# RADIAL FEEDER RELIABILITY EVALUATION IN THE PRESENCE OF STORAGE

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Electrical Engineering.

Visvakumar Aravinthan, Committee Chair

Chengzong Pang, Committee Member

Gamal Weheba, Committee Member

DEDICATION

To my parents

Vijayarani and Shantappa

## ACKNOWLEDGEMENTS

I would like to thank Wichita State University for giving me the opportunity to perform this research work. I am very grateful to my committee chair, Dr. Visvakumar Aravinthan, for his guidance and advice throughout my research studies. His technical ken and vision were deeply influential in this research work. I thank Dr. Chengzong Pang for his constant encouragement during my graduate studies. I would like to extent my thanks to committee member Dr. Gamal Weheba for his help and support. I am indebted to the faculty members of the Department of Electrical Engineering at Wichita State University for their fervent efforts to guide students. I also express my gratitude to Mohammad Heidari Kapourchalli and to all my friends at the lab for their support and comradeship.

Special thanks to my parents for being there for me through thick and thin and helping me in all my endeavors.

# DEFINITIONS

Customer based reliability indices are defined in the IEEE std. 1366-2012 that are widely used by the industry but this work uses only three of the widely reported reliability indices.

SAIFI: System Average Interruption Frequency Index

$$SAIFI = \frac{Summation\ of\ Total\ Number\ of\ Customers\ Interrupted}{Total\ number\ of\ customers\ served}$$

SAIDI: System Average Interruption Duration Index

$$SAIDI = \frac{Summation\ of\ Customer\ Minutes\ of\ Interruption}{total\ number\ of\ customers}$$

ENS: Energy Not Served Index

$$ENS = Total\ energy\ not\ supplied\ by\ the\ system$$

## ABSTRACT

Smart Grid demands changes to the existing distribution system. One of the ways to improve the operation of the distribution system is to use battery storage technology to aid the distribution network in minimizing the outage duration of the loads. The battery technology has the capability to improve the reliability of the system. This thesis work develops a pragmatic battery operation model and evaluates the reliability of the system using a simulation based technique. Different aspects of the battery such as state of charge, degradation of the battery capacity over time and limited capacity of the battery are included in the battery modeling. A modified Time Sequential Monte Carlo (TSMC) simulation technique is proposed in this work to include the failure effect of a component on its downstream elements.

To verify the truthfulness of the modified TSMC it is tested on a feeder from Roy Billinton Test System (RBTS). The results of the simulation are analyzed with TSMC and analytical techniques. Further, a feeder with battery storage is evaluated using the modified TSMC technique and the reliability indices are determined.

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## NOMENCLATURE

| | |
|---|---|
| OE | US Office of Electricity Delivery and Energy Reliability |
| IEEE | Institute of Electrical and Electronics Engineers |
| DOE | US Department of Energy |
| NREL | National Renewable Energy Laboratory |
| FMEA | Failure Mode and Effect Analysis |
| DG | Distributed Generation |
| RES | Renewable Energy Sources |
| RBTS | Roy Billinton Test System |
| TSMC | Time Sequential Monte Carlo |
| UPS | Uninterruptible Power Supply |
| BAT | Battery Available Time |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

According to the U.S Department of Energy (DOE) the United States needs to secure 25% of the energy from clean renewable sources by 2015 but only 5% of the total energy comes from renewable sources other than hydropower. Some of the issues are geographical spread of the demand and the generating areas. In reality, the geo thermal, wind and solar sources are located in remote areas while the actual demand for power is in thickly populated urban areas [1]. DOE also states that the current grid faces a challenge in incorporating variable sources of energy like wind and solar resources which are in great momentum right now.

To overcome the challenges faced by the existing grid, we need a new kind of electric grid that responds to the changes in demand and the inherent randomness in the system. Smart grid is one such electric system that is clean, efficient, reliable, resilient and responsive [2]. The DOE identifies the following principal functional characteristics of a smart grid [3].

- Ability to recover from power disturbances
- Fostering active involvement of consumers in various smart grid programs
- Immunity against various threats such as physical and cyber
- Maintaining sinusoidal nature of power to meet the needs of power quality
- Incorporating all conventional, renewable and storage energy sources.
- Encouraging the use of different smart grid products such as Advanced Metering Infrastructure (AMI) and Phasor Measurement Units (PMU)

- Optimal use of current grid assets and proficient operation of the grid

Smart grid also represents various programs such as demand response, automated interconnections and energy storage. Storage plays an important role in uninterrupted supply of power to consumers. Efficient energy storage acts as a leverage to solve the problem of power delivery during peak demand. Effective energy storage helps in power balancing in cases where generation availability is higher that the demand. With the help of various smart grid programs grid operators can take better decisions on incorporating different sources of generation into to the existing system. This gives them advanced control of power system to maintain energy reliability [4].

Energy storage and its impact on radial distribution systems is one of the motivations for this work. This work attempts to study the impacts of battery as a storage option on a radial network from a reliability point of view.

## 1.2 Thesis Outline

This thesis report is parted into5chapters. The first chapter explores the background on energy storage and introduces the role of energy storage in a smart grid. Chapter 2 presents a broad literature survey on the impacts of battery storage on reliability. It also explores the types of reliability evaluation techniques used for radial systems. Chapter 3 focuses on the reliability analysis of the system with finite storage and talks about the modeling of the system in the presence of battery as storage collocated with the load. Also the numerical analysis of the proposed method is illustrated in Chapter 4. Lastly, conclusions and ideas for future areas of work are given in Chapter 5.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Energy Storage

The Smart grid initiative has enabled continuous evolution of the power system and reliability is one of the central areas of smart grid. A typical system with storage in a distribution system is shown below in figure 1.Normally renewable generation does not follow the load and thus increased penetration of renewable generation requires storage to increase efficiency and provide reliable service to customers [5]. Various utility level options storage options are available in the form of air, batteries, electric vehicles, hydrogen, hydroelectricity, superconducting magnetic energy and thermal energy [6].

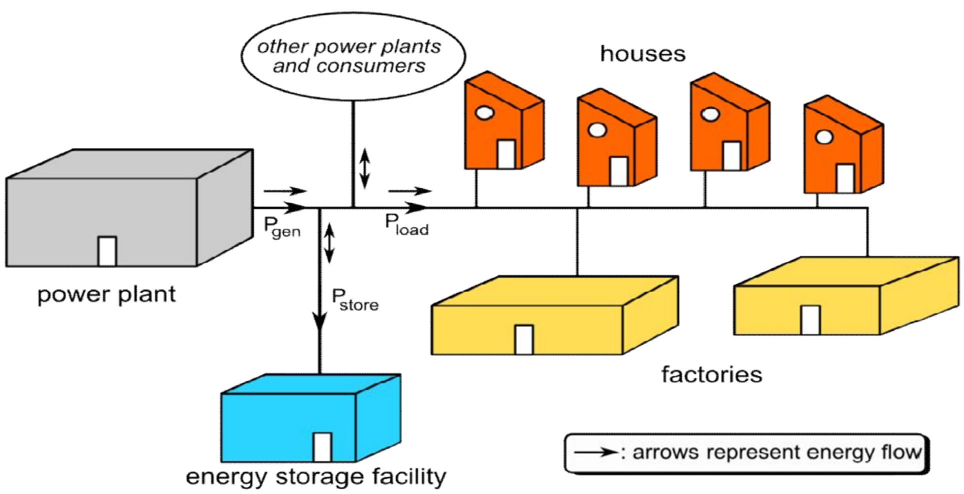


Figure.1: Energy Storage in a radial distribution network[7]

Among the other choices battery storage is a realistic option when storage is co-located with the load, as it does not have geographical limitations and can it be situated close to the demand centers.

## 2.2 Impact of Battery on Reliability Evaluation.

A diagram below shows the interaction of various sources of energy with the central power plant. To handle the intermittent nature of various sources of energy, battery as a storage technology is used. Battery storage also smoothens the fluctuations in the supply of power and helps provide a reliable service to consumers. Thus the modeling of battery has to be done considering various factors such as size, available capacity, state of charge and degradation of the battery over time.

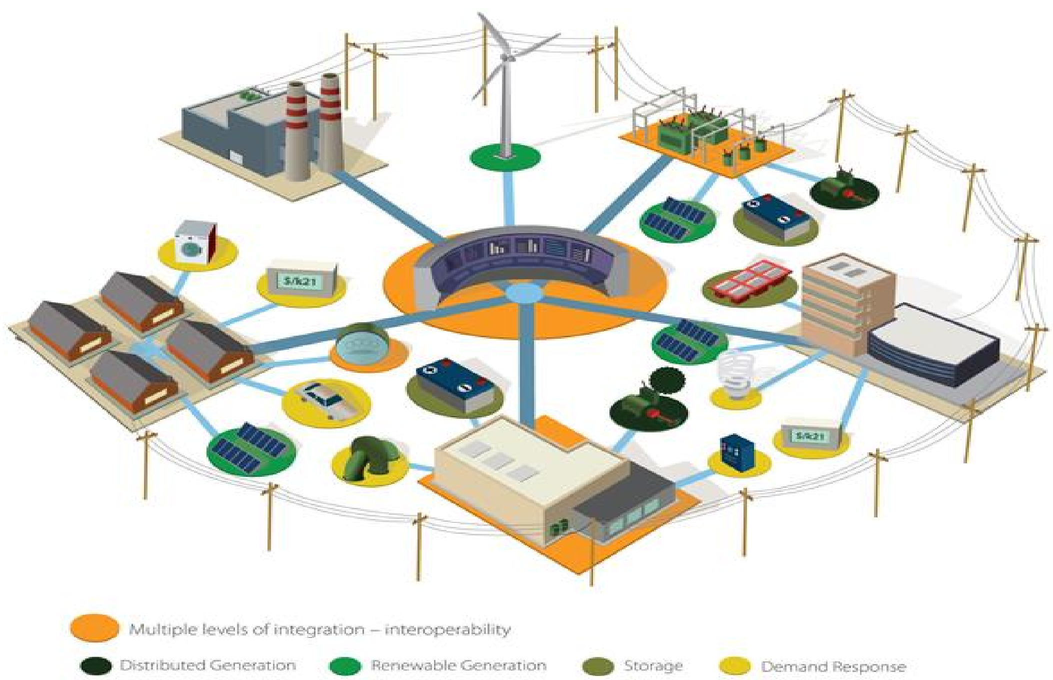


Figure.2: Interaction of various energy sources with central power plant [8].

Liang et al., developed a semi Markov model to evaluate the dependability of power system with UPS but assumed that the battery units are fully charged before the next failure of the component [9]. This assumption may not be valid in a smart grid scenario as the battery is used for other purposes such as power factor correction and power quality applications and the charge may not be at 100 percent at any given time.

Billinton et al., evaluated the impact of storage using an analytical approach but did not take into account the chronological state of charge of the battery [10]. The state of charge of the battery and its degradation over time has to be considered for accurate results. Singh et al., performed reliability analysis by using minimum cut-set method [11]. But one of the limitations of this technique is that it considers the battery to be of very high capacity and also assumes that the battery is capable of supplying loads for the entire repair time of the failed component. In reality, the size and capacity of the battery have limitations which have to be taken into account while performing reliability calculations.

Many studies performed by Billinton et al., in [12] assume that, in the event of a system failure there are no restrictions on the amount of load that can be supplied through an alternative source. Even if there is a limitation on transfer of loads, it is allocated a fixed probability of transfer and then the outage time of the system is computed. In a deregulated environment there are a lot of restrictions on alternative supply such as battery and all the loads may not be transferred based on a fixed probability. There may be cases where battery can supply only a part of the system to reduce the outage time. This has to be included to in reliability modeling of the system.

This thesis work weights all the factors affecting the battery modeling as discussed above and proposes a methodology using a sequential simulation technique to make the reliability computation as pragmatic as possible.

## 2.3 Reliability Evaluation Methods

Reliability studies deals with customer interruptions both momentary and sustained. Traditionally analytical techniques have been developed and used in reliability evaluation of many systems. Load point and reliability indices have been computed analytically by Billinton and Goel[13]. Carpaneto et al., assessed the probability distributions of reliability indices for large distribution networks using an analytical approach [14]. However, as the complexity of the system increases the need for composite models and assumptions also increase, which reduces the accuracy of reliability computation significantly [12].

Traditional reliability evaluation is based on Failure Mode and Effect Analysis (FMEA) method and the effects of failure of a component are studied on the load points. In an environment where power flow is not always radial, the intermittent nature of the loads has to be evaluated along with the reliability computation of other components in the system according to Singh et al., [15].

To respond to the stochastic nature of the system many simulation techniques have been utilized. Wang et al., presented an algorithm which is an extension of analytical simulation approach for radial networks. This algorithm is can be applied to large radial/meshed networks and it can handle the effects of fault isolation and load restoration. Carpaneto and Chicco proposed a characteristic function based approach to evaluate the probability density functions of distribution system reliability indices [16].

Although many techniques have been used in the past, simulation techniques have an advantage over the other techniques as they are flexible to changes in the system and provide a pictorial representation of variability of many reliability indices.

Simulation techniques weigh all the aspects and contingencies inherent in the power system including random events such as outages and repair of elements, dependent events, load variations and variations in energy input. Also the these techniques evaluate the effects accurately using heavy tailed distributions such as the chi-squared, log normal or weibull distribution as described by R Billinton and Li Wenyuan.[17] Many examples where real systems have properties of a skewed distribution are discussed in [12].

## 2.4 Simulation Approach using Monte Carlo

Monte Carlo simulation technique uses the concept of random numbers to model the non-deterministic events and random number generation is pivotal to all Monte Carlo simulations

In reliability assessment of distribution systems, the sequential sampling for components such as tie lines, switches breakers and transformers can be simulated by a two state Markov model as shown in figure 3. The average failure rate is given by $(\lambda)$ and the average restoration rate is represented by $(\mu)$ then the probability that the component is in 'UP' state is given by $(P_u)$ and the probability of the component in down state is given by$(P_d)$ [15].

$$P_u = \frac{\mu}{\lambda+\mu} \tag{2.1}$$

$$P_d = \frac{\lambda}{\lambda+\mu} \tag{2.2}$$

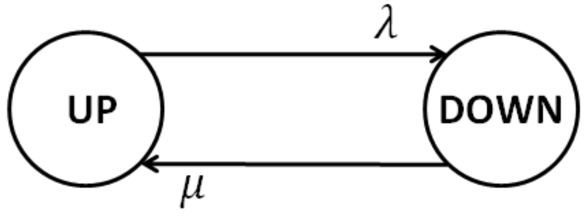


Figure.3: Two state Markov model

In distribution systems, Monte Carlo simulations are performed for a particular period of time (such as a year). Large number of simulations is usually required as the output of each simulation is different. It is mathematically shown by Richard E Brown [18] as:

$$\bar{x} = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} x_i \tag{2.3}$$

Where, $\bar{x}$.is the expected value $x_i$ is the result of the simulation $i$ and $N$ gives the number of simulations. The decision of number of simulations is an important step in the Monte Carlo simulation. In case of modeling of a rare event, the number of simulations should be sufficiently large to allot a high probability of occurrence for a rare event. For example, if the failure rate of a component is 1 in 100 years, then 1000 simulating years are needed to include this probability while a smaller sample size of sample year may not [18].

Monte Carlo has many advantages such as the ability to give information on variability of indices unlike analytical methods which give a single value. Also, Billinton et al., described that it can be used to model rare events which although occur infrequently can have detrimental effects on the system. The events such as cascading failures, non-exclusive events and conditional probability [12] can be modeled using this technique. Some of the disadvantages of Monte Carlo technique are the need for large number of random years which increases the computational burden and the lack of precision to incorporate the impact of small changes in bigger systems [18].

Monte Carlo simulations can be performed using two methods: Sequential and Non-sequential. One of the sequential approaches is presented in the next section.

## 2.5 Time Sequential Monte Carlo Technique

The Time Sequential Monte Carlo (TSMC) simulation is a probabilistic technique that simulates the operating life of a component sequentially in time through a series of operating and repair cycles as shown in figure 4.This information or history of cycles is used to calculate the system reliability indices.

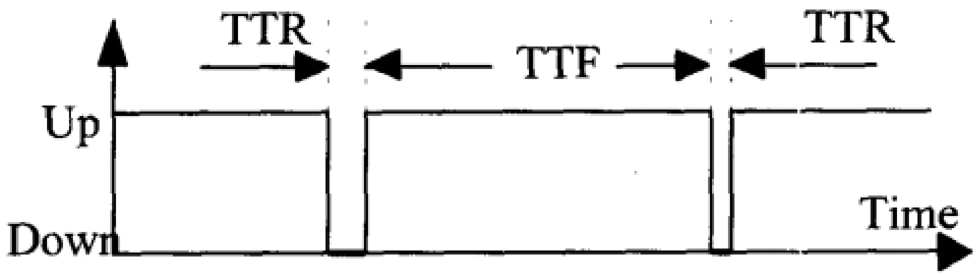


Figure.4: Component operating/repair cycles [19]

The time for which the component remains operational is called time to fail $(TTF)$ and the time for which the component is under repair is termed as time to repair$(TTR)$. Billinton et al., described that the $TTF$ and $TTR$ are random variables and the probability density function used to simulate these times are Normal, Gamma, Lognormal, Poisson and Exponential distributions. In reliability studies of distribution systems, exponential distribution is used. Exponential variate$(\tau)$ can be generated by generating a uniform random number between 0 and 1, then it is converted to an exponential distribution by using the equation (2.4) given below [12]

$$\tau = -\left(\frac{1}{\lambda}\right) \ln (U) \tag{2.4}$$

Where, $\lambda$ is the transition rate and $U$ is a uniformly distributed random number.

The Time Sequential Monte Carlo Simulation technique used for reliability evaluation is explained with the help of a flow chart shown in figure 5. First the system parameters such as failure rate, repair rate, location of the components and load data are defined at the beginning of the simulation. The number of sample years $N$ and the simulating period $T$ are set.

The Simulation begins with the generation of $TTF$ for all the components in the system using equation (2.4). Out of all the components in the system an element with a minimum $TTF$ is selected as the component the least $TTF$ fails first. The impact of this element failure on the system is evaluated further into the simulation. The location of the failed element is identified and$TTR$ and $TTS$ (if applicable) are generated for the failed element using appropriate probability density function of the element. Then number and outage duration of all the load points that are affected by the failed element are recorded. The failed element is repaired and brought back to its operating mode by generating a new random $TTF$ . The system clock time $t$ is less than the simulating time $T$ then the search for the element with minimum time to fail starts again, otherwise, the average failure rate and outage durations are calculated followed by the system indices.

The simulation ends if the total number of simulating years is greater than the set parameter. Once the simulation has been performed for all the sample years, the average values of the system indices such as $SAIFI, SAIDI$ and $ENS$ is calculated. The indices $SAIFI, SAIDI$ and $ENS$ are the average measures of the number of interruptions, the duration of interruptions and the energy not supplied during the interruption respectively. A complete flowchart of the Time Sequential Monte Carlo Technique is shown in figure 5.

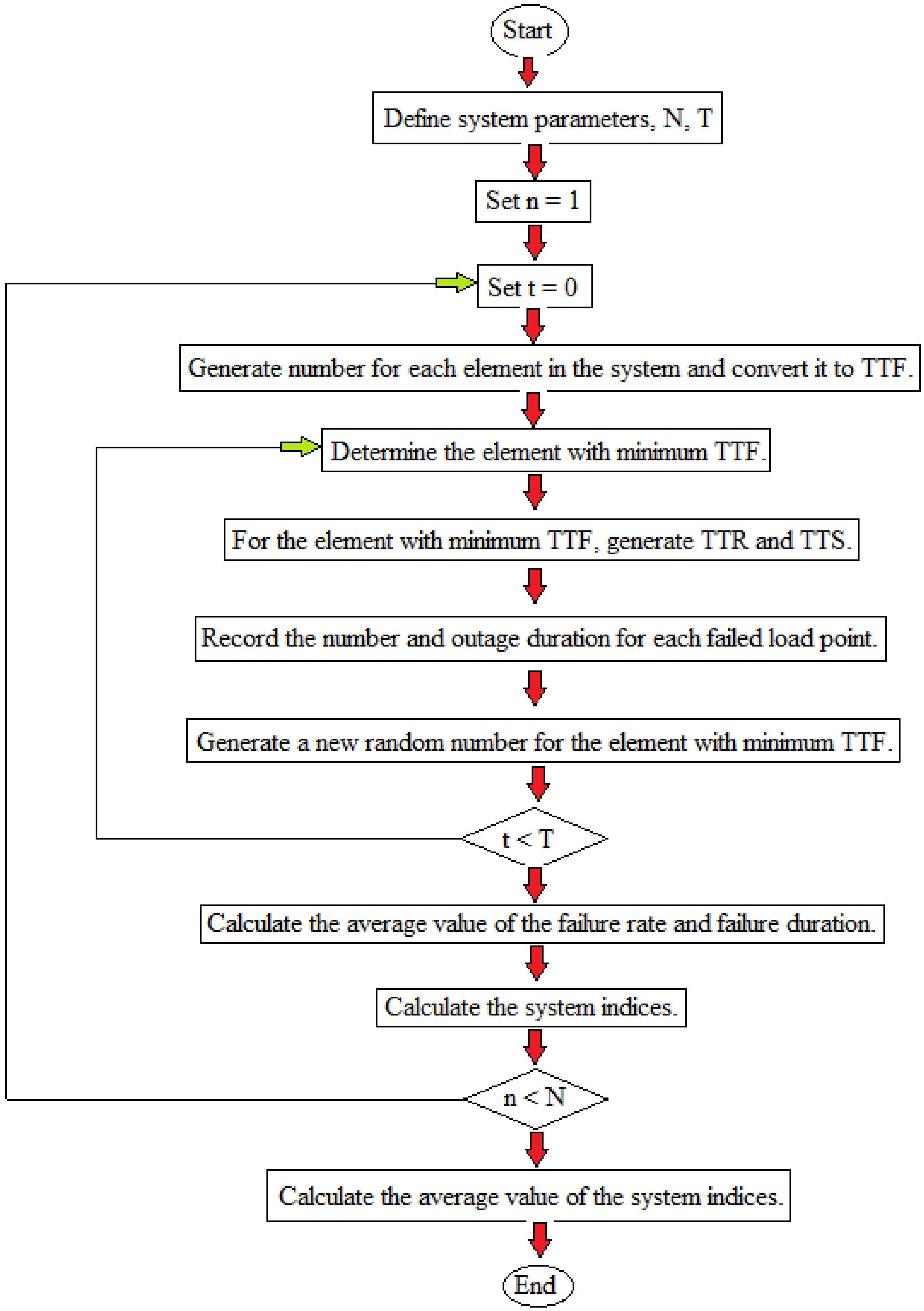


Figure.5: Flow chart of time Sequential Monte Carlo Simulation Technique

## 2.6 Scope of This Work

This work focuses on developing a reliability evaluation framework for radial distribution feeders in the presence of battery storage collocated with load. One of the applications of collocated battery storage is to support the load during an outage. First, a modification to time sequential simulation is proposed and to verify the veracity of the algorithm it is tested on one of the feeders from Roy Billinton Test System (RBTS) and the results are compared with Time Sequential Monte Carlo (TSMC) Simulation technique. Next the algorithm is tested one a sample 3 bus feeder with Uninterruptible Power Supply (UPS). The UPS is modeled such that the battery system along with the control and switching has finite failure rate and the capacity degrades as the battery ages and the state of charge of the battery has a heavy tailed distribution.

The focus of this work is limited to reliability evaluation and thus the peak shaving applications and power quality support through the battery are out of the scope of discussion here. However, it is assumed that the battery will be in operation throughout its life and helps the outage reduction whenever necessary

## CHAPTER 3

## RELIABILITY ANALYSIS WITH FINITE STORAGE

### 3.1 Modeling Methodology

The modeling is divided into different areas, namely the formation of load point evaluation matrices, the modified Time Sequential Monte Carlo method and an improved battery model which are then combined to evaluate the system reliability as shown in figure 6. Each block in the flow chart is explained in detail in further sections 3.2 through 3.5.

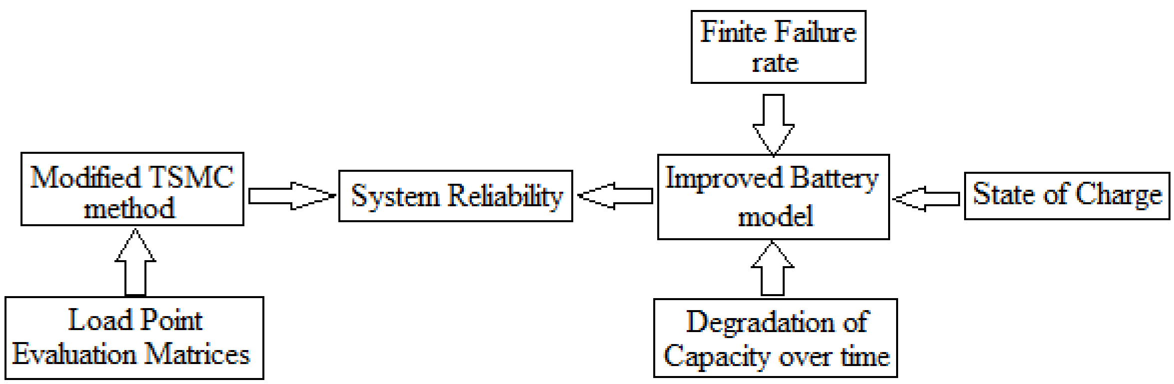


Figure 6: Flow chart of modeling methodology

### 3.2 Load Point Evaluation Matrices

Load point failure calculation in a large distribution system is complex [20]. If the load points that would be affected by failure of a particular component are known in advance or could be computed directly the computational burden could be reduced thus saving time. This work proposes a technique using matrices to determine the load points that are affected by the failure of a particular element.

The process to build the matrices is shown below with the help of a simple two node feeder in figure 7. On the figure A and C are feeder sections and B and D are laterals with finite failure and repair rate.

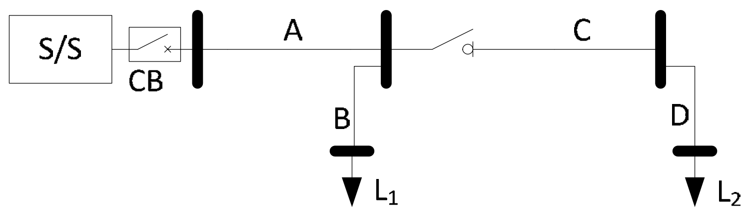


Figure.7:A simple two node feeder

- Element Switching Matrix (ESM)

  For each element the primary isolation switch or protection device is identified by this matrix. A unique number is assigned to each protection element in the network. Depending upon the network configuration, the effect of failure of a particular breaker/isolator is noted. The ESM gives information about a particular switch that responds the failure of an element associated with it. Example, for a system shown in figure 5 if the circuit breaker is denoted by 1 and the isolator is denoted by 2, then

$$ESM = \begin{bmatrix} 1 & 1 & 2 & 2 \end{bmatrix}$$

- Element load Point Matrix (ELM)

  When an element in the network fails, this matrix is used to determine whether the load points sees a repair time, switching time or restoration time by an alternative source. The rows of ELM represent the elements and the columns represent the load points. Example, for the system shown in figure 5 repair time is represented by 1, switching time is represented by -1 and the restoration by an alternative source by 2, then

$$ELM = \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ -1 & 1 \\ -1 & 1 \end{bmatrix}$$

These matrices are used as inputs to modified TSMC to give information about the system configuration and the protection scheme in the network. This simplifies the computational intensity in calculating the effect of failure of every component in the system on the load points.

### 3.3 Modified Time Sequential Monte Carlo

The Time Sequential Monte Carlo does not consider the failure of downstream components while the upstream component is under repair, but with sufficient simulations this effect gets corrected and the results become reasonably accurate. To incorporate the effect of one element on the failure of a component downstream to it a modification to the TSMC is proposed.

The modification to TSMC is as follows. A new random time to fail($TTF$) for the failed element is generated, the $TTF$ of every element incorporating the outage time is updated using the following relationship.

$$TTF_i(new) = TTF_i(new) + \beta(t).(TTR_k - TB_i) \tag{3.1}$$

Where, subscript $i$ denotes every element that saw the outage due to failure of an element$k$. $\beta(t)$, is a probability distribution function associated with the prolonged life of the component $i$, $TTR_k$ is the time to repair for the element $k$ and$TB_i$ is the time that the component was active due to the availability of an alternative source such as a battery operation. In the absence of a battery the parameters $TB_i$ is set to zero and $\beta(t)$ is set to one.

The aim was to compare the reliability indices namely SAIFI, SAIDI and ENS of the proposed algorithm with time sequential technique and analytical values. Hence, the simulation was carried out without the battery. To validate the usability of the modified algorithm, it was tested on one of the feeders from RBTS Bus 2 shown below in figure 8.

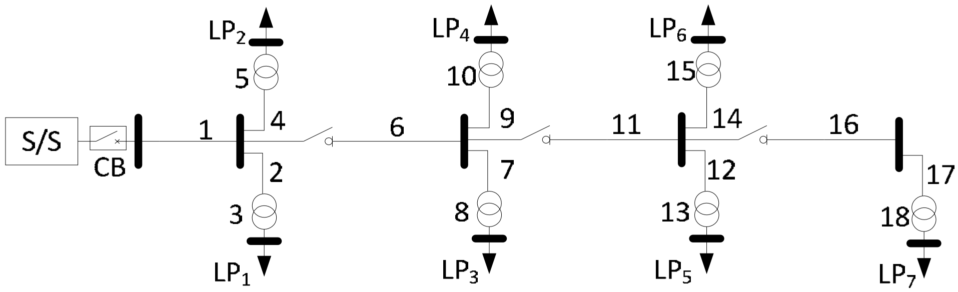

Figure 8: Feeder F1 of bus-2 (RBTS) [38]

The TSMC and the modified TSMC are compared in figure 9. Even though the SAIFI and ENS have the same error, SAIDI computation using the modified TSMC reduces the simulation error. Since, the use of battery does not affect the number of interruptions seen by a load point, rather it reduces the outage time so the battery usage is expected to improve SAIDI but will have minimum impact on SAIFI.

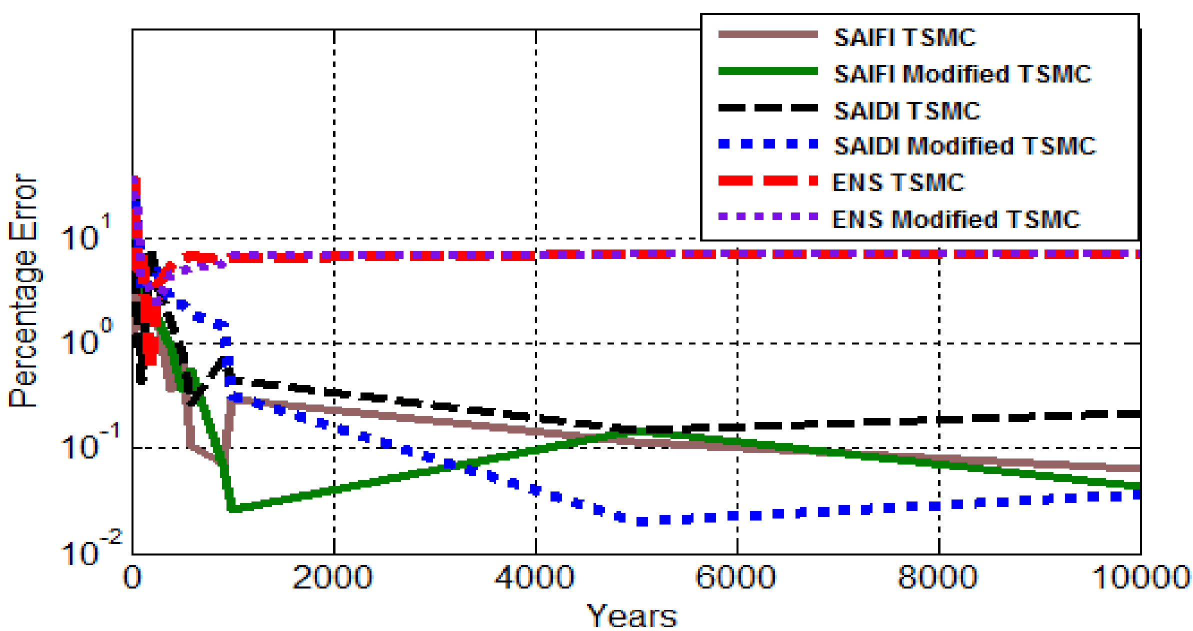


Figure.9: Performance plots of the two methods for feeder F1

From figure 9it can also be conferred that modified TSMC method converges faster with less error compared to the TSMC and analytical techniques. It uses lower number of sample years and reduces the computational effort. Therefore the proposed modified TSMC is ideal for reliability analysis in the presence of battery.

## 3.4 Improved Battery Model

The capacity of the battery to supply power during an outage is subject to factors such as finite failure rate, time dependent capacity and the state of charge of the battery. A detailed explanation of each of the factors is provided in the sections below.

### 3.4.1 Finite Failure Rate

During an outage the battery can supply power to the loads only if it is operating which means it has a finite failure rate and there is possibility that the battery and the other components in the Uninterruptible Power Supply (UPS) may be under repair. Hence the failure and repair rate of every component is considered.

The UPS considered for the study here is a non-redundant uninterruptible power supply type [21] shown in Figure 10

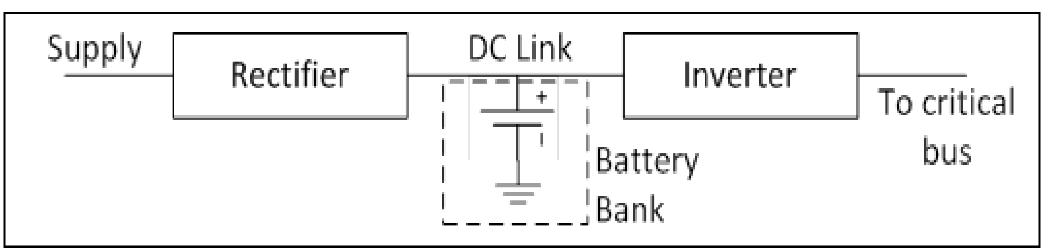


Figure.10: Non-redundant uninterruptible power supply.

The reliability data for the complete UPS is given in table 1. Using the values in table 1, overall failure rate and repair rate of the UPS system was calculated and used in the simulation.

TABLE 1

UPS DATA [11]

| Component | Failure rate (f/hr) | Repair time (hr) |
|---|---|---|
| Supply | $6.1259 \times 10^{-5}$ | 5.66 |
| Inverter | $1.4305 \times 10^{-4}$ | 107 |
| Rectifier | $4.3349 \times 10^{-6}$ | 39 |
| Battery | $3.5706 \times 10^{-6}$ | 24 |

### 3.4.2 State of Charge (SoC)

State of charge of thee battery is expected to be 100% of the available capacity. However in its operating life due to the randomness in charging and discharging the available charge can be less than 100%. To include the skewness of the state of charge (at a time charge can be much less than 100% of the available capacity) a two parameter weibull distribution with a heavy tail is selected in this work. The state of charge of the battery is given by,

$$SoC = wei(1,1.1) \tag{3.2}$$

### 3.4.3 Degradation of Capacity over Time

Battery has a limited life and the capacity of the battery reduces with its age so a model is developed to determine the capacity of the battery with age using [22]. This battery capacity data is used to develop the following relationship.

$$C(t) = (\alpha t^5 - \theta t^4 + \vartheta t^3 - \varepsilon t^2 + \rho t + \sigma)C \tag{3.3}$$

Where, $t$ is age of battery in years, $C$ is the design capacity, and constant parameters are $\alpha = 1.72 \times 10^{-4}$, $\theta = 0.0107$, $\vartheta = 0.24$, $\varepsilon = 2.47$, $\rho = 11.43$ and $\sigma = 86.4$. The generated polynomial is plotted in Figure 11.

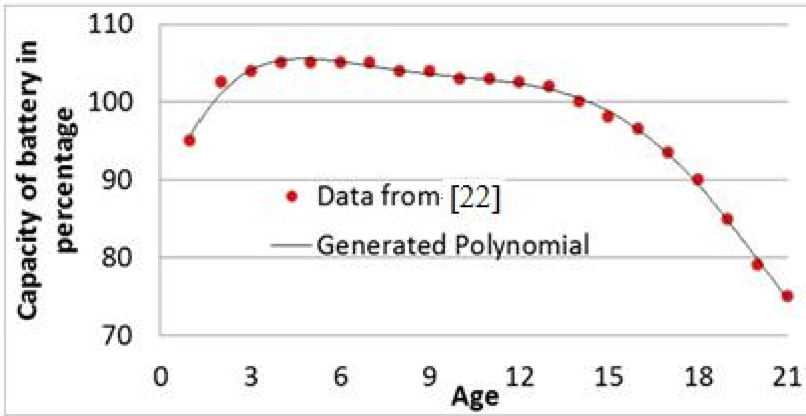


Figure.11: Battery Capacity vs. age

The time for which the battery can supply power at any given point of time in the simulation is dependent on the available capacity$C(t)$ based on the degradation over age and state of charge ($SoC$).

$$Battery\ energy = C(t) \times SoC \tag{3.4}$$

$$Battery\ Available\ Time(BAT) = \frac{Battery\ energy}{Average\ power\ required\ at\ the\ load\ points} \tag{3.5}$$

Depending on the state of the UPS: operating/ repair, the battery available time is used to restore load points.

### 3.5 System Reliability

The system reliability computation is explained using a sample two bus system with UPS shown in figure 12.Before the outage computation, the location of the fault is identified using load point evaluation matrices. The battery available time is computed using available capacity and the state of charge of the battery.

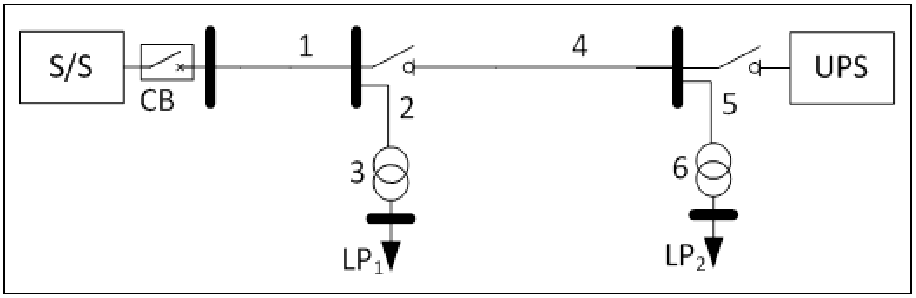


Figure.12: A two bus system with UPS

A detailed flowchart of the outage computation algorithm for load points is shown in figure 11. It is used in conjunction with the modified TSMC technique to determine the outage $(UA)$ of the load point which is collocated with the load.

**Outage time computation for Load Point 1 $(LP1)$**

**Case 1**: Failure at the downstream of closest switch to $(LP1)$

The outage time seen by the load point is equal to the switching time $(SW)$.

**Case 2**: Failure at the upstream of closest switch to $(LP1)$

The outage time seen by the load point is equal to the sum of repair time $(TTR)$ of the failed component and switching time$(SW)$.

**Outage time computation for Load Point 2 $(LP2)$**

**Case 1**: Failure at the downstream of closest switch to $(LP2)$

The outage time for $LP2$ is zero if the time to bring the UPS online is assumed negligible in other words the switching time for UPS is zero.

**Case 2**: Failure between switch close to $LP2$ and $LP2$

The outage time seen by the load point is equal to the sum of repair time $(TTR)$ of the failed component and switching time$(SW)$.

**Case 3**: Failure in the downstream away from the closest switch.

***<u>Sub case 1</u>*: No limitation on battery capacity

If there are no limitations on the capacity of battery in the UPS and it can supply for the entire repair time of any component. The outage time is just the switching time of the switch close to$LP1$.

***<u>Sub case 2</u>*: Finite battery capacity

The outage computation in this case is subjected to several conditions and is explained with the help of a flow chart shown in figure 10.

If the battery available time($BAT$) is less than $TTR$ and $SW$ of the component then the condition below are executed.

***<u>Condition 1</u>***:$BAT$ is greater than the time to fail of the battery $TTF_B$

The battery goes through the cycle of repair every time it fails during this sub condition until the total time which is the sum of time to fail($TTF_B$) and time to repair($TTR_B$) of battery exceeds the $BAT$.

If the $TTR$ of the component is greater than the$TTF_B$, then the outage time is the difference of $TTR + SW$ and the up time($UP$) of the battery. Otherwise, the outage time is the sum of $SW$ and the time for which the battery was able to supply power when it was up and running.

***<u>Condition 2</u>***:$BAT$ is less than the time to fail of the battery $TTF_B$

The outage time is the difference of $TTR + SW$and the$BAT$.

If the battery available time($BAT$) is greater than $TTR$ and $SW$ of the component then the condition below are executed..

***<u>Condition 1</u>*****:**$TTF_B$ is less than $TTR + SW$

The outage time is computed in the same way as discussed earlier when the $BAT$ is greater than the time to fail of the battery $TTF_B$.

***<u>Condition 2</u>*****:**$TTF_B$ is greater than $TTR + SW$

The outage time is just the switching time ($SW$).

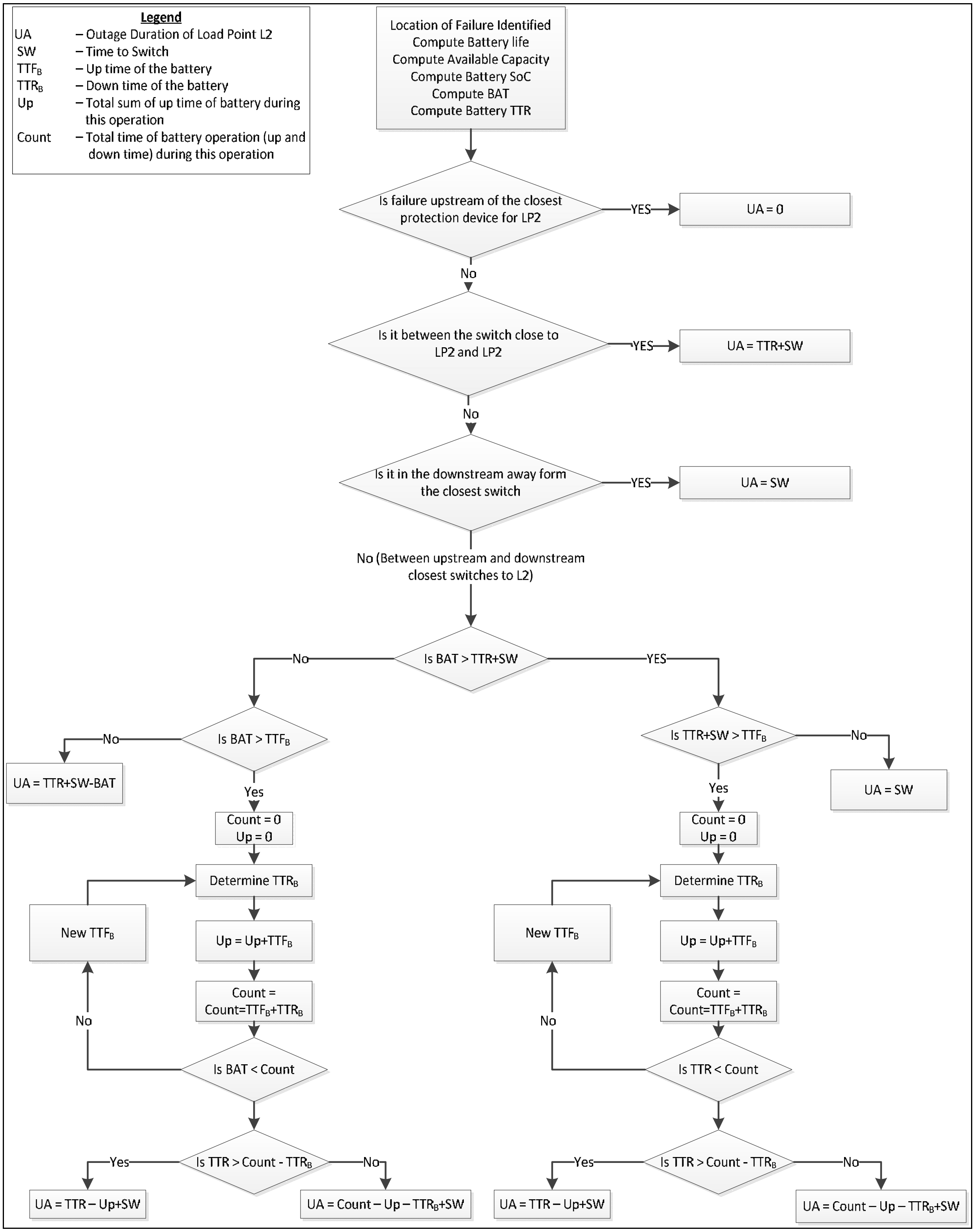


Figure.13: Flowchart of outage computation algorithm for the load point collocated with battery

# CHAPTER 4

# NUMERICAL ANALYSIS

## 4.1 Test System

One of the feeders of the Roy Billinton Test System (RBTS) - F1 of bus 2 is used for the study. Also a sample two node feeder was used. The details of the feeders are given below.

- The feeder F1 is considered with the help of data from [23]. Overhead lines are used for all the 11KV feeders and lateral. The feeder and the lateral are of the three given lengths, 0.6 km/0.75 km/0.8 km only. The customer data is given in table 2. The fuses and disconnects are assumed to be 100% reliable. The veracity of the modified time sequential algorithm is tested on this feeder.

TABLE 2

CUSTOMER DATA – FEEDER F1 [19]

| **Load Points** | **Load level per load point (MW)** | | **Number of customers** |
|---|---|---|---|
| | **Average** | **Peak** | |
| 1 | 0.535 | 0.8668 | 210 |
| 2 | 0.535 | 0.8668 | 210 |
| 3 | 0.535 | 0.8668 | 210 |
| 4 | 0.566 | 0.9176 | 1 |
| 5 | 0.566 | 0.9176 | 1 |
| 6 | 0.454 | 0.7500 | 1 |
| 7 | 0.454 | 0.7500 | 10 |

Table 3 shows the component data of all the components used in the feeder F1. The fuses and disconnects are assumed to 100% reliable hence their data is not used.

TABLE 3

COMPONENT DATA – FEEDER F1 [19]

| **Component** | **Failure rate (f/yr)** | **Repair time (hr)** |
|---|---|---|
| Main line | 0.04875 | 5 |
| Lateral line | 0.039 | 5 |
| Lateral line | 0.052 | 5 |
| Main line | 0.04875 | 5 |
| Lateral line | 0.052 | 5 |
| Lateral line | 0.039 | 5 |
| Main line | 0.04875 | 5 |
| Lateral line | 0.052 | 5 |
| Main line | 0.04875 | 5 |
| Lateral line | 0.039 | 5 |
| Lateral line | 0.052 | 5 |
| Transformer | 0.015 | 200 |

- A sample two node feeder with a UPS connected at the node two is used. The two load points connected to the nodes have 10 customers each and an average load of 484 KW respectively. Tests of battery collocated with load are performed on this feeder.

The component data of individual load points for the two bus system is given in the table 4.Furthermore, the switch used at the UPS is considered normally open and the time required to bring the UPS online is considered negligible for the purposes of study in this work.

TABLE 4

COMPONENT DATA-TWO BUS SYSTEM

| **Component** | **Failure rate (f/yr)** | **Repair time (hr)** |
|---|---|---|
| Main Line | 0.04875 | 5 |
| Lateral Line | 0.039 | 5 |
| Main Line | 0.04875 | 5 |
| Lateral Line | 0.052 | 5 |
| Main Line | 0.04875 | 5 |
| Transformer | 0.015 | 200 |
| UPS | 1.8 | 74.96 |

## 4.2 Results

Figure 14 shows the results of analysis done to evaluate the performance of modified TSMC in the presence of battery. The SAIDI of modified TSMC is computed by averaging 100 runs for 100,000 years and compared with TSMC and analytical values. From the figure it could be conferred that the proposed modified TSMC performs better than the TSMC and the SAIDI is close to the analytical value.

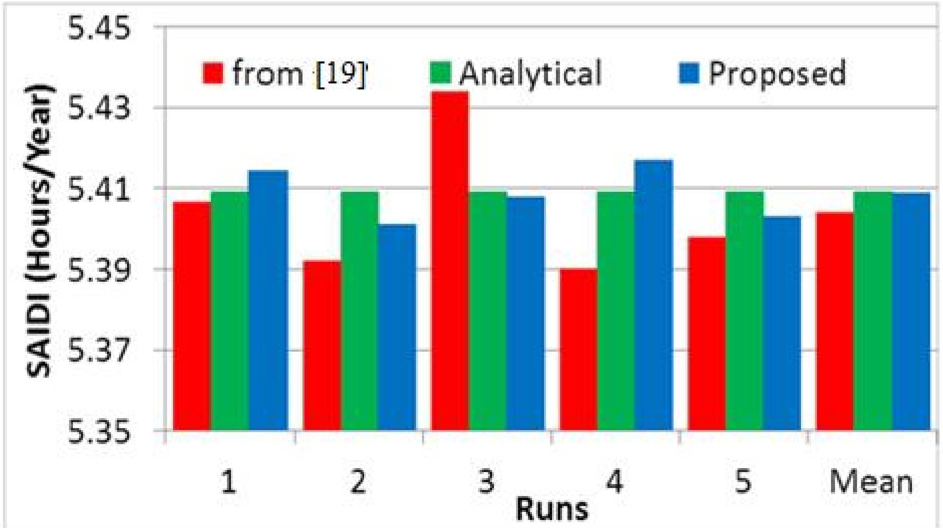


Figure.14: Comparison of SAIDI

A comparison of SAIFI computed by different methods is made in figure 15. As expected modified TSMC has no significant improvement on SAIFI computation compared to TSMC. Since having a battery in the system does not affect the overall SAIFI of the system, these results revalidate the need for the proposed algorithm. [19]

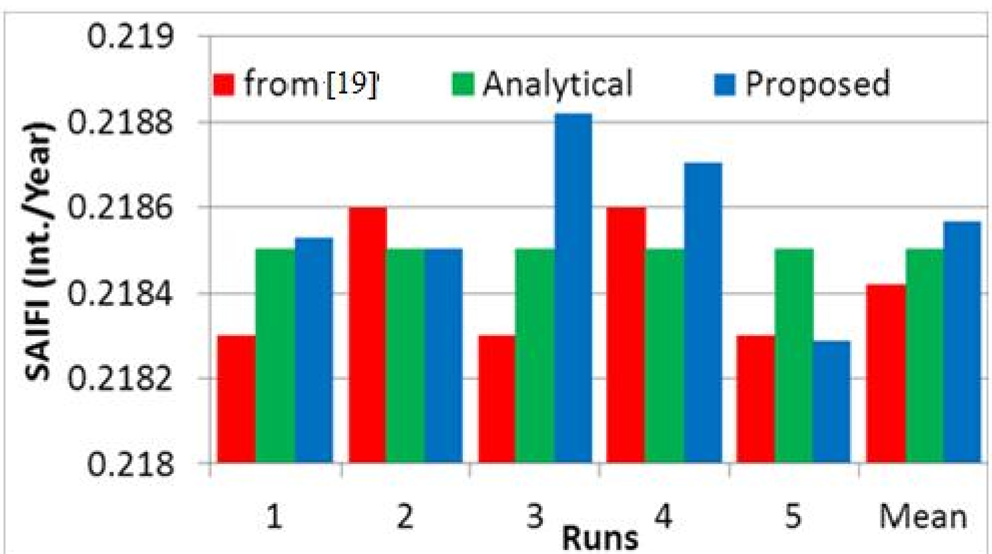


Figure.15:.Comparision of SAIFI

The effect of UPS failure rate, UPS repair rate and the battery capacity on SAIDI are evaluated in this work. Figure 16 depicts the impact of various UPS failure rates and battery capacity on SAIDI. From figure 16 it can be inferred that that the higher the battery capacity lower is the SAIDI. However, the failure rate of the UPS has negligible effect on SAIDI. This is due to the conditional occurrence of battery failure when supporting the outage reduction, which has a relatively small possibility.

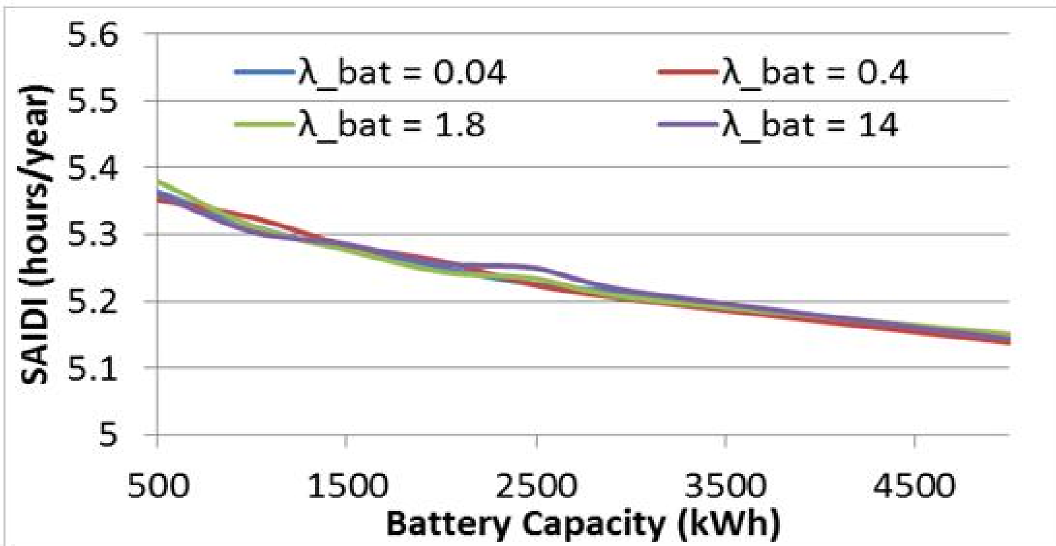


Figure.16: Effect of failure rate and battery capacity on SAIDI

Similar trends were observed when the impact of UPS repair rate was studied on SAIDI. The plots in figure 17 show that the repair rate also has negligible influence on SAIDI for similar reasons discussed before.

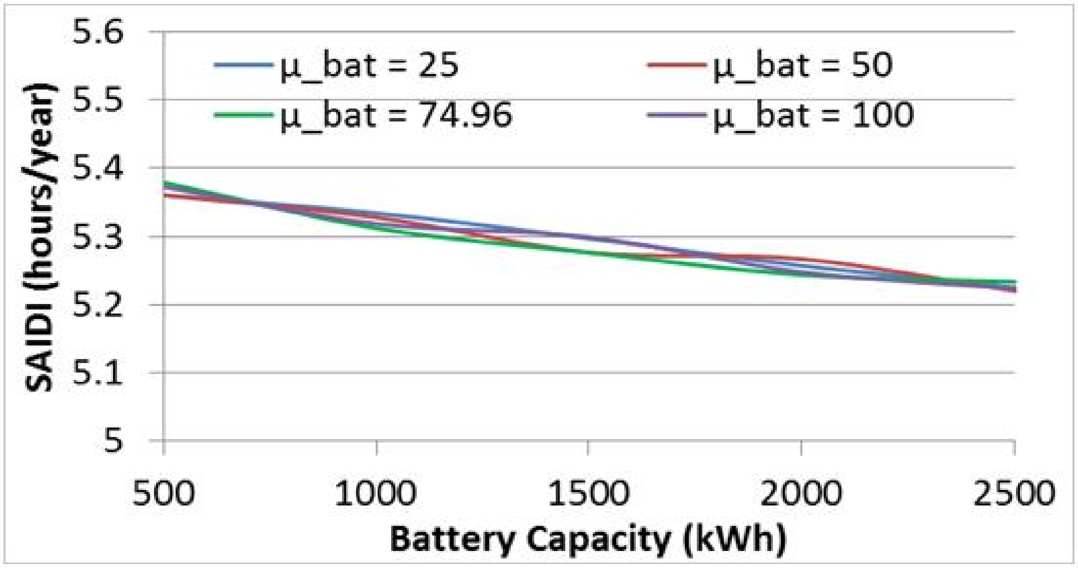


Figure.17: Effect of repair rate and battery capacity on SAIDI

# CHAPTER 5

# CONCLUSIONS AND FUTURE WORK

## 5.1 Conclusion

This thesis presents a reliability evaluation method in the presence of battery as an alternative supply to reduce the outage in a smart grid environment. First, In order to improve the SAIDI computation a modified time sequential is proposed and the feasibility of usage is explored. The results are verified and compared with a sequential technique. The proposed method works to the advantage as it used in reliability studies with battery and UPS system.

Second, the proposed method is tested on a simple test system with a battery collocated with the load. An algorithm to include the capacity degradation with age, state of charge of the battery and failure rate is also developed. Based on the simulations and results presented in this report it can be deduced that the utility should invest on increasing the battery capacity as an alternative to purchasing a highly reliable UPS system if reliability improvement is of prime focus.

## 5.2 Future Work

This thesis work evaluates the advantages of having a battery storage system close to a load from a reliability stand point but the other uses of battery can be explored in future. A detailed battery modeling could be used with multiple storages in a large system. Further areas where this work could be extended are as follows.

- Optimal placement of battery storage using genetic algorithm to improve the system reliability requirements.

- Using battery storage along with renewable sources of energy such as wind and solar and modeling them sequentially in time and studying their effects on the system.
- Integrating other smart grid programs such as electric vehicle and demand response along with storage to explore the best possible strategy for power dispatch.

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