**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

A Thesis submitted to the Department of Electrical and Electronic Engineering Of

BRAC University, in partial fulfillment of the requirements for the degree of

Bachelor of Science in Electrical and Electronic Engineering

Department of Electrical and Electronic Engineering

Brac University

June, 2020

©Brac University, 2020.

All rights reserved

**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

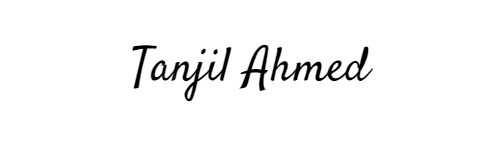
where this is appropriately cited through full and accurate referencing.

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**

**16121092**

****

**\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**

**Palash Chandra Ghosh**

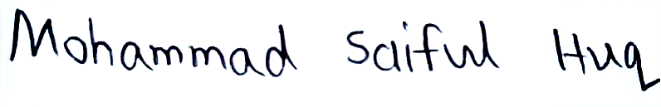
**16121079**

****

**\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**

**Rezuwan Hassan**

**16121073**

****

**\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**

**Mohammad Saiful Huq**

**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.

**Acknowledgement**

We would like to express the deepest appreciation to our supervisor, Dr. A. S. Nazmul Huda, Assistant Professor, Department of Electrical and Electronic Engineering, Brac University for his encouragement, continuing assistance, constructive feedback and recommendations during the entire study cycle that helped us to complete this thesis. We are truly thankful to Brac University for providing us with all of the materials necessary to complete the thesis successfully.

**Table of Contents**

**Declaration**................................................................................................................................ ii

**Approval**.................................................................................................................................... iii

**Abstract**..................................................................................................................................... iv

**Acknowledgement**..................................................................................................................... v

**Table of Contents**...................................................................................................................... vi

**List of Tables**............................................................................................................................. viii

**List of Figures**............................................................................................................................ ix

**List of Abbreviations**................................................................................................................. x

**Chapter 1: Introduction**............................................................................................................ 1

* 1. Importance of Reliability Analysis of Distribution System............................................ 2
  2. Proposed Approach........................................................................................................ 3
  3. Momentary Interruption................................................................................................. 3
  4. Thesis Outlines.............................................................................................................. 4

**Chapter 2: Approaches to Evaluate Reliability Indices** ......................................................... 5

2.1 Analytical Method........................................................................................................... 6

2.2 MC Method..................................................................................................................... 8

**Chapter 3: Methodology**........................................................................................................... 9

3.1 Generation of Operating History..................................................................................... 10

3.2 Modelling of Per Unit Interruption Cost.......................................................................... 10

3.3 Modelling of ENS and ECOST ....................................................................................... 11

3.4 Simulation Process.......................................................................................................... 12

**Chapter 4: Results and Analysis**............................................................................................... 14

* 1. Definition of Bus 4 Network.......................................................................................... 15
     1. Peak Load and Line Length Data............................................................................ 15
     2. Bus 4 System Data............................................................................................... 17

4.2 Comparison between Analytical and Simulation Results................................................ 19

4.2.1 Effect of Network Reinforcement.......................................................................... 19

4.2.2 Effect of Transformer Failure Rate ........................................................................ 21

4.2.3 Effect of Line Failure Rate...................................................................................... 23

4.2.4 Effect of Network Configuration and Customer Type............................................ 26

**Chapter 5: Conclusions**............................................................................................................ 29

5.1 Summary......................................................................................................................... 30

5.2 Future Work.................................................................................................................... 30

**References**.................................................................................................................................. 32

**List of Tables**

Table 4.1 Peak Loads in the RBTS

Table 4.2 Feeder types and lengths

Table 4.3 Customer data

Table 4.4 Loading data

Table 4.5 Customer Interruption (momentary) Cost Data

Table 4.6 Momentary Failure and Repair time

Table 4.7 Cases for study of the network reinforcement effect

Table 4.8 ENS and ECOST variation for network reinforcement

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

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

Table 4.11 Variation in ENS and ECOST for Network Configuration and Customer Type

**List of Figures**

Figure 3.1: Flowchart of ENS and ECOST estimation

Figure 4.1: Bus 4 distribution system for RBTS

**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. **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. **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. **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. **Thesis Outline**

In this paper, we propose an efficient methodology to improve a comparative measurement of the momentary interruptions and their damage in the power distribution system. This paper 's key material comprises 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 to Evaluate 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 λj, the average repair time rj and the average switching time sj 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 Uij, the failure rate λij and the failure duration *rij for* an affected load point ***i*** can be calculated using Equations (2.1), (2.2) and (2.3).

(2.1)

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

(2.2)

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

(2.3)

Where lj is the length of the line for affected load point *i.*

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

(2.4)

where f (*rij*) is the SCDF.

*Step 4****:*** Evaluate the energy not supplied *ENSij* and expected interruption cost *ECOSTij* of the load point *i* caused by failure element j.

(2.5)

(2.6)

Where Li is the average load point of i.

*Step 5:* Repeat 1-4 for all elements in order to calculate total load point *ENSi*, *ECOSTi* using the following equations:

(2.7)

(2.8)

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

*Step 6:* Repeat 5 until the *ENSi,* *ECOSTi* of all the load points are evaluated.

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

(2.9)

(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 be the factor for this study and is the expectation or quantity of interest. Also, let be the approximation to . If is the sample of and is the number of independent MC samples. Then, an unbiased MC estimator for is

(2.11)

where , is the variance of this estimate and the rms error is .

To achieve an accuracy of , it requires 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 and are the failure rate and repair time of a component , respectively. Also, consider the SDE of TTF is driven by the Brownian motion [20]. If is the TTF of an event at a time , then SDE of TTF with defined drift , volatility and initial TTF can be modelled using the Brownian motion on the whole time interval [] [21] as follows:

(3.1)

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

(3.2)

where are the normally distributed independent random variables. and . Using Equation (10), the operating history of component , could be generated as follows:

(3.3)

where 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 ( from SCDF, the interruption cost related to a load point failure for a duration can be expressed as:

**($/kW)**  (3.5)

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

* 1. **Modelling of ENS and ECOST**

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

**(f/yr)** (3.6)

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

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

**(f/yr)** (3.7)

where denotes the number of outage events interrupting the service of the load point . 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).

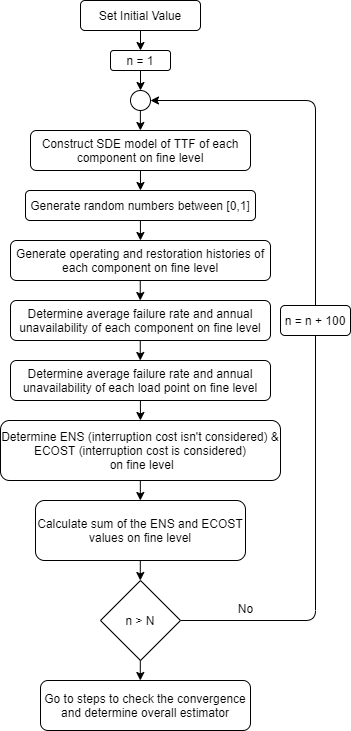
**(kWh/yr)** (3.8)

**(k$/yr)** (3.9)

where 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 (, initial sample size on each level (, 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** |

* 1. **Definition of Bus 4 Network**
     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].

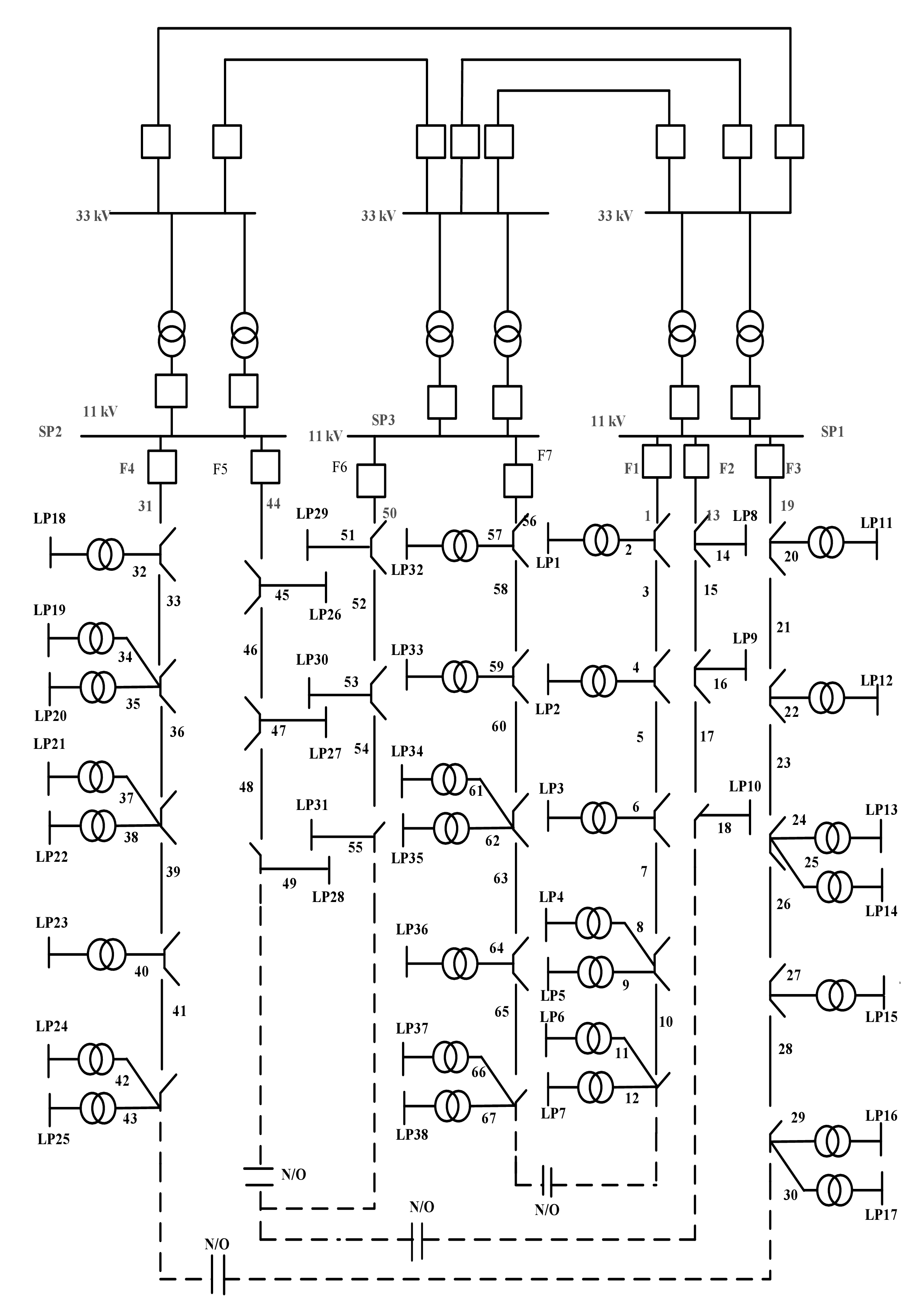
Table 4.1 Peak Loads in the RBTS

|  |  |
| --- | --- |
| 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 |

|  |  |  |  |
| --- | --- | --- | --- |
|  | Circuit Breaker |  | Switch (N/C) |
|  | Transformer |  | Switch (N/O) |

****

**Figure 4.1:** Bus 4 distribution system for RBTS

* + 1. **Bus 4 System Data**

The assumed reliability data for the components of the 33kV and llkV 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**

* + 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 |

* + 1. **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 |
| E | 0.005 | 15.11 | 15.11 | 0.4058 | 0.3948 |
| 0.01 | 15.83 | 15.83 | 0.4082 | 0.3968 |
| 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 |
| F | 0.005 | 60.27 | 60.26 | 0.9521 | 0.9469 |
| 0.01 | 63.53 | 63.49 | 0.9692 | 0.9626 |
| 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 |

* + 1. **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 |
| D | 0.025 | 31.05 | 31.04 | 0.2386 | 0.2377 |
| 0.05 | 34.66 | 34.66 | 0.3317 | 0.3296 |
| 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 |
| E | 0.025 | 16.83 | 16.82 | 0.1120 | 0.1081 |
| 0.05 | 19.07 | 19.06 | 0.1750 | 0.1691 |
| 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 |
| F | 0.025 | 74.07 | 73.22 | 0.4904 | 0.4875 |
| 0.05 | 81.83 | 81.95 | 0.6364 | 0.6327 |
| 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 |

* + 1. **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.

|  |
| --- |
| **References** |

[1] R. Billinton and P. Wang, "Distribution system reliability cost/worth analysis using analytical and sequential simulation techniques," *IEEE Transactions on Power Systems*, vol. 13, no. 4, pp. 1245-1250, 1998.

[2] R. Billinton, S. Ali, and G. Wacker, "Rural distribution system reliability worth evaluation using individual customer outage cost characteristics," *International Journal of Electrical Power & Energy Systems,* vol. 26, pp. 235-240, 2004.

[3] O. Dzobo, C. Gaunt, and R. Herman, "Investigating the use of probability distribution functions in reliability-worth analysis of electric power systems," *International Journal of Electrical Power & Energy Systems,* vol. 37, pp. 110-116, 2012.

[4] R. F. Ghajar and R. Billinton, "Economic costs of power interruptions: a consistent model and methodology," *International Journal of Electrical Power & Energy Systems,* vol. 28, pp. 29-35, 2006.

[5] P. Wang and R. Billinton, "Time sequential distribution system reliability worth analysis considering time varying load and cost models," *IEEE Transactions on Power Delivery,* vol. 14, pp. 1046-1051, 1999.

[6] R. Billinton and P. Wang, "Distribution system reliability cost/worth analysis using analytical and sequential simulation techniques," *IEEE Transactions on Power Systems,* vol. 13, pp. 1245-1250, 1998.

[7] A. Volkanovski, M. Čepin, and B. Mavko, "Application of the fault tree analysis for assessment of power system reliability," *Reliability Engineering & System Safety,* vol. 94, pp. 1116-1127, 2009.

[8] Y. Ou and L. Goel, "Using Monte Carlo simulation for overall distribution system reliability worth assessment," in *Generation, Transmission and Distribution, IEE Proceedings*, 1999, pp. 535-540.

[9] L. Goel and Y. Ou, "Reliability worth assessment in radial distribution systems using the Monte Carlo simulation technique," *Electric power systems research,* vol. 51, pp. 43-53, 1999.

[10] L. Goel, "Monte Carlo simulation-based reliability studies of a distribution test system," *Electric Power Systems Research,* vol. 54, pp. 55-65, 2000.

[11] R. Billinton and P. Wang, "Teaching distribution system reliability evaluation using Monte Carlo simulation," *IEEE Transactions on Power Systems,* vol. 14, pp. 397-403, 1999.

[12] Y. Hegazy, M. Salama, and A. Chikhani, "Adequacy assessment of distributed generation systems using Monte Carlo simulation," *IEEE Transactions on Power Systems,* vol. 18, pp. 48-52, 2003.

[13] R. Rocchetta, Y. Li, and E. Zio, "Risk assessment and risk-cost optimization of distributed power generation systems considering extreme weather conditions," *Reliability Engineering & System Safety,* vol. 136, pp. 47-61, 2015.

[14] J. A. Momoh, *Electric power distribution, automation, protection, and control*: CRC press, 2007.

[15] W. Li, *Risk assessment of power systems: models, methods, and applications*: John Wiley & Sons, 2014.

[16] R. Billinton and A. Sankarakrishnan, "A comparison of Monte Carlo simulation techniques for composite power system reliability assessment," in *WESCANEX 95. Communications, Power, and Computing. Conference Proceedings., IEEE*, 1995, pp. 145-150.

[17] R. Billinton and W. Li, "Distribution System and Station Adequacy Assessment," in *Reliability assessment of electric power systems using Monte Carlo methods*, ed: Springer, 1994, pp. 209-254.

[18] S. -. Yun, J. -. Kim, J. -. Moon, C. -. Park, S. -. Park and M. -. Lee, "Reliability evaluation of radial distribution system considering momentary interruptions," *In IEEE Power Engineering Society General Meeting*, Toronto, Ont., 2003, pp. 480-485.

[19] C. de Schryver, P. Torruella, and N. Wehn, "A multi-level Monte Carlo FPGA accelerator for option pricing in the Heston model," in *Proceedings of the Conference on Design, Automation and Test in Europe*, 2013, pp. 248-253.

[20] J. M. Harrison, *Brownian motion and stochastic flow systems*: Wiley New York, 1985.

[21] B. Oksendal, *Stochastic differential equations: an introduction with applications*: Springer Science & Business Media, 2013.

[22] M. Giles, "Improved multilevel Monte Carlo convergence using the Milstein scheme," In *Monte Carlo and quasi-Monte Carlo methods 2006*, ed: Springer, 2008, pp. 343-358.

[23] R. P. Broadwater, A. H. Khan, H. E. Shaalan, and R. E. Lee, "Time varying load analysis to reduce distribution losses through reconfiguration," *IEEE Transactions on Power Delivery,* vol. 8, pp. 294-300, 1993.

[24] R. N. Allan, *Reliability evaluation of power systems*: Springer Science & Business Media, 2013.

[25] A.S.N. Huda and R. Zivanovic, “An efficient method with tunable accuracy for estimating expected interruption cost of distribution systems,” *International Journal of Electrical Power & Energy Systems*, vol. 105. pp 98-109, 2019.

[26] R. N. Allan, R. Billinton, I. Sjarief, L. Goel and K. S. So, "A reliability test system for educational purposes-basic distribution system data and results," *IEEE Transactions on Power Systems*, vol. 6, no. 2, pp. 813-820, 1991.

[27] R. Billinton and S. Jonnavithula, "A test system for teaching overall power system reliability assessment," *IEEE Transactions on Power Systems,* vol. 11, pp. 1670-1676, 1996.