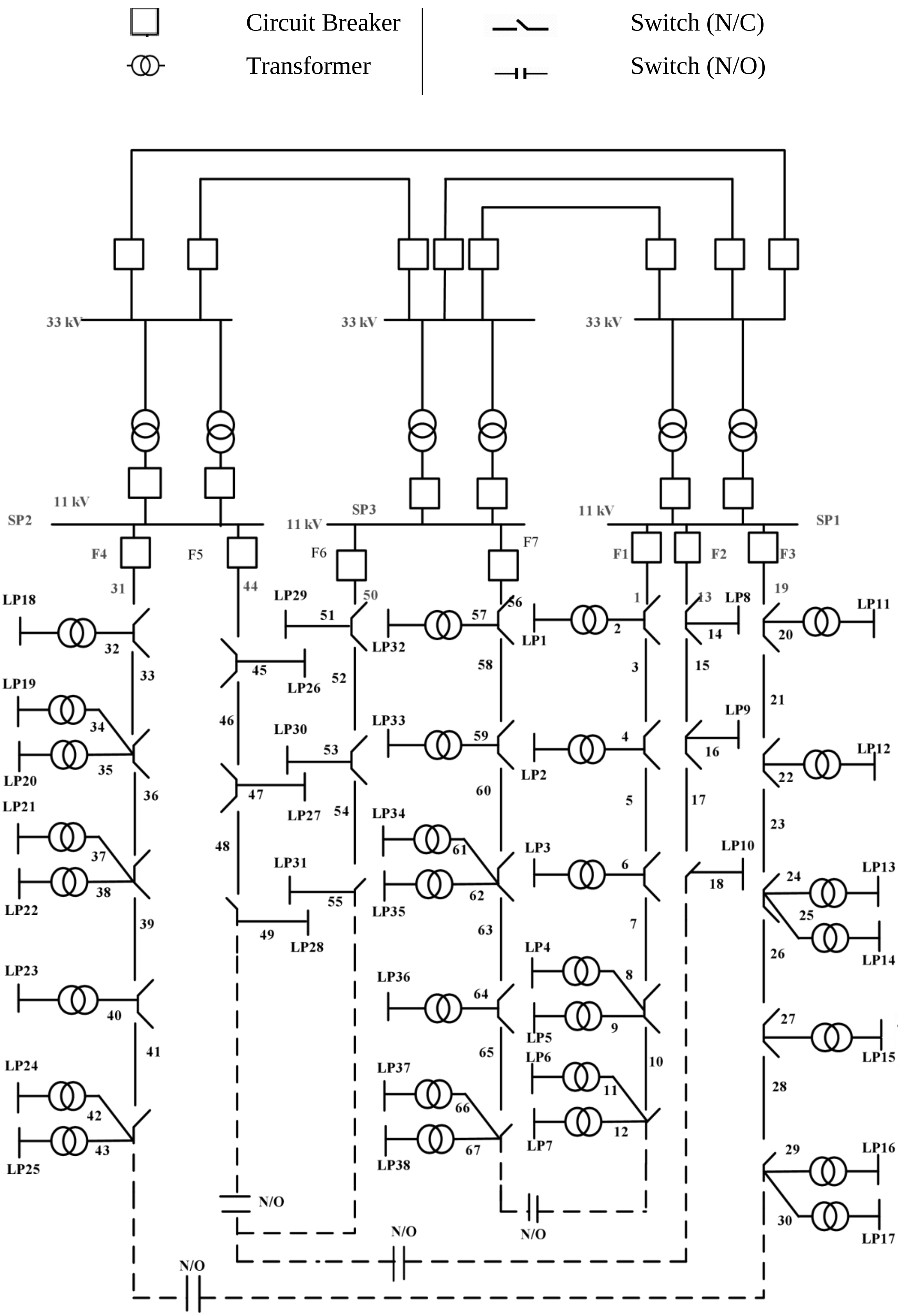

Figure 4.1: Bus 4 distribution system for RBTS

4.1.2 Bus 4 System Data

The assumed reliability data for the components of the 33 kV and 11 kV network as shown in Table 4.3 to Table 4.6. It contains adequate details to carry out the simple assessments used in this paper along with more detailed studies [18, 26].

Table 4.3 Customer data

Number of load points	Load points	Customer type	Load level per load point (MW)		Number of customers
			Average	Peak	
15	1-4, 11-13, 18-21, 32-35	residential	0.545	0.8869	220
7	5, 14, 15, 22, 23, 36, 37	residential	0.500	0.8137	200
7	8, 10, 26-30	small user	1.00	1.63	1
2	9, 31	small user	1.50	2.445	1
7	6, 7, 16, 17, 24, 25, 38	commercial	0.415	0.6714	10
Totals			24.58	40.00	4779

Table 4.4 Loading data

Feeder number	Load points	Feeder load, MW		Number of customers
		Average	Peak	
F1	1-7	3.51	5.704	1100
F2	8-10	3.5	5.705	3
F3	11-17	3.465	5.631	1080
SP 1 Totals		10.475	17.040	2183
F4	18-25	4.01	6.518	1300
F5	26-28	3.0	4.890	3
SP 2 Totals		7.01	11.408	1303
F6	29-31	3.5	5.705	3
F7	32-38	3.595	5.847	1290
SP 3 Totals		7.095	11.552	1293
Bus 4 Totals		24.58	40.00	4779

Table 4.5 Customer interruption (momentary) cost data

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

Table 4.6 Momentary failure and repair time

Components	Failure rate/yr	Repair time/hr
Line	0.16/km	3.0 hr
Circuit Breaker	-	-
Transformer	0.1	10.0 hr
Switch	0.5	-

4.2 Comparison between Analytical and Simulation Results

4.2.1 Effect of Network Reinforcement

Nearly eighty percent of consumer interruptions arise regardless of the failure in the delivery networks. The introduction of different safety and switching devices could reduce the occurrence and length of such interruptions and improve the efficiency of the network, in other words, additional service spending might minimize the interference costs. In Table 4.7 [25], six case studies are shown, where the existence of safety equipment and controls for the B4 system was listed in various combinations. ENS analytical method outcome is determined using equation 2.9 and ECOST from equation 2.10, and ENS simulation technique result is calculated using equation 3.8 and ECOST from 3.9, shown in table 4.8. The maximum value for ENS can be found in case B and the minimum value in case E from Table 4.8. Nevertheless, because of the same fuse design and alternative supply case A and E yield the same result in analytical method. The only change in a low voltage transformer does not affect the system. This goes the same for various case ECOST values. Although, in case B, any of these safety equipment becomes unreliable with time-consuming fixing of the transformer operation. Indeed, the more investment in the protective equipment reduces the effect of interruption and, as a result, the value of ENS and ECOST is lessened. Table 4.8 shows the analytical as well as simulation values. If we evaluate the values, the gap between analytical and simulation does not surpass ±5 percent, in reality only less than 2 percent for ENS and 4 percent for ECOST. The proposed method can estimate ENS and ECOST with an acceptable accuracy by comparing it with the analytical approximation and the proposed method is considerably more efficient than analytical estimation due to few factors such as time consumption, configuration and process development.

Table 4.7 Cases for study of the network reinforcement effect

Case	Disconnecting Switches	Fuses	Alternative Supply	Transformer Action Restoration
A	Yes	Yes	Yes	Repairing
B	No	No	No	Repairing
C	No	Yes	No	Repairing
D	Yes	No	Yes	Repairing
E	Yes	Yes	Yes	Replacement
F	Yes	No	No	Repairing

Table 4.8 ENS and ECOST variation for network reinforcement

Case	ENS (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	50.56	50.44	0.7626	0.7371
E	28.95	28.95	0.4523	0.4382
F	122.18	121.18	1.3231	1.2718

4.2.2 Effect of Transformer Failure Rate

Failure in the transformer, affects huge numbers of the delivery network. If the loss rate of transformers can be minimized, we will see a significant improvement in the delivery network. In our case, the BUS4 system has no transformer in feeder 2, feeder 5 and feeder 6 and if we test certain principles we will have the straightforward evidence that there is no shift in ENS, therefore ECOST is less than any other fault that exists in BUS4 network. To explain the impact better, we varied the rate of transformer failure from 0.005f/yr to 0.025f/yr with the increment of 0.005f/yr. Table 4.9 demonstrates that both ENS and ECOST are rising as transformer failure rate rises and we have considered 6 separate events, shown in Table 4.7. As we anticipated the previous impact in the rate of failure of the transformer, the maximum ENS observed in case B and the minimum in case E, where in analytical method, E provides the same value as in case A owing to the same specification of the fuses and alternate supply and this again goes the same for ECOST. In comparison, the MC process, which is far more efficient than the analytical performance in terms of time usage and consistency, has a reasonable precision rate not exceeding ±5%.

Table 4.9 Variation in ENS and ECOST for different transformer failure rate

Case	Transformer Failure Rate (f/yr)	ENS (kWh/yr)		ECOST (k$/yr)	
		Analytical	MC	Analytical	MC
A	0.005	15.11	15.09	0.4058	0.3945
	0.01	15.83	15.83	0.4082	0.3973
	0.015	16.56	16.56	0.4107	0.3994
	0.02	17.29	17.29	0.4131	0.4017
	0.025	18.02	18.02	0.4156	0.4041
B	0.005	87.83	87.79	1.0898	1.0859
	0.01	93.13	93.09	1.1076	1.1011
	0.015	98.43	98.41	1.1255	1.1185
	0.02	103.74	103.73	1.1433	1.1365
	0.025	109.04	109.04	1.1612	1.1539
C	0.005	46.68	45.48	0.6899	0.6702
	0.01	47.41	46.19	0.6924	0.6727
	0.015	48.14	46.93	0.6948	0.6753
	0.02	48.87	47.65	0.6972	0.6774
	0.025	49.61	48.34	0.6997	0.6799
D	0.005	24.49	24.49	0.6031	0.5997
	0.01	25.86	25.85	0.6104	0.6069
	0.015	27.23	27.23	0.6177	0.6139

	0.02	28.61	28.61	0.6249	0.6213
	0.025	29.98	29.98	0.6322	0.6287
	0.005	15.11	15.11	0.4058	0.3948
	0.01	15.83	15.83	0.4082	0.3968
E	0.015	16.56	16.56	0.4107	0.3991
	0.02	17.29	17.29	0.4131	0.4017
	0.025	18.02	18.02	0.4156	0.4037
	0.005	60.27	60.26	0.9521	0.9469
	0.01	63.53	63.49	0.9692	0.9626
F	0.015	66.79	66.68	0.9864	0.9808
	0.02	70.05	69.91	1.0037	0.9972
	0.025	73.31	73.08	1.0209	1.0121

4.2.3 Effect of Line Failure Rate

The rate of line failure has the most impact on the distribution system. As we mentioned previously and proved with the study, more the incidence of transformer failure, more the ENS and ECOST, but few feeders have no impact of transformer failure. The line failure rate, though, impacts the whole network more than any other flaw that occurs inside the BUS 4 network. To analyze the effect, a sensitivity analysis is conducted in which line failure rate ranges from 0.025 f/yr to 0.15 f/yr for BUS4 network to calculate ENS and ECOST. From Table 4.10, we can get the clear idea that, with the increase in line failure rate, the system ENS and ECOST are increasing at a greater rate. The overhead line is a very essential component of a feeder. Any failure at a feeder line section in the radial system could interrupt the function of all the feeder 's connected supply points. The suggested MC approach can accurately measure all line failure rates for both ENS and ECOST and is far more efficient than the analytical process. Likewise, the length of a transmission line significantly affects the analysis of ENS and ECOST, because a long line affects the amount of failure compared to the short line.

Table 4.10 Variation in ENS and ECOST for different line failure rate

Case	Line Failure Rate (f/yr)	ENS (kWh/yr)		ECOST (k$/yr)	
		Analytical	MC	Analytical	MC
A	0.025	16.83	16.82	0.1120	0.1079
	0.05	19.07	19.06	0.1750	0.1687
	0.075	21.33	21.31	0.2381	0.2308
	0.1	23.56	23.55	0.3011	0.2909
	0.15	28.05	28.05	0.4271	0.4151
B	0.025	118.96	118.96	0.5245	0.5213
	0.05	131.85	131.83	0.6920	0.6888
	0.075	144.75	144.74	0.8595	0.8538
	0.1	157.64	157.58	1.0271	1.0196
	0.15	183.43	183.36	1.3620	1.3533
C	0.025	21.76	21.56	0.1564	0.1519
	0.05	28.94	28.57	0.2638	0.2555
	0.075	36.12	35.56	0.3713	0.3595
	0.1	43.31	42.51	0.4788	0.4636
	0.15	57.66	56.51	0.6935	0.6722

	0.025	31.05	31.04	0.2386	0.2377
	0.05	34.66	34.66	0.3317	0.3296
D	0.075	38.28	38.27	0.4248	0.4221
	0.1	41.88	41.88	0.5153	0.5052
	0.15	49.11	49.07	0.7041	0.6998
	0.025	16.83	16.82	0.1120	0.1081
	0.05	19.07	19.06	0.1750	0.1691
E	0.075	21.32	21.31	0.2381	0.2312
	0.1	23.56	23.56	0.3011	0.2910
	0.15	28.05	28.05	0.4271	0.4125
	0.025	74.07	73.22	0.4904	0.4875
	0.05	81.83	81.95	0.6364	0.6327
F	0.075	91.89	90.97	0.7825	0.7781
	0.1	100.81	100.01	0.9286	0.9222
	0.15	118.61	117.74	1.2208	1.2196

4.2.4 Effect of Network Configuration and Customer Type

The influence of the ENS and ECOST variation in system structure and customer types using analytical and MC computation dependent approaches are shown in Table 4.11. For this reason, the RBTS distribution system linked to Bus 4 is considered [27]. There are three types of loads in the Bus 4 network, such as residential, small user and commercial, with a combined overall load capacity of 24.58 MW for all 38 load points. In most of the cases, residential type customers have higher ENS than commercial type customers and commercial has more ENS than small user type customers. It is due to the number of load points and the number of the customers. More the customers, higher the ENS. Residential type customer has 4700 number of customers, commercial type customer has 70 number of customers and small user type customer has 9 customers, in total 4779 number of customers in BUS4 distribution system. After reviewing the data in Table 4.11, we should have a good understanding that ENS is higher on that customer type, which has more customers or load points. Yet it is also shown, ECOST is higher in small user customer type. Which is due to the investment. There is no transformer in smaller user type customers, investment is less there. If there is alternative supply, fuses and transformer then investment is more, but those elements reduce the interruption cost. Therefore, more the investment lesser the ECOST and from Table 4.11, we can have the solid understanding that, residential type consumer has lesser ECOST than other two customer types. The results obtained from the proposed method should be in agreement with the results from the analytical method for validation. The results show that the values for ENS and ECOST using MC method are very close to analytical method values. These results are generally acceptable for quantification of an application with uncertainty. That confirms the reliability of the proposed MC approach. The MC process increases the empirical system's estimation performance by reducing time and enhancing design strategies. For example, the proposed method requires few numbers of iterations on the finest level and the analytical method needs every individual 38 load points calculations for ENS and ECOST estimation. MC method provides noticeably high accuracy for ENS and ECOST compared to the analytical method as shown in Table 4.11 due to the required time and easy design phase.

Table 4.11 Variation in ENS and ECOST for network configuration and customer type

Customer Type	Case	ENS (kWh/yr)		ECOST (k$/yr)	
		Analytical	MC	Analytical	MC
Small User	A	4.79	4.78	0.3008	0.2992
	B	19.43	19.42	0.7428	0.7376
	C	13.19	13.18	0.5041	0.5008
	D	5.84	5.77	0.4134	0.4101
	E	4.79	4.73	0.3008	0.2991
	F	14.37	14.29	0.6202	0.6161
Commercial	A	4.61	4.61	0.1157	0.1138
	B	32.72	32.72	0.5657	0.5614
	C	9.01	8.92	0.1735	0.1695
	D	10.05	10.04	0.2678	0.2659
	E	4.61	4.61	0.1157	0.1139
	F	32.72	32.72	0.5657	0.5634
Residential	A	18.65	18.64	0.0106	0.0104
	B	131.28	131.24	0.0535	0.0531
	C	35.47	34.70	0.0159	0.0154

D	33.23	33.23	0.0229	0.0227
E	18.65	18.64	0.0106	0.0103
F	71.52	70.69	0.0349	0.0347

Chapter 5

Conclusion

5.1 Summary

This thesis specifically demonstrates the application of the Monte Carlo (MC) method and analytical method. MC decreases simulation time by performing most of the low accuracy simulations at a consequently reasonable cost on the coarse grid systems and fairly few computations are performed at the high precision and high cost on computationally expensive fine grids. The key aim of this thesis is to compare the values of MC method with analytical process considering momentary interruption. The estimation of both ENS and ECOST is performed using MC and analytical processes.

Four specific consequences were addressed with accurate statistics and we attempted our best to explain that, momentary interruption in the distribution system has a noticeable impact. MC approach has modified the way of design to evaluate ENS and ECOST with reducing the time of the analytical process. Both measurements of MC method and analytical process were performed respectively by developing computer programs in MATLAB and databases in Microsoft Excel. Such models can be used to evaluate the reliability of the different distribution systems.

5.2 Future Work

Using the Multi-Level Monte Carlo (MLMC) method, ENS and ECOST can be evaluated in the future, which will reduce the computation time of both MC and analytical methods with high accuracy.

Additional algorithms, coding, methodology and decent test systems like Intel Core i7, 2.40-GHz processor are needed for estimating ENS and ECOST with MLMC. That is why, we fixed our core aim in this thesis to provide the estimation of the MC and analytical based ENS and ECOST to show the comparative analysis and also to present some sensitivity analysis that is essential to assess the large real-life structures. Different system data, algorithm and simulation strategies provided in this thesis should help the system developers to collect some valuable knowledge about the respective distribution system. We truly think that the method proposed in this thesis will be eligible to accelerate the process of decision making in improving the reliability of the distribution system.

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