Reliability Assessment of Microgrid Power Systems Using Analytic Hierarchy Process for Distributed Generation Selection

by

© Benjamin Danquah, BSc.

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Abstract

The primary aim of many electric utility providers is to provide electric energy to their customers as economical and reliable as possible. One of the ways to achieve this is the integration of distributed generation to form microgrid within the distribution network systems. Integration of microgrid into the distribution network has been on the increase in the past decade because it helps to reducing cost. Higher penetration of renewable energy resources in the microgrid also help to reduce the green house gas (GHG) from fossil fuel- based generation sources and its effect on the environment. It also helps to improve the reliability, as well as the overall efficiency of the distribution network system.

The main drivers for the application of distributed generators has been the cost of the technology, the availability of resource and the environmental effect. Many literature on reliability assessment of microgrid power systems focus on identifying the weak or critical components of the system as the main criteria for choosing distributed generators to be integrated into the network in the context of producing power that is economical to both the customer and the utility provider. Other literatures also consider the availability of the renewable resources of that geographic location.

This study seeks to consider three criteria in selecting the most suitable distributed generator for integration into the microgrid. The criteria include the cost of the technology, the environmental impact, and the reduction in the risk level in the power distribution network containing microgrid. Analytical hierarchy process is implemented to determine which of the distributed generators would be the most suitable with respect to the three criteria. It was determined that the wind turbine generator would be the most suitable DG for the microgrid implementation based on the final average priority ratio after the sensitivity analysis was performed.

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Dedicated to my son Ernest, my wife Francisca Ivy for being both a mother and father to our son in my absence, and my mother Matilda Winful.

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Chapter 1

Introduction

The conventional electric power is mostly centralized and generated from fossil fuel resources, which are being depleted with passage of time. The negative effects of fossil fuel resources on the environment have drawn the attention of researchers, government and non-governmental institutions to explore alternative power sources such as distributed generations. The integration of distributed generation units into the distribution system forms microgrids within the network. Most of the matured distributed generation technologies are the wind energy converters, solar photovoltaic cell, fuel cell, small hydro, mini hydro, micro-hydro, microturbines, diesel generators, and tidal power [1].

The conventional electric power system as shown in Figure 1.1, is centralized, in terms of its generation, transmission, distribution and control. The electricity is generated on a large scale at the generation plant, flows through the transmission network to the distribution network, then to the consumer load point.

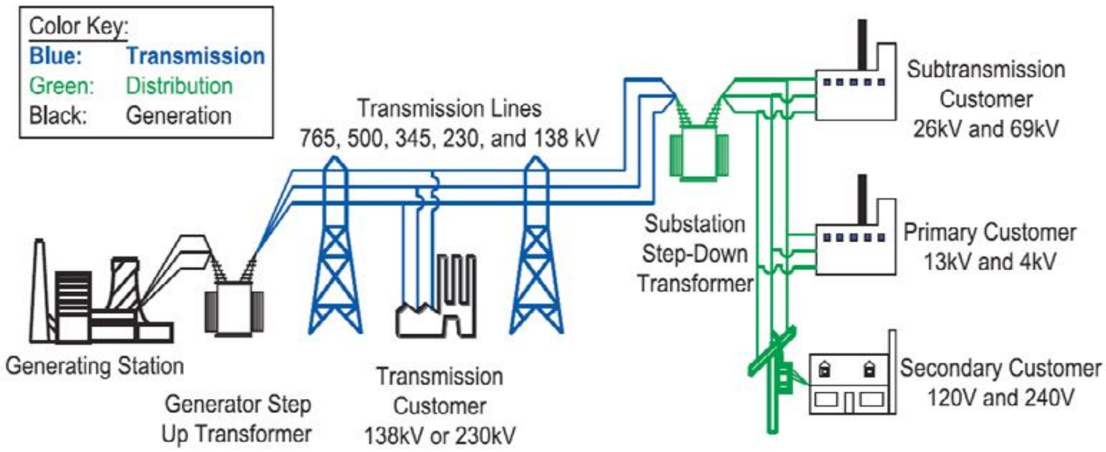

Figure 1. 1. Basic structure of a conventional power system [2]

The equipment in the power system infrastructure sometimes experience random failures, which might be outside the control of the power system personnel. Failure of any of these components in the grid may cause interruptions that may range from inconvenience to a few customers to major catastrophic disruption of power supply, loss of revenue to the utility company and other commercial users, and in some situations lost of lives and properties. The cost of the 1977 blackout that occurred in New York is suggested to be about $350 million of which 84% were indirect cost [2]. The inflation-adjusted cost of power outage to the North American economy from 2003 to 2012 has been estimated to range from $18 to $33 billion annually. These blackouts also affected water supply system, transportation and communication systems. These estimates are made up of direct and indirect cost [2].

As shown Figure 1.1, any failure or interruption that may occur at any point from generation through to the distribution side of the network, will affect many customers. Most of these interruptions are due to the slow response of switches, breakers, lack of automatic analytics and lack of situational awareness [2]-[6]. Adverse weather conditions can also cause the failure of the network or customer interruptions. The probability, frequency, and duration of interruptions in the electricity supply and their effect on customers can be mitigated, by the integration of distributed generation into the distribution network, thus improving the reliability of the power supply.

1.1 Distributed Energy Resources

In the conventional power networks, power is generated on a large scale mainly from fossil fuel-based generation plants and transported over the transmission lines to the distribution network where customer load-points are connected to the system. These conventional power generation systems are faced with several challenges, including gradual depletion of fossil fuel resources, pollution of the environment because of greenhouse gas emission (GHG), and poor energy efficiency [7].

Any failure upstream of the grid affects all loads served downstream until that failure is repaired. These problems have led to the emergence of a new trend of generating power locally, at the distribution voltage level using non-conventional and renewable resources such wind energy, solar energy, fuel cells, natural gas, biogas, biomass, microturbines and Stirling engines. These types of power is generated by the utility company or their customers; and are either integrated into the distribution network or operated as stand-alone. These types of power generators at the low voltage level are called distributed generation (DG) or decentralized power generation, and the energy resources are called distributed energy resources (DERs) [7-18]. The distributed generation is said to be grid-tied when it is integrated into a distribution network that is supplied by a grid or stand-alone when it is operated in isolation from the grid or in remote communities.

1.2 Microgrid Systems

Microgrids are small-scale low voltage (LV) supply network which consist of local distributed generation, load, energy storage, protection and control devices designed to supply electricity to small communities, commercial area, industrial site or an individual customer [7, 10]. Microgrid can be interconnected to the grid and operate in an island mode when there is an interruption in the main grid and it has the capacity to supply those loads. Microgrids, which consist of different generators, load and energy storage facilities, are referred to as active distribution network because they operate continuously most of the time either supplying power to the grid or to the storage system. In this case, power transmission is bi-directional. The differences between the conventional power plant and microgrid are as follows:

- Microgrids are much smaller compared to the conventional large power plants.
- Power is generated locally at the distribution voltage level and can be fed directly into the utility distribution grid.
- Microgrids are normally installed close to the customer load-point so electrical and heat loads can be efficiently supplied with negligible transmission losses.

A typical topology of a microgrid system is as shown in Figure 1.2 below.

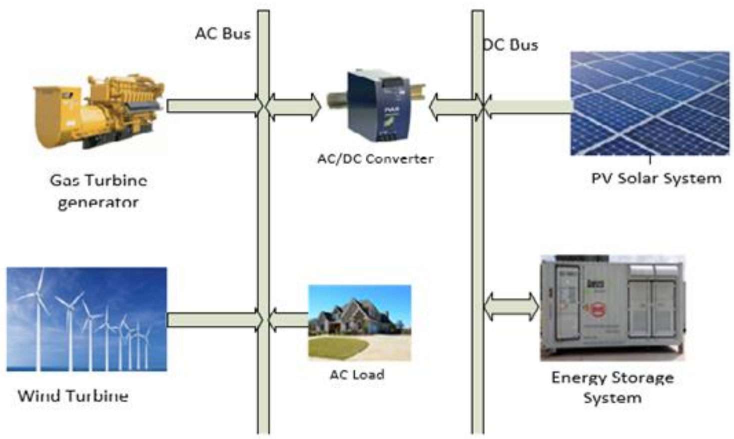

Figure 1. 2. A basic topology of microgrid power system [1]

The deployment of distributed generators in power distribution network to form microgrid, offer the following benefits to the utility providers, distributed generation owners and consumers.

- Reduction in Transmission and Distribution System Expansion losses: The proximity of the microgrid source to consumer load-points reduces the physical and electrical distance.

This helps to reduce transmission and distribution feeder congestion and, minimize the transmission and distribution losses.

- Cost saving: Customers have the freedom to choose the type of distributed generation due to their geographical location and cost of the technology. Efficiency is increased when used as combined heat and power, because the heat is not transported over a long distance to incur transmission losses. Overall, the investment in the expansion of the transmission and generation system will be reduced.
- Reliable Power Supply: Microgrid provides alternative supply to the customers whenever there is power outage from the main grid. The microgrid can only supply the load if it has enough capacity to do so.
- Green house gas reduction: Since 66.3% of the world electricity is generated from fossil fuel-based source as of 2015 [15], higher penetration of renewable energy in power generation reduces the gaseous and particulates that pollute the environment. This will also reduce the over reliance on fossil fuel to minimize its depletion.

1.3 Definition of Power System Reliability

The primary function of electric power system is to generate enough power to meet the load demand of the customers both large and small, with reasonable assurance of continuity and quality. The overall ability of the system to provide adequate power to the customers is associated with the term reliability. The concept of power system reliability is very broad and covers the entire network of power system. For this reason, the reliability evaluation of power system, both deterministic and probabilistic has been divided into two aspects of system adequacy and security as shown in Figure 1.3 [3, 14].

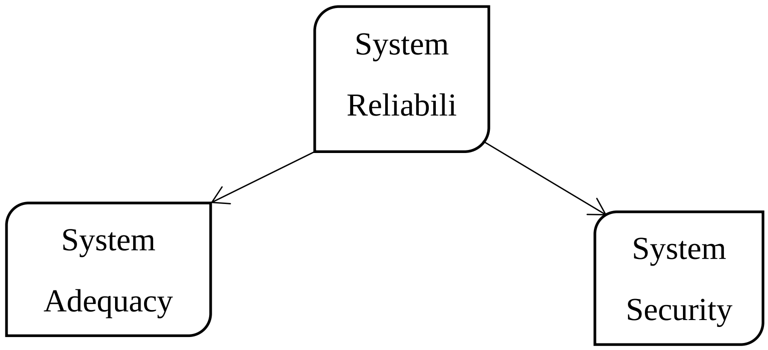

Figure 1. 3. Subdivision of power system reliability

System adequacy relates to existence of power system infrastructure to facilitate the generation of sufficient power to meet customer load demand. The infrastructure includes generation facilities, transmission and distribution network to transport the power to the customer load points. System security relate to the system's ability to respond to transient and dynamic disturbances. These disturbances may be internal or external and may lead to power losses [14]. Most power system reliability techniques presently fall in the domain of the adequacy assessment. The techniques presented in this work also fall in the adequacy domain as well.

1.4 Objectives of the Thesis

Risk assessment of power systems are performed to identify critical component of the network to aid maintenance and future investment planning [14]. Reliability assessment of power system is carried out to ensure that all components of the system perform their stated functions under stated operational conditions to provide continuous and economic power supply to consumers

[3, 4]. These two assessments are very much related because, whereas risk assessment identifies the critical component of the system, reliability assessment use the average risk values (failure rate) of the component to quantify their average contributions to power supply interruption, and the cost of the interruptions to both the consumer and the utility provider.

Many research works on reliability assessment of power systems with integration of distributed generators, consider a particular type of distributed generator, using the availability of resources of the geographical location of system as the main criteria for selecting the distributed generator [16, 18]. There are few other studies that compare hybrid combination of both diesel and renewable distributed generators on one hand and all renewable distributed generators on the other, to see which of these combinations are both economical and improve the network reliability [19].

There are not many literatures on reliability assessment of power system that investigate the selection of appropriate distributed generators based on the relative comparison of the benefits of the various types of DGs. This thesis develops an approach for selecting DGs for integration into microgrid power system based on economic, reliability and environmental considerations. The quantitative procedure outlined in this thesis provides a basis for broadening the criteria to the selection of different DGs, thus reducing the subjectivity of the qualitative expert judgement that is used in the analytic hierarchy process.

1.5 Thesis Organization

Chapter 1 introduces the concept of reliability of power systems. Advantages of distributed generators over conventional power systems, certain renewable resources and the concept of microgrid are also presented. Works related to the present study are reviewed and summarized in chapter 2. In Chapter 3, a brief review of different reliability techniques and approach is presented. In chapter 4, risk analysis and reliability techniques such as analytical, failure mode effect analysis (FMEA)/ failure mode effect and critical analysis (FMECA), reliability block diagram (RBD) applied to IEEE RBTS-Bus 6 are presented. In Chapter 5, the application of analytic hierarchy process to select the most suitable distributed generators for integration into the microgrid is presented. Finally, the conclusion of the thesis and future work are presented in Chapter 6.

Chapter 2

Literature Review

2.1 Introduction

Utility data show that, distribution system failures cause 80% of the customer average outage interruptions [2]. For this reason, researchers and utility providers have proposed several techniques and methodologies of evaluating the reliability of distribution systems. This section of the thesis reviews works related to risk analysis and reliability assessments of power systems as well as the selection of the most suitable distributed generators.

2.2 Risk Analysis and Reliability Assessment of Power Systems

2.2.1 Integration of Distributed Generators into Microgrids

Risk assessment and reliability assessment of power systems employ radial distribution network in modelling several techniques. The techniques used in power systems reliability evaluation can be divided into two basic categories of analytical and Monte Carlo simulation methods. The analytical techniques are highly developed and have practically been used in both academic research and in the power industry for several years [3, 4, 14]. These conventional techniques are generally based on failure mode effect analysis (FMEA). It is a systematic approach, which determines all possible failure modes of each component and its effect on the system [14, 120]. Every possible failure event of each component of the distribution system is analysed to determine its effect on the load points. A list of the final failure event is prepared to evaluate the basic load-point indices. Conventionally, the FMEA technique has been used to evaluate radial distribution systems. In a complicated distribution network configuration, the list of basic failure modes will be lengthy and would require a lot of effort and time to evaluate the network [14, 20].

References [21, 23] present reliability test system called Roy Billinton Test System (RBTS). The RBTS is used to evaluate distribution network using the analytical technique. Billinton and

Wang [20] introduced the analytical approach called the “reliability-network-equivalent approach”. The approach replaces some portions of the network with equivalent elements to decompose the network into simple radial network for evaluation. When applied to large and complex distribution network, this approach results in simpler analysis.

Fault tree analysis (FTA) which is one of the most widely used tools for risk and reliability assessment, is used to evaluate the reliability of island microgrid during emergency operation [16]. The drawback of fault tree analysis is that it is mostly useful for small and medium scale systems. Fault tree implementation is almost impossible with interconnected systems.

References [20 -27] demonstrate the application of both analytical and Monte Carlo techniques of reliability assessment of distribution networks which do not include distributed generators.

Billinton and Wang in [24] developed an algorithm to evaluate the reliability of a complex distribution system using Monte Carlo simulation. The algorithm was applied to a distribution system of the RBTS, which is used mainly for rural distribution network.

Bie et al. [13] evaluated a system using Monte Carlo simulation technique. The concept of virtual power plant (VPP) was introduced to model a microgrid connected to different intermittent power sources. Non-sequential Monte Carlo simulation was then adopted to evaluate the reliability of the active distribution system under different operation modes of single and multiple contingencies.

This work addresses the intermittent nature of renewable resources of both wind turbine and photovoltaic. It fails to demonstrate the criteria used in selecting the various DGs.

Sanghvi in [17], presented cost-benefit reliability evaluation of customer interruptions.

Atwa et al. [25], proposed a methodology to optimally locate different renewable distributed generators in the distribution network that will reduce annual energy losses in the network. Their proposed methodology was based on generating probabilistic generation-load model that combines all the possible operation conditions of the renewable distributed generators with their probabilities. The main objective function of the work was to minimize the annual energy losses of the distribution network system. The results showed that, the application of any of the chosen distributed generators (wind, solar, and biomass) in any combination reduced the systems annual energy losses. However, the most significant reduction was recorded when biomass is in the mix. There are no stated criteria for choosing these distributed generators, except for the fact that the wind speed data and the solar irradiation of the geographical location are modelled.

Wang and Billinton [16], proposed a method of assessing the benefit of adding wind turbine generators to the distribution network by introducing four new reliability indices. In this work, auto-regressive and moving average time series model was used to model the wind speed data in Regina and North Battlefield, both in Saskatchewan. Monte Carlo simulation was used to estimate reliability indices like expected energy not supplied (EENS) and expected interruption cost (ECOST) of the load-point (LPs) in the network. These indices are used in arithmetic relationships to determine their proposed reliability indices. The proposed reliability indices are wind generation interruption energy benefits (WGIEB), wind generation interruption cost benefits (WGICB), the equivalent number of conventional generators (ENCG), and equivalent conventional generator capacity (ECGC) of 1MW wind turbines. The proposed methodology was applied to RBTS-bus 6 to determine the benefit thereof. The work estimated some improvement in the reliability indices depending on the geographical location and the number of wind turbines installed in the farm.

Conti et al. [26] presented a generalised analytic method of reliability evaluation of network with different DGs in microgrid and smart grid networks. The formulated arithmetic relationships for this work are derived based on five case assumptions of fault location on the network, relative position of the fault to the switches, type of DGs, and the load-points. When fault occurs, the local DGs operate in an island mode, supplying power to the LPs downstream of the fault based on their adequacy. The probability of adequacy of the DGs are derived using annual load model of the LPs, generation model of the DGs and the clustering technique based on central centroid sorting process. Conti et al. [26] demonstrated significant improvement in the reliability of the network, but the work did not address the question of how to choose the DGs in the system under investigation.

Wang et al. [27], proposed several metrics that could be used to evaluate the reliability and economics of distribution system that contains microgrid. In this process, two-step Monte Carlo (MCS) was adopted for the reliability assessment. Firstly, the microgrid was considered as an equivalent load connected to the distribution network at the point of common coupling (PCC) while the reliability of the rest of the distribution network was assessed. Secondly, MCS was also used to asses the reliability of the microgrid containing distributed generators whiles the rest of the network was considered as an equivalent conventional generator model. In performing the reliability assessment of the microgrid, several operational reliability indices of the microgrid operations are proposed to facilitate that assessment. Indices to assess the economic benefit of the microgrid was also proposed. All the proposed indices together with the IEEE Standard 1366-2001 reliability indices are used to asses the reliability of the network that has three scenarios with different combinations of the distributed generators. All these scenarios show divers degrees of economics and reliability improvement of the network after DGs are integrated based on the combination.

Adefarati and Bansal [18], presented work that evaluates the reliability and the economic benefits of distribution system that includes microgrids. The microgrids contain distributed generators like diesel generators, wind turbine generators, photovoltaic solar system and battery storage system. In this work, the key performance indicators such as net present cost (NPC), cost of energy (COE), annualised cost of the system (ACS), annual fuel cost (AFC), annual energy cost (AEC), and annual maintenance cost (AMC), are used to asses the economics and the environmental benefits of the networks. Markov process is used to assess the reliability of the network in terms of indices such as the expected energy not supplied (EENS), expected interrupted cost (ECOST), system average interruption frequency index (SAIFI), and system average interruption duration index (SAIDI). The result of their work show that the reliability, economics and environmental benefits of the network are improved with the integration of distributed generators into the microgrids. The literature cited above considered the integration of distributed generators into microgrids either based on the renewable resource of the geographic location or a combination of arbitrary distributed generators without clear criteria for their selection. However, there are multi-criteria decision-making (MCDM) tools such as AHP, which can be used to select the most suitable distributed generators among several alternatives [30]-[38].

2.2.2 Selection of Suitable Distributed Generators for Microgrids

Algarin et al. [33], used Analytical Hierarchy Process (AHP) to select the most suitable renewable resources for electricity generation in rural Columbia. Criteria considered in this work include technical, economic, social, environmental, and risk. Among alternative energy sources such as solar PV, wind turbine, biomass and small hydro power plant (SHPP), solar PV was selected as the most suitable renewable DG.

Rojas-Zerpa et al. [34], presented a method of using AHP, and multi-criteria and optimization solution (VIKOR) tool, in selecting distributed generator for rural Venezuela. While the AHP use criteria based on expert judgements to select the most suitable DG among alternatives, VIKOR rank a compromise alternative when the decision maker has no relative preferred criteria among the alternatives.

Bevilacqua and Braglia [38] proposed a methodology that used AHP to select the best maintenance procedure for an Integrated Gasification Combined Cycle (IGCC) plant in Parma, Italy. The five possible alternative maintenance procedures that were compared are preventive maintenance, corrective maintenance, opportunistic maintenance, predictive maintenance and condition-based maintenance. Bevilacqua and Braglia [38] used Interactive Structural Modelling process for identifying and summarising relationships among all the specific factors for problem formulation in the AHP process. In the end, preventive maintenance was projected to be the most suitable maintenance procedure for the IGCC plant.

2.3 Summary

Most of the literature reviewed considered the integration of distributed generators into distribution system to form microgrid either based on the renewable resource of the geographic location or the arbitrary combination of certain DGs without clear criteria of their selection. Other literature used multi-criteria decision-making tools such as AHP and VIKOR to select DGs for implementation into microgrid. These literatures convert qualitative expert judgement into quantitative criteria, which are used for the selection process. This process is very subjective. The current work uses analytic technique to evaluate the failure probability of the LPs in the network; FMEA and RBD for risk mitigation; and AHP for the selection of the DGs for the microgrids. The subsequent chapters present the development of the approach for the reliability and risk assessment of the RBTS-Bus 6 systems.

Chapter 3

Risk and Reliability Concept in Power Systems

3.1. Introduction

Risk is defined as the product of the probability of potential failure and the consequence of that failure [32]-[37]. The reliability of a component or system is defined as the probability of the component or system to perform its design function for a given period under stated operational conditions. The implication of these two terms, risk and reliability are identical but inversely proportional. A system with a higher reliability means that the risk level is lower and vice versa [3], [39]-[44]. Risk evaluation should not only consider the probability of potential failure but the consequential effect of the potential failure on customers, utility providers and the environment. Risk in power system is manage by performing the following tasks [40]:

- Perform risk evaluation of the system
- Determine measures to reduce the risk level
- Determine and justify the acceptable risk level

Reliability is often denoted by the survival function, which is calculated using the cumulative distribution function of the failure probabilities *F (t)* [6].

$$F(t) = \int_t^{\infty} \lambda \, e^{-\lambda t} = 1 - e^{-\lambda t} \quad (3.1)$$

$$R(t) = 1 - \int_0^t \lambda . e^{-\lambda s} \, ds = e^{-\lambda t} \quad (3.2)$$

where;

$F(t)$ is the probability that a failure occurs before time t

R(t) is the reliability function

λ is the failure rate

Failure rate (λ) is the reciprocal of the mean time to failure (MTTF) and is defined as the number of failures of a component in a given period of time divided by the total number of periods the component has been in operation. Repair rate (μ) which is the reciprocal of mean time to repair (MTTR) is also defined as the number of times a component is repaired in a given time divided by the total number of times the component is repaired [44].

Failure rate of deteriorating equipment is best explained by the "bathtub curve" shown in Figure 3.1. It describes the life cycle of products or systems.

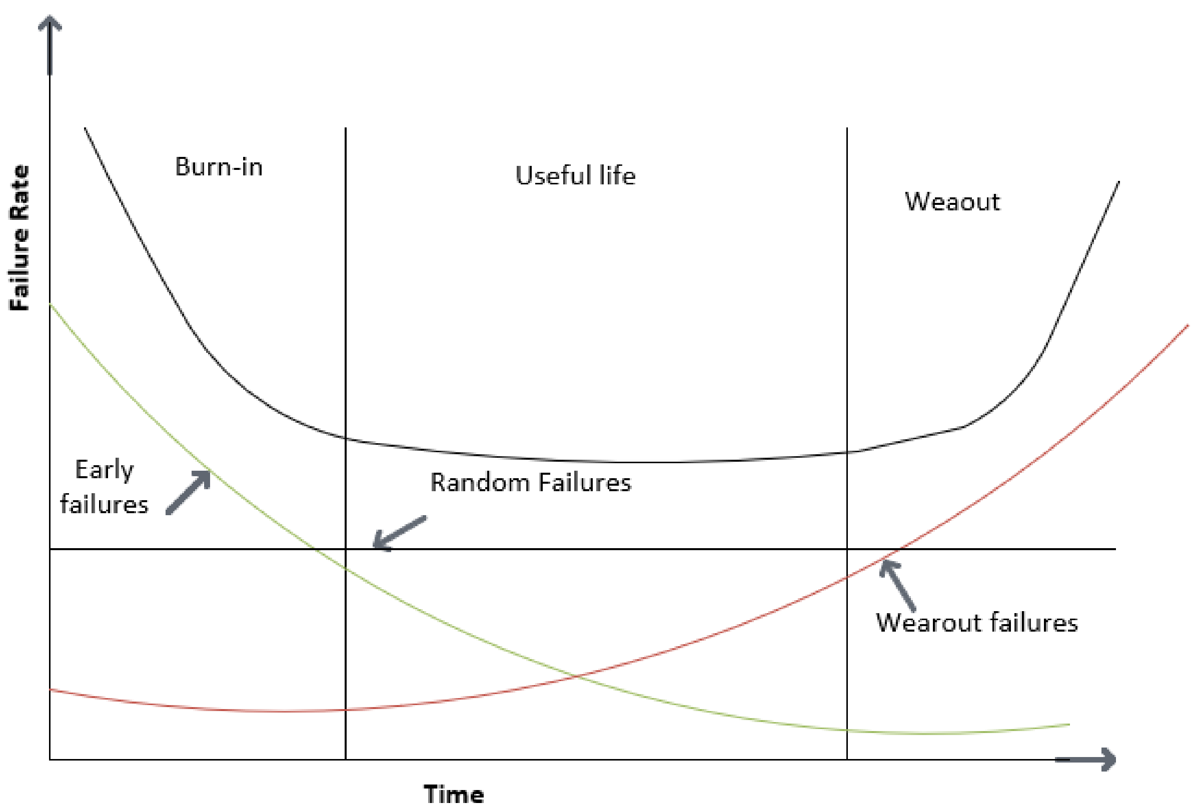

Figure 3.1. The bathtub curve

Failure rate of components decrease early in their life cycle and is described on the bathtub curve as the “burn-in” or infant mortality period. The useful life period follows the infant mortality period. Here, components have relatively low and constant failure rate. The last period of the life cycle is the wear-out period. In the wear-out period, the products experience increasing failure rate. The characteristics of the bathtub curve are summarized in Table 3.1 below.

Table 3. 1. Characteristics of Bathtub Curve [45]

Age	Characterized by	Caused By	Safeguard
Burn-in	Decreasing failure rate	Manufacturing defects, Poor quality control, Welding flaws, cracks etc.	Burn in testing, Screening, Quality control, Acceptance testing.
Useful life	Constant failure rate	Environment, Random loads, Human error, Chance events.	Redundancy Excess Strength.
Wear out	Increasing failure rate	Fatigue, Corrosion Aging, Friction, Cyclic loading.	Derating, Preventive Maintenance, Replacement

Most electrical equipment failure occurs in the useful period with constant failure rate which is described by the exponential distribution reliability of equation (3.2).

Reliability analysis is an essential study for the design, operation, maintenance, and planning of power systems [40]. For example, with specific reliability requirement, an optimum maintenance strategy can be formulated to minimize the operational cost. In fact, good maintenance schedule influences the deterioration process, failure rate, thereby improving the reliability of components and systems [445].

Billinton et al in [3, 14] categorize reliability in power system into adequacy and security, but the North American Reliability Council (NERC), have added another category in terms of power quality.

Power system quality deals with power conditioning and harmonic characteristics [40]. Reliability may have a broad definition, but the analyses are performed from diverse perspectives. In power systems, reliability assessment is done from two main perspectives. These are consumer's perspective and utility perspective [45]. What most electricity consumers care about is to have continuous and, quality power supplied at very economic rate. The utility provider's perspective deals with adequacy of generation, sufficient transmission facilities, and the reliability of the distribution network to serve customers [46].

3.1.1. Functional Zones of Power Systems

Power systems in general, have been categorized into functional zones for the purposes of planning, organization, and operation. The functional zones are generation facilities, transmission facilities, and distribution facilities. These functional zones can also be grouped into hierarchical levels as shown in Figure 3.2. Hierarchical level I (HL I) comprises the generation system, hierarchical level II (HL II) consist of the generation and the transmission systems, while hierarchical level III (HL III) is made up of the generation, transmission, and distribution systems [3, 14].

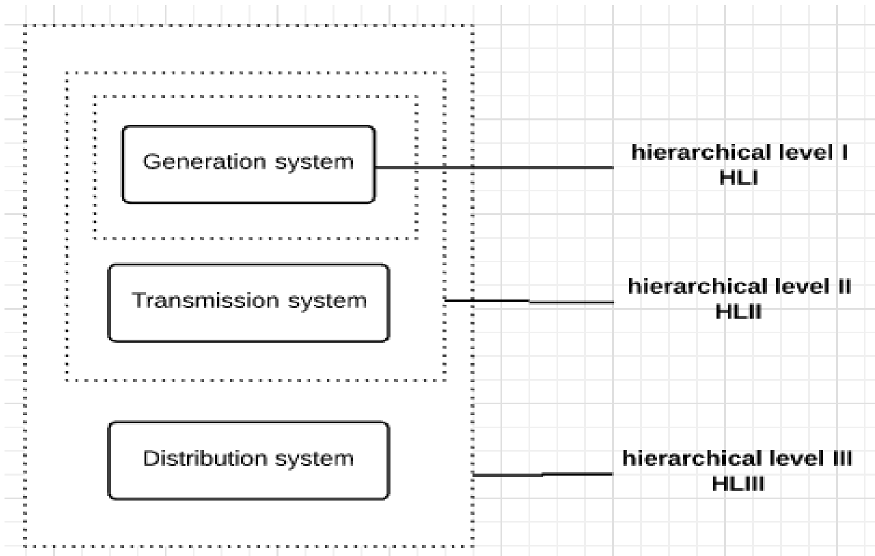

Figure 3. 2. Hierarchical levels in power systems

Adequacy studies are mostly done based on the functional zones and not the hierarchical levels. Hierarchical levels in power systems can be used in adequacy evaluation but hierarchical level HLIII which involves the distribution system would be very complex since it will include all the other hierarchical levels. Here, the distribution functional zone is used for the study, but the adequacy indices of HL II are used as the input. The distribution functional zones studies are done to assess the consumer load point adequacy.

3.1.2. Reliability Indices

There are two types of distribution systems: radial and meshed systems [3, 4, 6, 14]. This study uses the radial system of distribution. The techniques for radial distribution are based on failure-mode effect analysis which considers all the possible failures events and restoration processes. The reliability evaluation of the distribution system or the adequacy evaluation of the customer load points considers three factors:

- Frequency of interruptions
- Duration of interruptions
- Severity or consequence of the interruptions

Frequency and duration of interruptions are very important considerations from both customer and utility perspectives, and the last factor represents customers' perspective.

In evaluating the reliability of distribution system, there are three basic load point indices which are normally used [14, 24, 45, 46]. They are the average failure rate, average outage time, and the average annual outage time. For a general radial distribution system, the average failure rate (λ_i), average annual outage time (U_i), and average outage time (r_i) for a load-point *i* can be calculated using the following equations [4, 6]:

$$\lambda_i = \sum_{j=1}^{n} \lambda_j \tag{3.3}$$

$$U_i = \sum_{j=1}^{n} \lambda_j r_j \tag{3.4}$$

$$r_i = \frac{U_i}{\lambda_i} \tag{3.5}$$

where *n* is the total number of components which affect the load-point i, λ_j is the average failure rate of element *j* and r_j is the average restoration time used to restore the load-point i when component j failed. The overall performance indices and definitions used in this study are as follows [3, 4, 14, 46, 51]:

System Average Interruption Frequency Index (SAIFI) - describes how often the average customer experiences a sustained interruption over a period of time. It is usually measured in years.

$$SAIFI = \frac{\Sigma\ Total\ Number\ of\ Customers\ Interrupted}{Total\ Number\ of\ Customers\ Served} = \frac{\sum_i Ni}{N_T}\ \text{(int./cust.yr)} \tag{3.6}$$

where N_i and N_T are the number of customers who experienced interruptions due to outage *i* and the total number of customers respectively.

System Average Interruption Duration Index (SAIDI) - describes the total duration of interruption for the average customer during a period of time. Measured in minutes (hours) of customer interruption.

$$SAIDI = \frac{\Sigma\ Customer\ Interruption\ Durations}{Total\ Number\ of\ Customers\ Interrupted} = \frac{\Sigma i.r_i\ N_i}{N_T}\ \text{(hr/cust.yr)} \tag{3.7}$$

where r_i is the interruption duration due to outage *i*

Customer Average Interruption Duration Index (CAIDI): indicates the average time required to restore service.

$$CAIDI = \frac{\Sigma\ \text{Customer Interruption Durations}}{Total\ Number\ of\ Customers\ Interrupted} = \frac{SAIDI}{SAIFI}\ \text{(hr/int)} \tag{3.8}$$

Expected Energy Not Supplied (EENS) – describes the cumulative amount of energy that is not provided to the customers and it is usually stated for duration of a year.

$$EENS = \sum L_i \times r_i\ \text{(kWhr/cut.yr)} \tag{3.9}$$

where L_i is the average number of customer loads.

Average Systems Available Index (ASAI) – describes the average availability of service per customer served by the utility.

$$ASAI = \frac{Customer\ Hours\ Service\ Availability}{Customer\ Hours\ Service\ Demand} = \frac{N_T \mathrm{T} - \Sigma i.r_i\ N_i}{N_T.T} \tag{3.10}$$

where T is the duration for reporting the index, which is usually one year (there are 8,760 hours in a non-leap year and 8,784 hours in a leap year).

Average Service Unavailability Index (ASUI) – describes the average number of hours the service is unavailable per customer.

$$ASUI = \frac{Customer\ Hours\ of\ Unavailability\ Service}{Customer\ Hours\ Demanded} = 1\text{-}ASAI \tag{3.11}$$

3.2. Reliability Evaluation Methods

Reliability evaluation methods have generally been divided into two basic categories namely, analytical techniques and simulation techniques. The analytical methods develop mathematical models to represent the systems and evaluate the reliability indices from these mathematical models [6]. The Monte Carlo simulation methods evaluate the indices by simulating the actual process and the stochastic behavior of the systems. There are advantages and disadvantages of any of these methods or techniques. The analytical methods are very efficient when used for the evaluation of small and non-complex systems. With complex and large networks, the Monte Carlo simulation technique is more efficient [18, 20, 26] The Monte Carlo simulation can also simulate the probability distribution of systems failure and the restoration. Few techniques of the analytical and the simulation methods are reviewed in this section.

3.2.1. Fault Tree Analysis (FTA)

Fault tree analysis is an analytical technique where a top event or an undesired state of the system is specified, and the system is presented graphically to systematically link all the possible causal events that lead to the undesired event [43, 44], [52]-[55]. Fault tree analysis can be either qualitative or quantitative. Qualitative analysis involves the use of graphical models to systematically identify all the possible basic events that can lead to the undesired event at the top from occurring. For quantitative analysis, fault tree is implemented with failure probability data of the basic events to estimate the probability of the top event occurring.

Fault tree is constructed using gates and events. The most common gates used are the “OR” and the “AND” gates to connect all basic events to the top event. The top event is the output of the gate and the lower events are the input to the gate. The “AND” gate connects all events on the same level which must occur to cause the undesired event to happen. The “OR” gate also connects a group of events which either of them occurring will cause the top or undesired event to happen [52]. Figure 3.3 shows a basic structural model of a fault tree.

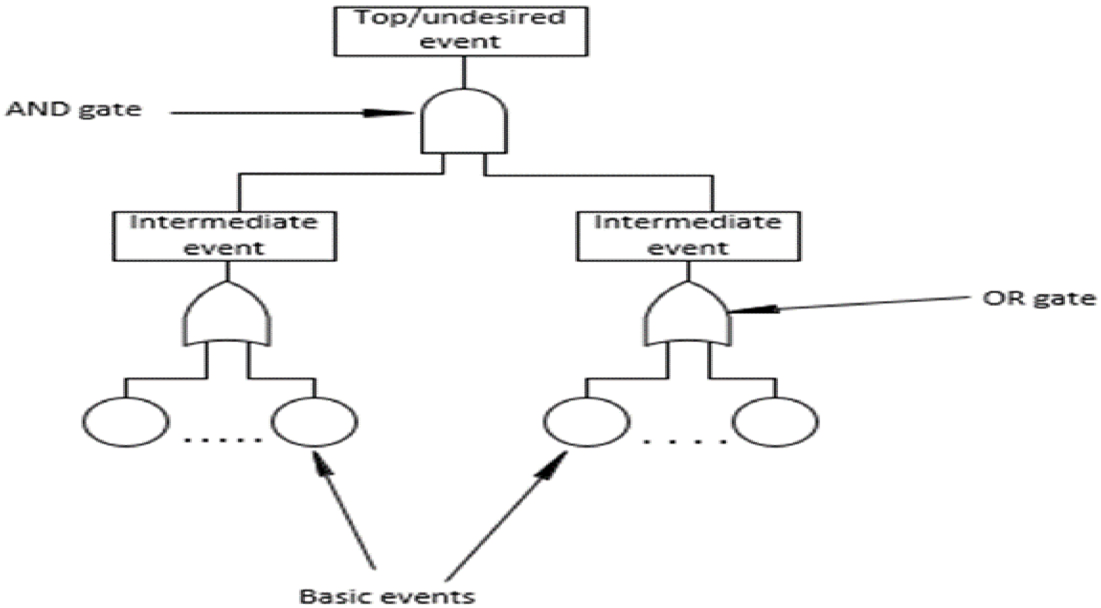

Figure 3. 3. Basic structural model for fault tree analysis

3.2.2. Failure Mode Effect Analysis (FMEA)

It is a systematic approach which details all possible failure modes, component by component in the system to determine their resulting effect on the system [20]. Most conventional methods of evaluating distribution system reliability are based on failure mode effect analysis. In practice, FMEA is used in almost all process failure analysis from design to the implementation level [39]. The FMEA analysis describes an inherent failure mode that may lead to system failure, determines their effect on the system and devises ways of minimizing their occurrence or their consequence. These failure events are listed and used for the calculation of the basic load-point indices. The effects of these events are specified and ranked. The ranking is done by determining the critical or risk priority number (RPN) of each failure event and its resulting effect on the system. These rankings are based on the probability of occurrence of the failure mode, the severity of its effect on the system, and its detectability [39], [56]-[59]. The failure mode or event with highest ranking number represents the area of the highest risk in the system. Measures are then taken to mitigate or minimize the occurrence of these failures.

FMEA is a powerful risk and reliability tool that has been used in many industries for a while, but it also has some deficiencies [57]. In a complex system with complicated configurations that has variety of components, the list of failure events will be lengthy. This would require a considerable amount of analysis when FMEA is used. In like manner, using FMEA to evaluate the reliability of large radial distribution system is also difficult.

3.2.3 Markov Models

Markov analysis is a random process where the probability of a system undergoing a transition from one state to another depends only on the present state and not on any other state that the system has gone through. In other words, the transitional probability does not depend on the previous state of the system [45, 53,54]. This is equivalent to the memoryless of the exponential distribution. The Markov analysis considers the system to be in several states. One possible state is that all the components of the system are working. Another possible state of the system is that, one component of the system has failed (down) while other components of the system are working (up) [45, 53]. Figure 3.4 shows a two-state transitional diagram of a repairable system where λ, denotes the failure rate and μ, represents the repair rate. At each state of the transition, several possible events can be used to define the transitioning process from one state to the other.

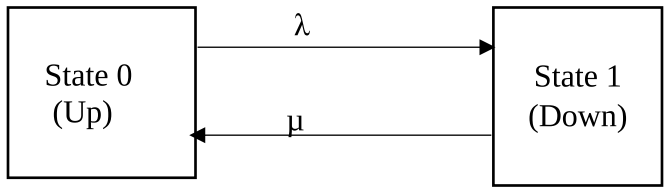

Figure 3. 4. Two state transition system

In general, Markov models can either be continuous or discrete both in time and space [4].

In system reliability evaluation, space is represented by discrete functions because it represents the present condition and the present location of the systems' component. But time can be either discrete or continuous.

The main advantage of the Markov model is that all states and the transitions between them are abundantly clear. It is very effective when applied in modeling the outages of individual components of the system. The main disadvantage of this model is the difficulty that may arise when applied to very large and complex systems. For a two state (up and down) system with N components, the number of system's state is 2^N [55]. With large N, it become almost impossible to draw the state space diagram. In the same manner, it will be very difficult if not impossible to apply the Markov processes to a large and complex power distribution or radial network.

3.2.4. Reliability Block Diagram and Other Analytical Techniques

There are other number of analytical techniques that are used in reliability analysis of power systems. Among them are Minimum Cut-set, and Network-Reduction techniques [38, 47]. These techniques involve the reduction of the number of components by putting the series component together and the parallel components also together from which series and parallel equivalent of the components are formed. Figures 3.4 and 3.5 show series and parallel systems respectively, while Figure 3.6 also show the equivalent systems after they have been reduced using equations (3.12) – (3.14) for the series reduction and (3.15) – (3.16) for the parallel reduction of the system [40]. The equivalent system is then used to estimate the load point reliability indices. The series and parallel components reduction technique is also called the reliability block diagram (RBD). The equations for the series and parallel network reductions are as follows:

$$\lambda_{eq} = \lambda_1 + \lambda_1 \tag{3.12}$$

$$r_{eq} = \frac{\lambda_1 r_1 + \lambda_2 r_2 + \lambda_1 \lambda_2 r_1 r_2}{\lambda_{eq}} \tag{3.14}$$

$$\lambda_{eq} = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2} \tag{3.15}$$

$$r_{eq} = \frac{r_1 r_2}{r_1 + r_2} \tag{3 .16}$$

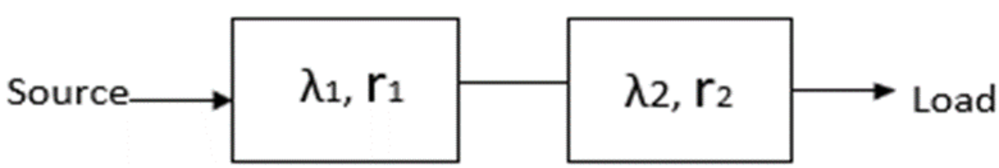

Figure 3. 5. Series systems

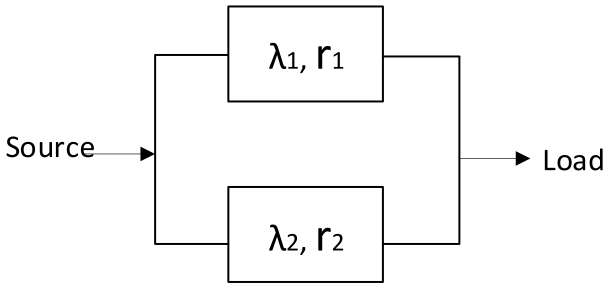

Figure 3.6. Parallel System

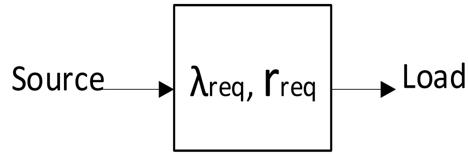

Figure 3.7. Equivalent systems

3.2.5. Monte Carlo Simulation

The other basic reliability technique used in evaluating the reliability of power system is the Monte Carlo simulation method. This simulation technique estimates the reliability indices by simulating the actual process and the random behaviour of the system [6]. With this method, the problem is treated as series of experiments performed by way of simulation [4]. The data required for this technique are failure and repair rates data of the components and the system configuration. Failure and restoration time samples used for the reliability indices estimation are generated randomly based on probability distribution. First, a random sample is generated to represent the failure component base on a probability distribution. Another random value is generated to represent the restored component. These random generated values are between

[0, 1]. These values are used for the reliability indices calculation. After several iterations, the expected reliability of the system is calculated, where the estimated values of reliability indices can be represented by a probability distribution for that index [56].

There are two types of Monte Carlo simulation methods: 1) non-sequential Monte Carlo simulation; and 2) sequential Monte Carlo simulation.

The non-sequential Monte Carlo simulation is also called the state sampling method. With non-sequential approach, the state of the components is estimated by sampling its probability in that state, and all the individual components sampled states are combined to form the systems state. The determination of the state is based on uniformly random generated variable between 0 and 1. The state of the component is considered to be “Up” if it is greater than the failure probability otherwise the state will be “Down”. The main demerit of the non-sequential approach is that, the simulation is unable to capture the chronology of time-dependent events of the system. Therefore, the system failure frequency and mean failure duration are obtained by approximation [56].

Sequential Monte Carlo approach is the simulation process where the chronological time events of the system are simulated. This approach is categorised into two: 1) state duration sampling approach, and 2) state transition sampling approach. With the state duration approach, the component state duration probability distribution is sampled. The initial state of all components is first specified, and the duration of each component residing in that state is sampled and the probability distribution of the state duration is also assumed [3]. With the state transition approach, the transitional probability of the component from one state to the other is sampled. The main advantage of the sequential Monte Carlo simulation is its ability to accurately evaluate the frequency and frequency duration of components. It is also able to calculate probability distribution of system reliability indices [3, 53, 54, 60].

3.2.6. *Bayesian Network*

Bayesian networks (also known as belief network, belief net, or causal networks) are direct acyclic graphical representation of joint probability distribution. In Bayesian network (BN), variables are represented by nodes and the link between the variables are referred to as probabilistic influence [61]-[64]. Bayesian networks convert the probability density functions that regulate a set of random variables considering a set of conditional independent statements and a set of conditional probability functions (CPFs). BN is made up of qualitative part, which is the direct acyclic (DAG) part where the nodes represent the random variables and the quantitative part which is the set of CPFs. Reliability analysis in BN considers both discrete and continuous variables [63], [65, 66]. BN have several advantages in its applications and notable among them are:

- BN models are powerful tools for graphical representation of relationships between a set of variables and dealing with uncertainties in systems.
- BN approach allows for qualitative inferences without the computational inefficiencies of traditional joint probability determinations.
- BN approach allows for easy refining of the network, that is, additional variables can easily be added and mapping from the mathematics to other common reference points.
- BN has the flexibility of allowing for evidence to be entered into the network and updating the network to propagate the probabilities to each node.

3.3. Summary

There are several techniques that are used for the reliability assessment of engineering systems. In this chapter, many reliability techniques such as the fault tree, analytical technique, RBD, FMEA, Markov process, Monte Carlo simulation, and Bayesian network are discussed. Even though several reliability assessment techniques are discussed in this work, the following techniques are implemented for this study: the analytical technique, FMEA and the RBD because they are simple to implement, widely used and fit the scope and objective of this work better. Application of a different tool called AHP was used for the decision-making process in this work and is presented in the next chapter.

Chapter 4

Risk and Reliability Evaluation of Network

4.1. Introduction

The risk and reliability methods (analytical technique, FMEA, RBD) discussed in chapter 3 are implemented using the feeder 4 of IEEE RBTS bus 6 network. It is a standard power system network showing how the component in network are interconnected. This network was designed by Prof. Roy Billinton, to test power systems reliability, hence the name Roy Billinton Test System (RBTS and is presented in Appendix A). F4 is the main feeder (main transmission line) and F5, F6, F7 are the subfeeders (lateral or sub transmission lines). Switch S is a sectionalizer, an automatic protective device which switches off the main line upstream when there is a fault to protect the network downstream. Switches b5, b6, and b7 are circuit breakers. The function of the circuit breaker is also to protect the network by interrupting the flow of overcurrent due to overload or short-circuit. The main feeder transports the power from generation to the customer load-points (LP18…LP40) through distribution transformers (T18…T40). The load-points are connected either directly to the main transmission line or the lateral transmission lines (35…64). Figure 4.1 is a modified IEEE-RBTS Bus 6 which is considered for this study.

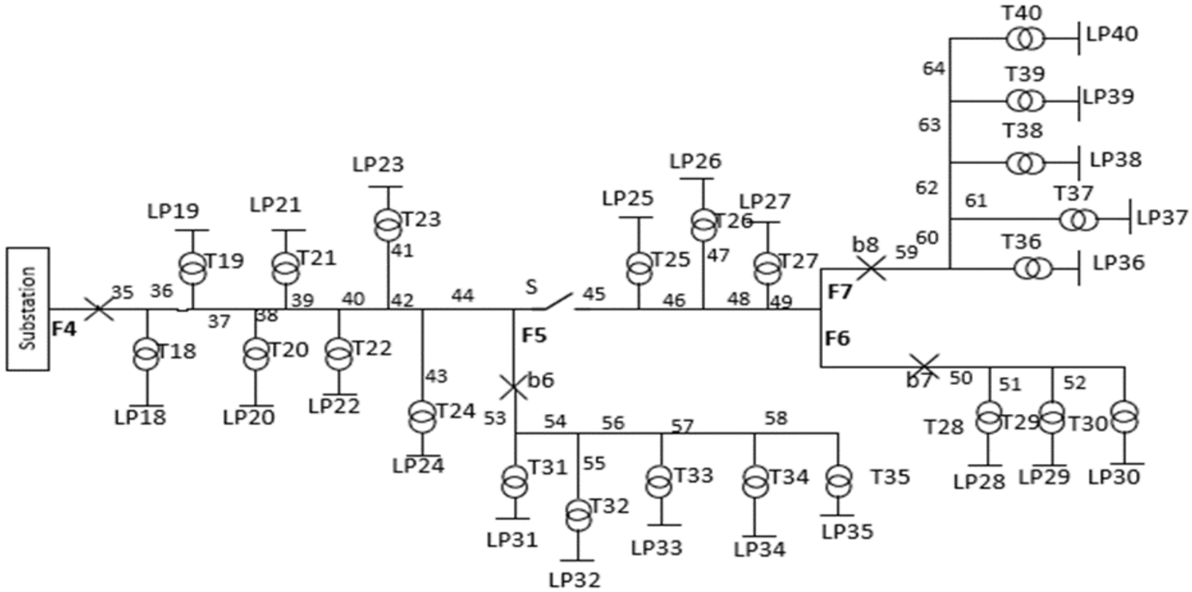

Figure 4. 1**.** Modified distribution system of RBTS-Bus 6

Data for this study was obtained from [21, 23]. Table 4.1 shows the data for feeder sections, and the corresponding sectional lengths for an 11kV feeder and its lateral distributers. The reliability data of the distribution system components and the customer data are shown in Table 4.1 and Table 4.2 respectively.

Table 4. 1. Reliability and system data [21]

Component	Failure rate (λ)	Repair time (r)
Lines (11 kV)	0.065 (failure/yr*km)	5 (hr)
Transformers (11/0.415 kV)	0.015 (failure/yr)	200 (hr)

Table 4. 2. Feeder sections and length [23]

Length (km)	Feeder section numbers
0.8	55
0.9	38 44
1.6	37 39 42 49 54 62
2.5	36 40 52 57 60
2.8	35 46 50 56 59 64
3.2	45 51 53 58 63
3.5	48

In this chapter, quantitative risk evaluation of the network was performed using the analytical technique. Risk matrix was developed to aid in categorizing the risk level, and to determine the acceptable risk level. RBD was used to estimate the RPN number and risk matrix was developed to categorize the risk.

4.2 *Analytical Evaluation of the Network without DG*

4.2.1 Evaluation of the Network without DG

The analytical technique adopted in this study is the "reliability network equivalent approach" [20, 46]. The main principle of this approach is to decompose large and complex distribution networks into a series of simple radial system by replacing portions of the network with equivalent elements. Equations (3.3) - (3.5) cannot be directly applied to calculate the basic load-point indices of the complex networks so the following procedures are used to transform the whole distribution network into a series of simple radial distribution system. The first step in this approach is to calculate the equivalent lateral sections of feeders F5, F6, and F7 using the following equations [20, 46]:

$$\lambda_{fi} = \sum_{i=1}^{m} \lambda_i \tag{4.1}$$

$$U_{fi} = \sum_{i=1}^{m} \lambda_i r_i \tag{4.2}$$

$$r_{fi} = \frac{U_{fi}}{\lambda_{fi}} \tag{4.3}$$

$$\lambda_{fj} = \sum_{i=1}^{n} \lambda_j \tag{4.4}$$

$$U_{fj} = \sum_{i=1}^{n} \lambda_j r_j \tag{4.5}$$

$$r_{fj} = \frac{U_{fj}}{\lambda_{fj}} \tag{4.6}$$

where λ_{fi} and r_{fi} are the total equivalent failure rate and the restoration time of the failed components which are not isolated by disconnects in the subfeeder and *m* is the number of such components.

The parameters λ_{fj} and r_{fj} are the total equivalent failure rate and the switching time of the failed components which can be isolated by disconnect (S) in the lateral section and *n* is the total number of such elements. Using successive network equivalents (detailed calculation is presented in Appendix B), the system of Figure 4.1 is transformed into a general distribution system as shown in Figure 4.2.

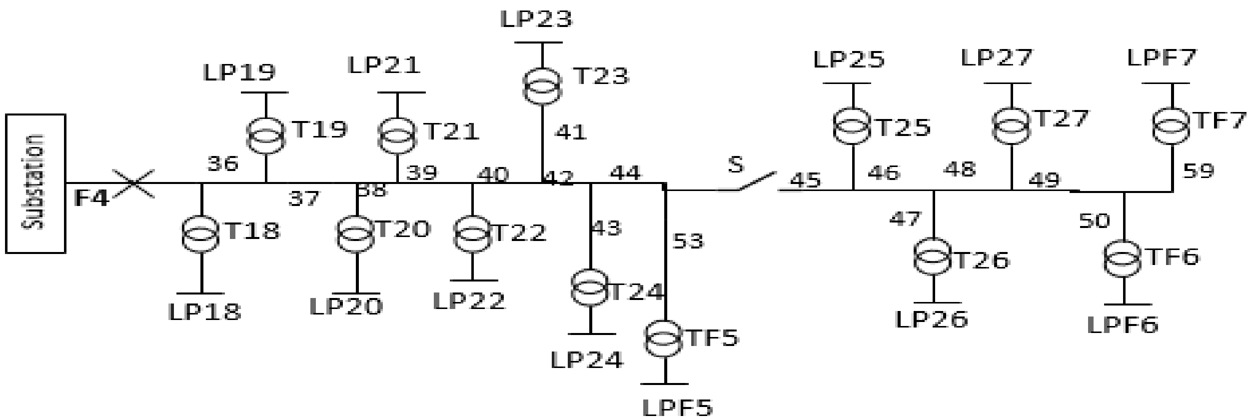

Figure 4. 2. A general distribution form of modified RBTS Bus 6 feeder

Table 4. 3. Basic total equivalent reliability indices for subfeeders

Subfeeders	Total equivalent failure rate (f/yr)	Restoration Time (hrs)	Average annual Outage Time (hrs/yr)
F5	0.865	5	4.323
F6	0.553	5	2.763
F7	0.839	5	4.193

Once the equivalent total failure rates and restoration times are calculated, and the network is reduced to a general radial distribution form, the three basic reliability indices can be calculated using equations (4.1) – (4.3).

4.2.2 Reliability Block Diagram

The system is then converted into reliability block diagram where the transformers and load-points are merged into the blocks. These blocks are joined together by the main section of the transmission lines and the lateral transmission lines. Power supply to the customer is connected at the load-points, therefore if any section of the transmission line fails, customers downstream will have no power supply. Figure 4.3 shows the reliability block diagram. The diagram is used to perform the risk assessment of the network.

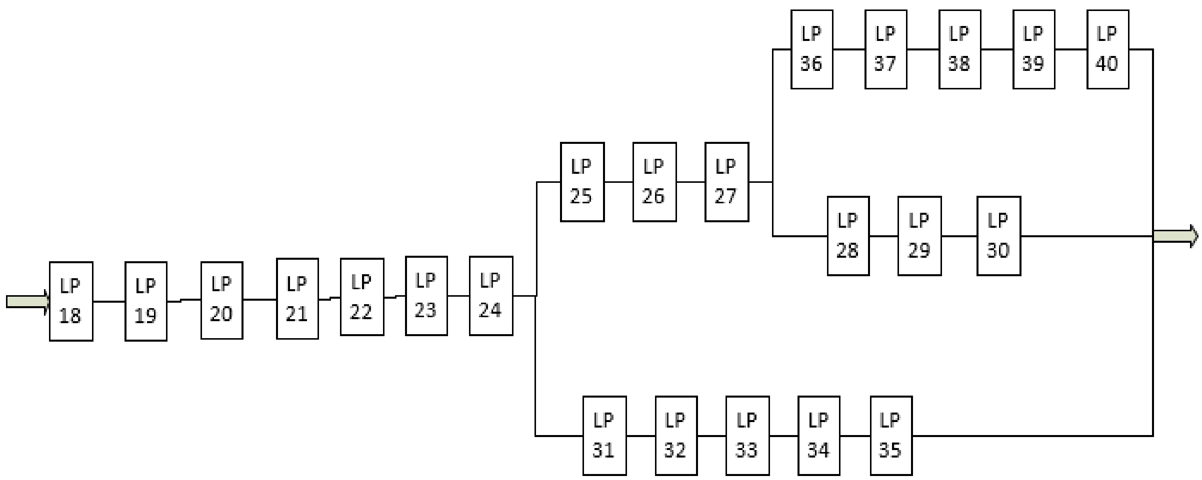

Figure 4. 3. Reliability block diagram presentation of the modified RBTS-bus 6

The risk assessment of the network shown in Figure 4.1 was done in terms of RPN calculation using the three factors of probability, severity and detectability of potential risk [57]-[59].

$$RPN = Severity\ (S)*Probability\ (P)*\ Detectability\ (D) \qquad (4.7)$$

Severity (S): The effect or the consequence (severity) of potential failure at any of the load-points will vary. This will depend on the type of load that it serves. In this study the severity or consequence (which are used interchangeably), ranges from 1 to 10. The assigned values are based on the criticality of the load served. For example, the load–point connected to a hospital is ranked highest (10) because failure of it may lead to loss of life and other problems lack of access to health services. Table 4.4 shows the load-points, load types and the severity of potential failure.

Table 4. 4. Load-points, load types and the severity of potential failure

Load-point	Consumer type	Severity
21 22 26 28 32 35 36	Residential	5
18 30	Government Buildings/ Institutions	6
23 26 39	Farms	4
34 40	Small Industries	8
33	Water Treatment Plant	9
24 29	Office Buildings	7
19 25 27	Traffic/ Street Lights	2
31 37	Hospital	10
20	Public Library	3

Probability (P): The probability of failure of the load-points are evaluated from their failure rates. Generally, the probability of failure evaluates the frequency of the potential risk associated with the failure modes in the network [40]. It shows the probability that the consequence or severity of the potential risk is because of the failure mode. Here, the probability of failure of the load-points are calculated using their failure rate. The 'reliability-network-equivalent approach proposed by R. Billinton in [20], was adopted in this study. The probability of failure for the load-points are calculated using equation (3.1). Failure rate for the gas turbine generator, wind turbine and the photovoltaic are adopted from [67], [68] and [69] respectively. Here, $F(t)$ was calculated for the time of 5 years for the purpose of this study. For the purpose of this work, the failure rate indices of the load-points are divided by 1000 before using them to determine the probability of failure for the said load-points. This was done because the failure rates being an average value are higher. Such values will always result in very high probability of failures.

Detectability (D)

The lateral section of the network, which connects the load-points to the main feeder section, has series components and as such, any component failure of the section will result in customer supply interruption. Most of the distribution networks are monitored in real time and faults can be detected through PLC monitoring or Supervisory Control and Data Acquisition (SCADA) system. For the most part, these failures are detected so the detectability is ranked on the scale of 10. The above risk factors (severity, probability and detectability) are used to calculate and rank the RPN of the block diagram as shown in Figure 4.4.

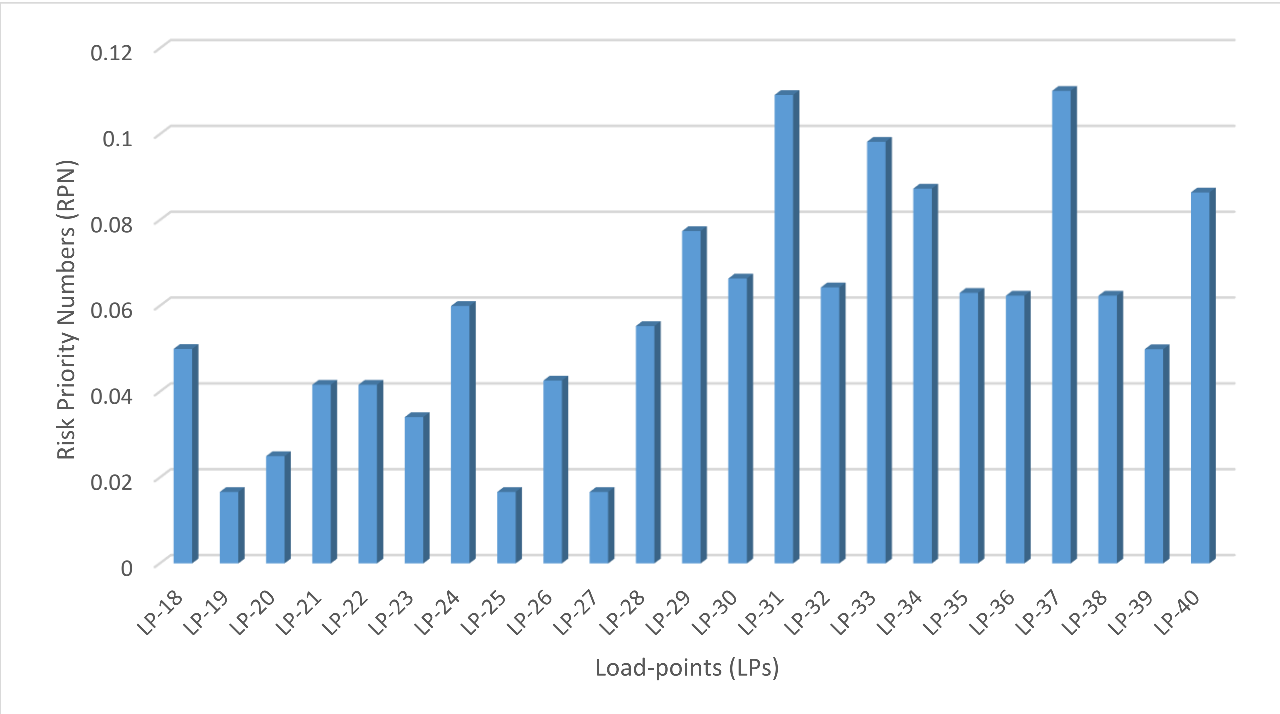

Figure 4. 4. Bar graph of RPN values of the various load-points

It can be noticed from Figure 4.4 that, the load-points LP-31 and LP-37, which serve the loads of hospitals, have the highest RPN numbers. In other words, the risk levels at these load-points are highest. The results for the failure rates, probability of failure, risk factors and the load-points rankings are presented in Table 4.5.

Table 4. 5. Load-points failure rates, failure probabilities, risk factors and risk ranking

Load-point	Failure Rate (f/yr)	Normalized Failure Rate (f/yr)	Probability of Failure	Severity	Detectability	RPN	Rank
LP-18	1.6725	0.00167	0.00833	6	1	0.0500	15
LP-19	1.6725	0.00167	0.00833	2	1	0.0167	1
LP-20	1.6725	0.00167	0.00833	3	1	0.0250	6
LP-21	1.6725	0.00167	0.00833	5	1	0.0416	11
LP-22	1.6725	0.00167	0.00833	5	1	0.0416	11
LP-23	1.7115	0.00171	0.00852	4	1	0.0341	10
LP-24	1.7213	0.00172	0.00857	7	1	0.0600	17
LP-25	1.6725	0.00167	0.00833	2	1	0.0167	1
LP-26	1.7115	0.00171	0.00852	5	1	0.0426	13
LP-27	1.6725	0.00167	0.00833	2	1	0.0167	1
LP-28	2.225	0.00223	0.0111	5	1	0.0553	16
LP-29	2.225	0.00223	0.0111	7	1	0.0774	23
LP-30	2.225	0.00223	0.0111	6	1	0.0664	22
LP-31	2.537	0.00254	0.00278	10	1	0.0279	8
LP-32	2.589	0.00259	0.0129	5	1	0.0643	21
LP-33	2.537	0.00254	0.00279	9	1	0.0251	7
LP-34	2.537	0.00254	0.00279	8	1	0.0223	5
LP-35	2.537	0.00254	0.0126	5	1	0.0630	20
LP-36	2.511	0.00251	0.0125	5	1	0.0624	18
LP-37	2.559	0.00256	0.00281	10	1	0.0281	9
LP-38	2.511	0.00251	0.0125	5	1	0.0624	18
LP-39	2.511	0.00251	0.0125	4	1	0.0499	14
LP-40	2.511	0.00251	0.00277	8	1	0.0221	4

4.2.3 Risk Matrix

To manage the risk level in the network, a risk matrix was developed, based on the RPN and its factors. Risk matrix is a matrix that is used in risk assessment to define risk level in a system using the probability of failure and the severity of the failure. In the risk matrix, the probability of failure of the load-points are divided into five categories as shown in Table 4.6.

Table 4. 6. Categories of potential failure probability ratings and meaning [57, 58]

Probability Rating	Meaning
1 – Improbable failure	Very unlikely that a failure will occur
2 – Remotely failure	Unlikely that failure will occur
3 – Occasional failure	Occasional failure occurrence
4 – Probable failure	Probable possible failure occurrence
5 – Frequent failure	Frequently possible failure occurrence

Severity of the failure is also divided into four categories (minor-1, medium-2, critical-3, and catastrophic-4). The risk matrix values are product of probability of failure and the severity. Practically, there is no zero risk level so a decision has to be made to choose a risk level that will be tolerated in any engineering system. The “Maximum Tolerable Risk” [41], for the purpose of this study it is assumed to be 0.04. Table 4.7 shows the matrix table.

Table 4. 7. Risk Matrix

Probability	**1**	**0.016**	**0.028-0.032**	**0.056-0.064**	**0.084 -0.096**	**0.112 – 0.128**	**0.140 – 0.160**
	2	**0.014**	**0.024-0.028**	**0.048-0.056**	**0.072 – 0.084**	**0.098 – 0.112**	**0.120 – 0.140**
	3	**0.012**	**0.020-0.024**	**0.040-0.048**	**0.060 - 0.072**	**0.080 – 0.096**	**0.100 – 0.120**
	4	**0.010**	**0.016-0.020**	**0.032-0.040**	**0.048 – 0.060**	**0.064 – 0.080**	**0.080 – 0.100**
	5	**0.008**	**0.008-0.016**	**0.024-0.032**	**0.040 – 0.048**	**0.056 – 0.064**	**0.072 – 0.080**
			Consequence				

From the matrix, the RPN values up to 0.04 are considered acceptable risk level. With this value, the severity of the failure will be almost negligible. The risk level in yellow or RPN numbers from 0.04 to 0.064 may be tolerated. Thus, that risk level might be attended to only if it is technically justifiable and economically viable. The RPN values above 0.064 that fall in either the orange or the red color has risk levels that are not acceptable. These risk levels need immediate remedial actions to mitigate or reduce their consequence [40, 57, 58]. Color coding of the risk levels in the risk matrix is explained in Table 4.8

Table 4. 8. Criticality of the risk level

<table>
<tr><th colspan="2">Criticality (C)</th><th rowspan="2">Risk Level</th></tr>
<tr><th>Degree of Criticality</th><th>Value Range</th></tr>
<tr><td>Minor</td><td>0.000 - 0.040</td><td>Acceptable</td></tr>
<tr><td>Medium</td><td>0.040 - 0.056</td><td rowspan="2">Tolerable</td></tr>
<tr><td>High</td><td>0.056 - 0.064</td></tr>
<tr><td>Critical</td><td>0.064 - 0.100</td><td>Unacceptable</td></tr>
<tr><td>Catastrophic</td><td>> 0.100</td><td>Unacceptable</td></tr>
</table>

4.3 Effect of DGs on the RPN at the identified load-points

It can be observed from Figure 4.4, that most of the load-points have their RPN numbers above 0.04. Considering the critical nature of some of the loads that are served by these load-points, load-points LP-31, LP-33, L-34, LP-37, and LP-40 would need some mitigation measures to bring their RPN values or the risk level into an acceptable range. To achieve this, it is proposed that distributed generators are to be integrated into the network to serve those critical load-points to operate in parallel with the main power supply. Various distributed resources are suggested to be installed at the identified load-points to determine which of the distributed generators would improve the system better. There are several distributed technologies that are being used for microgrid implementation [7, 9]. The distributed resources considered in this study are gas turbine generators, wind turbines, and photovoltaic (PV) with nominal output ratings of 1 MW. These DGs are considered because they are among the most matured DG technologies. The renewable ones have several benefits as discussed in earlier chapters. Gas turbine was considered because it can be classified as either a renewable or non-renewable depending on the source of the gas. It also produces less pollution than other fossil fuel technologies. The implementation of these DGs in the network resulted in significant reduction of the risk level of the critical load-points. The percent reduction of the RPN was estimated using the following equation:

$$RPN\ Reduction = \frac{RPN_1 - RPN_2}{RPN_2} * 100 \tag{4.10}$$

where RPN_1 is the initial RPN number prior to the DG integration and RPN_2, the post DG integration RPN.

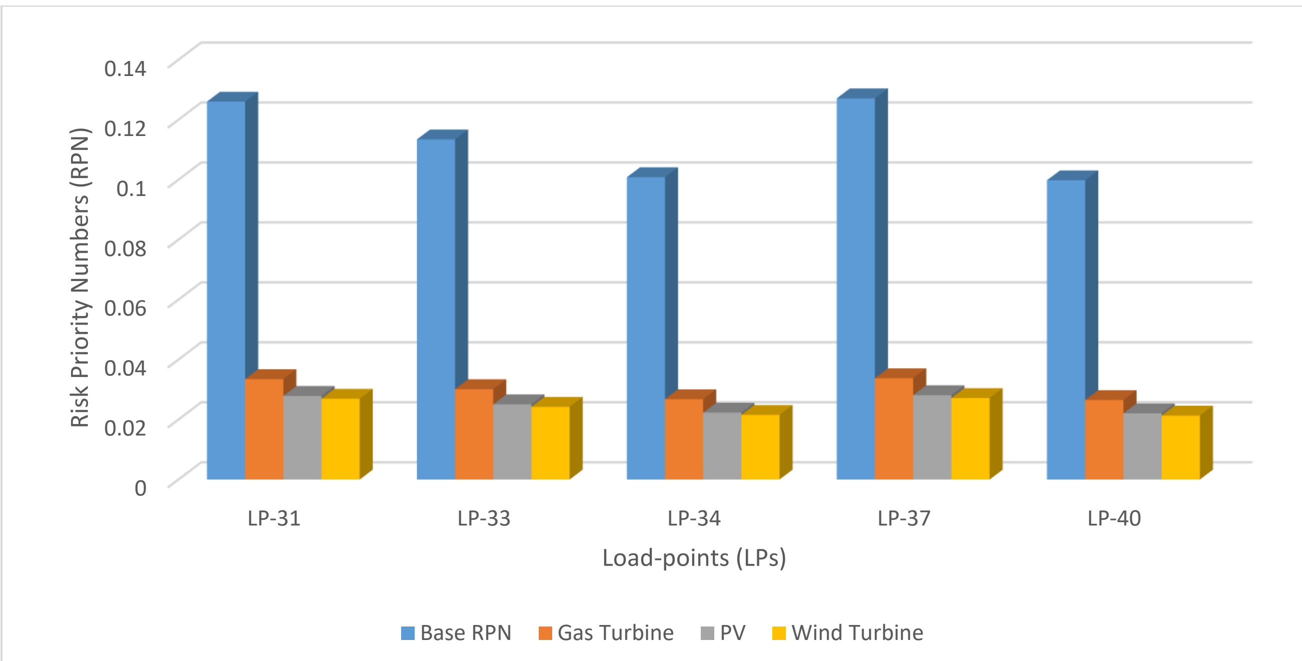

Figure 4. 5. Bar graph of risk level (RPN) reduction with DG implementation at certain LPs

Figure 4.5 shows how the DGs reduce the risk level (RPN) of the critical load-points in the network. It can be observed from Figure 4.5 that, the wind turbine reduces the risk level of the load-points better than the PV and the gas turbine in that order. The percent risk reduction level for the DGs are 2.76 %, 3.52 %, and 3.68 %, for the gas turbine generator, photovoltaic and wind turbine generator respectively

4.4 Summary

The analytical technique is used to calculate the failure rates of the modified IEEE RBTS-Bus 6 network. Failure mode effect and critical analysis (FMECA) is used to calculate the RPN and developed a risk matrix to establish a tolerable risk value in the network. A reliability block diagram is developed and used to assess the risk level in the network. The approach is then used to determine the risk level at the load-points with distributed generators installed at various critical load-points. The goal is to establish the effect of the distributed generators on the risk level at the load-points in the network. Having been able to determine how much the distributed generators can reduce the risk level, the issue that needs to be addressed is how to choose a particular distributed generator to serve a particular load? The next chapter employs a multi-criteria decision-making tool called the analytic hierarchy process to make that choice.

Chapter 5

Analytic Hierarchy Process

5.1. Introduction

The previous chapters presented measures taken to reduce the risk level at the load-points. It is practically impossible to achieve zero risk level because of the random nature of events that leads to failure in power systems [40]. Accepting a risk level or performing mitigation procedure to reduce the risk level is a decision-making process. Quantitative risk evaluation forms the basis of this process, but technical, economic, societal, and environmental assessment must also be considered in the decision-making process [38]. Among these factors, the quantitative risk evaluation (level of risk reduction by DGs), economical (cost of DG technology) and the environmental risk (environmental impact of the DGs) are considered as the criteria for the decision-making process in this study. The decision-making process in this study is to choose a particular DG that can serve the loads. A decision-making tool referred to as analytic hierarchy process (AHP) is used for this process.

5.2 Analytic hierarchy process

Analytic Hierarchy Process is a multi-criteria decision-making tool, which evaluates alternatives with respect to multiple criteria to achieve a solution to a problem [30]-[32]. The process requires inputs and subjective expert judgements to measure relative proportions between alternative quantities [30]. Saaty et al [30, 31], originally developed this tool, and it is widely used across most industry and academia. The implementation of the analytic hierarchy process involves the following steps:

1. Build a model that represents the decision. The model should have hierarchical levels with the desired goal (in this study, most suitable distributed generator) at the top, criteria at the second or the intermediate level, and alternatives at the bottom.
2. Derive priority ratios for criteria. This is done by doing pair-wise comparison of the importance of the criteria with respect to the desired goal. The numerical scale for the criteria used for the pair-wise comparison is adopted from [30].

   The level of the consistency of the judgement for the priority ratio is verified. The consistency level is measured in terms of consistency ratio (CR).
3. Derive priority ratios for the alternatives. The priority ratios for the alternatives are derived with respect to each of the criterion separately, following the same procedure as in step 3. The level of the consistency is also verified, and adjustment made accordingly.
4. Derive priority ratios for the overall system. This process is called the model synthesis.
5. Perform sensitivity analysis
6. Finally, choose the best alternative with the highest priority ranking.

Figure 5.1 below, illustrates the analytic hierarchy process.

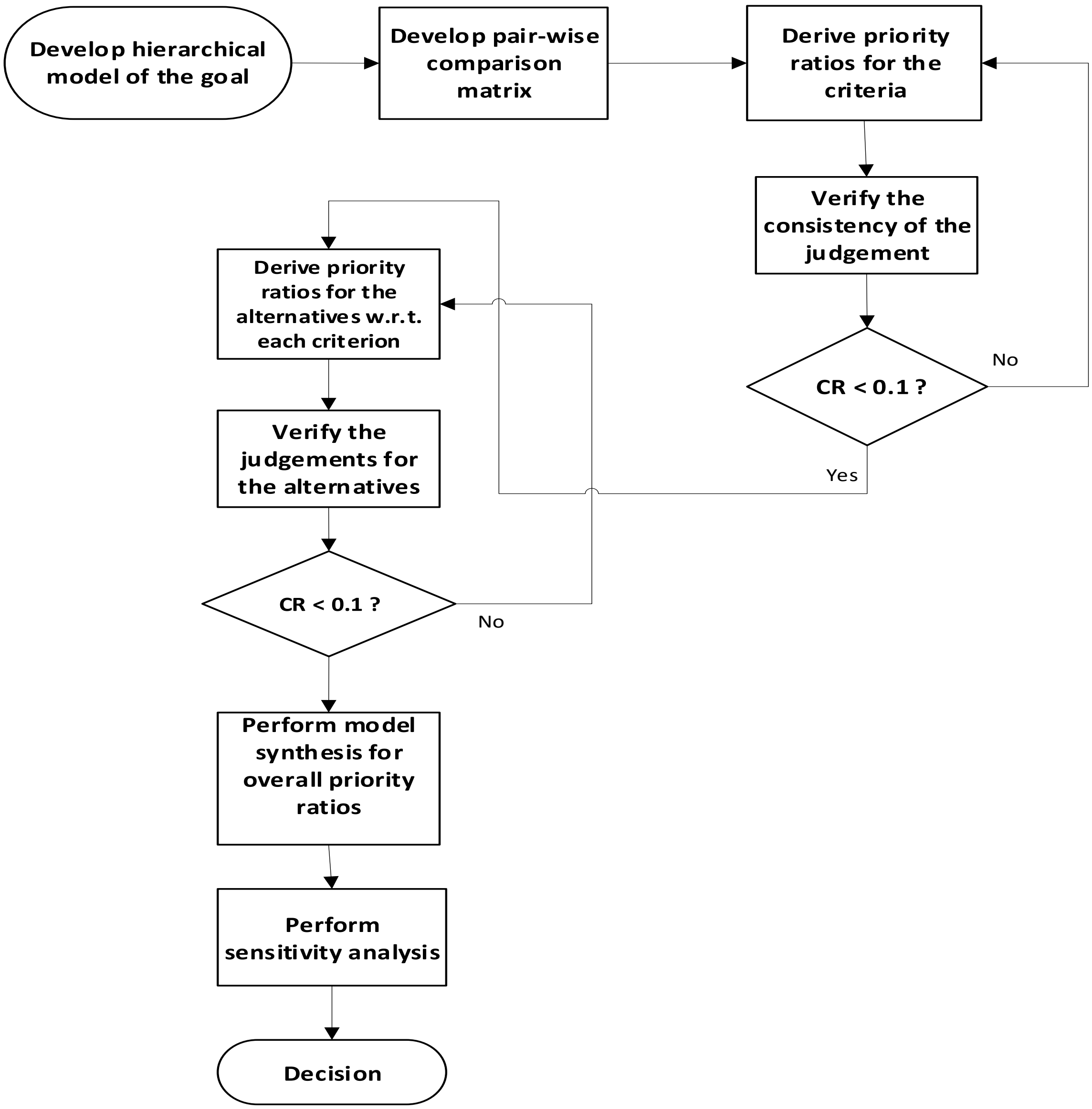

Figure 5. 1. Flowchart of the analytic hierarchy process

5.3. System description and model development

In this study, the hierarchical model for the decision is developed with the goal at the top level being the most suitable distributed generator for the microgrid power system. Level two of the model represent the criteria and is made up of cost of DG technology ($/kW), level of risk reduction (risk mitigation) by DGs at the load-points, and the environmental impact of the distributed generators. Level three is made up of the alternative DGs, namely, photovoltaic solar system (PV), wind turbine generator (WTG) and gas turbine generator (GTG). Figure 5.2 shows the hierarchical model of the system.

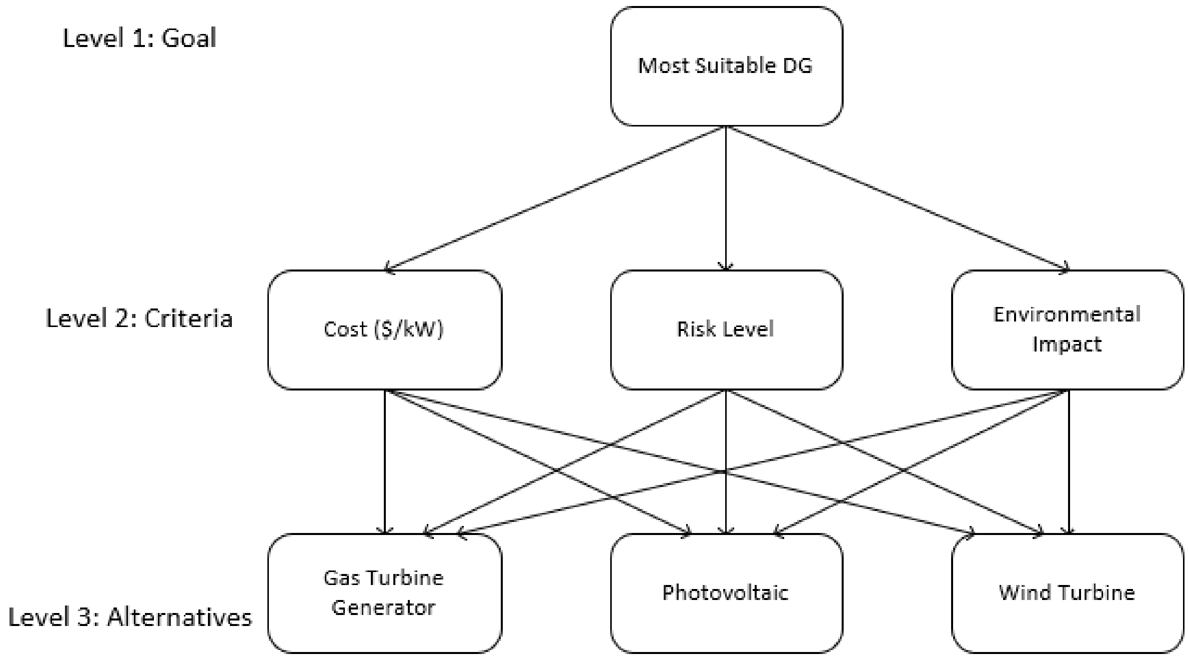

Figure 5. 2 Three level hierarchy for the DG selection

The cost of the DG technology used in this study was adopted from the 2016 report of the U.S. Energy Information Administration (EIA) [70]. From that report, the overnight cost for each type of the DG technology consist of civil ad structural cost, mechanical equipment supplies and installation, electrical and instrumentation control, project indirect cost, and owners' cost. Other aspect of the cost are the variable O&M cost and the fixed O&M cost. The total overnight cost is expressed as follows:

$$C_{Total} = ON_C\ (\$/kW) + F_{O\&M}\ (\$/kW\text{-}yr) + V_{O\&M}\ (\$/MWh) \quad (5.1)$$

where ON_C is the overnight cost, $F_{O\&M}$ is the fixed operation and maintenance cost and $V_{O\&M}$ is the variable operation and maintenance cost

The cost parameters adopted from the report are for DGs with nominal output power of 1 MW. The risk criterion is how much (percentage wise) each DG contribute to reduce the risk level at the load-points. The environmental impact is the measure of the negative effect the DGs will have on the environment when deployed. The environmental impact can be emission of green house gas (GHG), the noise level when the DGs are in operation, as well as the land area the DG technology covers when deployed. Table 5.1 shows the amount of emission that goes into the atmosphere when the selected DGs are deployed.

Table 5. 1. Amount of emission released from the DG technology into the environment [70]

Distributed generators (DGs)	**SO_2 (lb/ MMBtu)**	**NO_X (lb/MMBtu)**	**CO_2 (lb/MMBtu**
Gas turbine generator	0.001	0.03	117
Photovoltaic	0.00	0.00	0.00
Wind turbine	0.00	0.00	0.00

Table 5.2 shows the values for the criteria for the alternative DGs considered for this study. The values for the environmental impact (emissions from the DGs), and the cost for the DGs are adopted from [60], and the risk level mitigation (level of risk reduction) are the analytical risk estimation from chapter 4 using (4.10).

Table 5. 2. Cost, risk level mitigation and environmental impact of the DGs in this study [70]

Distributed generators (DGs)	**Cost ($/kW)**	**Risk level mitigation (%)**	**Environmental Impact**
Gas Turbine Generator	1,122	0.737	High
Photovoltaic	2,605.5	0.779	Very Low
Wind Turbine	1,916	0.786	Low

5.4. Deriving priority scales for the criteria

Deriving the priority scales is performed by weighing the importance of one criterion relative to the other and assigning a numerical value based on their importance. An $n \times n$ matrix (5.2), is developed for the pair-wise comparison which has the relative weighted importance of the criteria as its element [30, 31,32]. These elements a_{ij}, are the results from the pair-wise comparison (w_i/w_j) between *i* and *j* terms using Table 5.3.

$$A = \begin{bmatrix} 1 & a_{ij} & \cdots & a_{1n} \\ 1/a_{ij} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \qquad (5.2)$$

For example, in the second row, if the *i*th value is slightly important than the *j*th value, the assigned value will be 3.

Table 5. 3. Saaty's pair-wise comparison scale [24, 25, 26]

Definition of elements	Assigned value
If the *ith* value is equally important to the *j*th value	1
If the *i*th value is slightly important than the *j*th value	3
If the ith value is more important than the jth value	5
If the *ith* value is strongly more important than the *j*th value	7
If the *ith* value is extremely more important than the *j*th value	9
Intermediate values	2, 4, 6, 8
If the *i*th value of the pair-wise comparison is equal to one of the values above, the *j*th value then becomes its reciprocal.	Reciprocals

Having developed the pair-wise comparison matrix, the consistency of the judgement is verified to ensure that there is a reasonable level of proportionality and transitivity [22].

The level of consistency is measured in terms of consistency ratio (CR), expressed as:

$$CR = CI/RI \tag{5.3}$$

$$CI = (\lambda_{max} - n)/(n - 1) \tag{5.4}$$

where CI is the consistency index, and RI, the random consistency index. The random consistency index is an estimated average from large random matrix where n is the number of criteria as in Table 5.4 [24, 25, 26].

Table 5. 4. Average random consistency Index [24]

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

For a system where n is equal to 5, RI is 1.11. For every pair-wise comparison matrix, the consistency ratio, CR should be less than or equal to 0.1, otherwise the judgement of the decision maker must be reviewed [24, 26, 61].

In developing the pair-wise comparison matrix for this study, Cost ($/kW) criterion was considered to be from *equally important to moderately important* than the Risk criterion, then the cell between these criteria will have the ratio of Cost ($/kW)/Risk. Numerically, the ratio of importance between Cost ($/kW) and Risk is 2. The reciprocal of this comparison, which is the relative importance of Risk/ Cost ($/kW) is 1/2. Similarly, the Cost ($/kW) criterion is considered *very strongly to extremely important* than Environmental Impact criterion. The numerical value for this relative comparison, Cost ($/kW)/Environmental Impact, from Table 5.3, will be 8 and the reciprocal will also be 1/8. Again, the risk criterion was considered to be *strongly more important* than Environmental impact and as such the ratio for that relative comparison (Risk/Environmental Impact) is 5. The reciprocal of this relative comparison is 1/5. When the importance of a criterion is compared to itself, for example Risk/Risk; Cost ($/kW)/ Cost ($/kW); and Environmental Impact/ Environmental Impact; the ratio of such comparison is 1. The relative comparison matrix of the criteria is equivalent to matrix A, in equation (5.2), and is presented in Table 5.5 and Table 5.6.

Table 5. 5. Pair-wise comparison of criteria

Most Suitable DG	Cost ($/kW)	Risk Mitigation	Environmental Impact
Cost ($/kW)	1	2	8
Risk Mitigation	1/2	1	5
Environmental Impact	1/8	1/5	1

Table 5. 6. Pair-wise comparison of criteria showing decimal figure

Most Suitable DG	Cost ($/kW)	Risk Mitigation	Environmental Impact
Cost ($/kW)	1	2	8
Risk Mitigation	0.5	1	5
Environmental Impact	0.125	0.2	1
Sum	1.625	3.2	14

Having developed the pair-wise comparison table for the criteria, we proceed to sum each column of the matrix and divide the cells by the columns' total to normalise the matrix. From the rows in the normalised matrix, the final priority numbers for the criteria are obtained by taking the average of each row as shown in Table 5.7. For example, with Cost criterion row,

$$\frac{0.615+0.571+0.625}{3} = 0.604$$

Similarly, the priorities for Risk Mitigation and Environmental Impact are estimated and presented in Table 5.7. From Table 5.7, it could be deduced that the highest priority among the criteria is Cost ($/kW), followed by Risk Mitigation, and Environmental Impact respectively.

Table 5. 7. Normalized criteria pair-wise comparison and priorities

Normalized criteria pairwise comparison & priorities				
Most Suitable DG	Cost ($/kW)	Risk Mitigation	Environmental Impact	Weighted Priorities
Cost ($/kW)	0.615	0.571	0.625	0.604
Risk Mitigation	0.308	0.357	0.312	0.326
Environmental Impact	0.0769	0.0714	0.0625	0.0703
Sum	1	1	1	

5.4.1. Consistency of the Judgement

In checking the consistency of the judgement, the *CI* is calculated. This was done by first, multiplying each of the columns of the pair-wise comparison matrix by the corresponding priority matrix of the criteria. For example, Cost column will be $0.6040x0.1$= 0.0604; $0.6040\ x0.5 = 0.3020$; $0.6040x0.125 = 0.0755$. This was repeated for the columns of Risk and Environmental Impact. Secondly, the rows of the new matrix are summed up, and each of the summed-up value is divided by the corresponding priority number. The average of the last column becomes the eigenvector, $\lambda_{\max}\ = 3.006$.

From (5.4), $CI = \frac{(3.006-3)}{3-1}$ = 0.00277

From (5.3) and RI from Table 5.4; $CR\ =\ CI/RI$ = $\frac{0.00277}{0.58} = 0.00478$.

Since the consistency ratio (0.00478) is less than 0.1, it can be concluded that the judgement for the comparison matrix is reasonably consistent.

5.5 Deriving priority scales for the alternatives

The third step in the analytic hierarchy process is to derive priority ratios for the alternative DGs with respect to each of the criterion. A pair-wise comparison matrix was first developed for the alternative DGs with respect to Cost criterion, following the same procedure described earlier. Similarly, comparison matrices are developed for the alternative DGs with respect to Risk Mitigation and Environmental Impact. The respective comparative matrices for the alternatives are developed using the numerical scale of Table 5.3 and Table 5.4. The rest of the process follows the same procedure as the derivation of the priority ratios for the criteria.

5.5.1 Comparison matrix for the alternatives with respect to Cost ($/kW)

The least expensive DG is considered more important than the expensive ones.

From Table 5.2., the least expensive of the alternative is the gas turbine generator and as such, it is rated relatively more important, followed by the wind turbine and the photovoltaic respectively. The gas turbine is rated relatively *strongly more important* when compared with the photovoltaic; gas turbine is relatively rated *moderately more important* when compared to the wind turbine; and the wind turbine is also rated *moderately more important* when compared with the photovoltaic. The pair-wise comparison of the alternatives with respect to the cost of the technology is presented in Table 5.8, and Table 5.9. with the priority ratios.

Table 5. 8. Pair-wise comparison for alternatives with respect to Cost ($/kW)

Cost ($/kW)	Gas Turbine	Photovoltaic	Wind Turbine
Gas Turbine	1	5	3
Photovoltaic	1/5	1	1/3
Wind Turbine	1/3	3	1
Sum	1.533	9	4.333

Table 5. 9. Normalised pair-wise comparison for alternatives with respect to Cost and their priority ratios

Cost ($/kW)	Gas Turbine	Photovoltaic	Wind Turbine	Weighted Priority
Gas Turbine	0.652	0.556	0.692	0.633
Photovoltaic	0.131	0.111	0.0769	0.106
Wind Turbine	0.217	0.333	0.231	0.260
Sum	1	1	1	

$$\boldsymbol{\lambda_{max} = 3.038; \quad CR = 0.0329}$$

5.5.2 Comparison matrix for the alternatives with respect to Risk Mitigation

With level risk mitigation, the relative weighted importance of the alternative DG is directly proportional to how much each DG reduces the risk level at the load-point. Thus, the alternative DG with the highest percentage risk level reduction at the load-point is rated more important. In this study, wind turbine is rated more important, followed by PV and gas turbine generator respectively. Gas turbine was rated from *moderately to strongly more important* than the photovoltaic; gas turbine was rated *strongly more important* than the wind turbine; and the photovoltaic was rated *from equally important to moderately more important* when compared to the wind turbine. The pair-wise comparison for the alternative DGs with respect to risk level mitigation are presented in Table 5.10 and Table 5.11.

Table 5. 10. Pair-wise comparison for alternatives with respect to Risk Level Mitigation

Risk Level Mitigation	Gas Turbine	Photovoltaic	Wind Turbine
Gas Turbine	1	1/4	1/5
Photovoltaic	4	1	1/2
Wind Turbine	5	2	1

Table 5. 11. Normalised pair-wise comparison for alternatives with respect to Risk Level Mitigation and their priorities ratios

Risk Level Mitigation	Gas Turbine	Photovoltaic	Wind Turbine	Weighted Priority
Gas Turbine	0.100	0.0769	0.118	0.0980
Photovoltaic	0.400	0.308	0.294	0.334
Wind Turbine	0.500	0.615	0.588	0.567
Sum	1	1	1	

$$\boldsymbol{\lambda_{max} = 3.0247; CR = 0.0213}$$

It can be deduced from Table 5.11 that, the alternative DG with the highest priority ratio is the wind turbine followed by the photovoltaic and the gas turbine respectively.

5.5.3 Comparison Matrix for the Alternatives with respect to Environmental Impact

To develop the pair-wise comparison matrix for the alternative DG with respect to the environmental impact, green house gas emission and the noise level from each alternative DG when deployed is considered. The alternative with the least GHG emission and noise level is rated relatively more important when compared with the other alternatives. Photovoltaic is considered *extremely important* relative to the gas turbine; wind turbine is also considered *strongly more important* when relative to the gas turbine; and the photovoltaic is considered *from* *equally important to moderately more importan*t when compared to the wind turbine. The pair-wise comparison for this process are presented as in Table 5.12, and Table 5.13 with the priority ratios.

Table 5. 12. Pair-wise comparison for alternatives with respect to Environmental Impact

Environmental Impact	Gas Turbine	Photovoltaic	Wind Turbine
Gas Turbine	1	1/9	1/5
Photovoltaic	9	1	2
Wind Turbine	5	1/2	1

Table 5. 13. Normalised pair-wise comparison for alternatives with respect to Environmental Impact and their Priority

Environmental Impact	Gas Turbine	Photovoltaic	Wind Turbine	Weighted Priority
Gas Turbine	0.0667	0.069	0.0625	0.066
Photovoltaic	0.600	0.621	0.625	0.615
Wind Turbine	0.333	0.310	0.313	0.319
Sum	1	1	1	

$$\boldsymbol{\lambda_{max} = 3.0025; CR = 0.0019}$$

It can be deduced from Table 5.13 that the photovoltaic has the highest priority ratio when the alternative DGs are compared with respect to the environmental impact.

5.5.4 Deriving the overall priority of the network (Model Synthesis)

After deriving the priority ratios for the criteria and the alternatives, the next step is to derive the overall priority ratios for the model. This process is called the model synthesis. For example, the cost criterion has a priority ratio of 0.604, and that of the gas turbine with respect to cost is 0.633. Therefore, the weighted priority of gas turbine relative to cost is $0.604\ x\ 0.633 = 0.383$. Similarly, the weighted priority ratio of PV with respect to cost is $0.604\ x\ 0.106 = 0.0641$. The same procedure is followed to obtain the weighted priority for each alternative relative to each criterion.

The final priority ratio for gas turbine (FP_{GT}) is obtained as follows:

$FP_{GT} = 0.604\ x\ 0.633 + 0.326x0.0982 + 0.0703x0.066 = 0.419$.

The final priority ratio for the photovoltaic (FP_{PV}) is obtained as follows:

$$FP_{PV} = 0.604x0.106 + 0.326x0.334 + 0.0703x0.615 = 0.216$$

The final priority ratio for the wind turbine (FP_{WT}) is obtained as follows:

$FP_{WT} = 0.604x0.260 + 0.326x0.568 + 0.0703x0.319 = 0.364$

The resultant matrix for the overall priority for the preferred alternative DG is presented in Table 5.14.

Table 5. 14. Overall weighted priorities

	Cost($/kW)	**Risk Mitigation**	**Environmental Impact**	**Overall Priority**
Criteria	0.604	0.326	0.0703	
Gas Turbine	0.383	0.031	0.0046	0.419
Photovoltaic	0.064	0.109	0.0432	0.216
Wind Turbine	0.157	0.185	0.0224	0.364

It can be noted from Table 5.14 that, the preferred or the most suitable DG is the Gas Turbine with priority ratio of 0.419 followed by the Wind Turbine and the Photovoltaic with priority ratios of 0.364 and 0.216 respectively.

5.6 Sensitivity analysis of the model

In performing the sensitivity analysis, the following three scenarios were considered;

Scenario 1: Equal weight of importance for all criteria.

All the criteria are equally weighted at 0.333. In this scenario, the overall priority for the gas turbine, photovoltaic, and the wind turbine is 0.267, 0.351, and 0.382 respectively as shown in Table 5.16. This means that, the choice of DG for when all criteria are equally important would be the wind turbine.

Scenario 2: Environmental impact weighted 0.50, risk mitigation importance weighted 0.25, and cost of the DG also weighted 0.25. In this scenario, the overall priority ratio for the gas turbine is 0.216, photovoltaic and wind turbine are 0.418 and 0.366 respectively, as shown in Table 5.17. In order words, the wind turbine would be chosen if reducing emission is considered the most important criteria.

Scenario 3: Risk mitigation importance is weighted 0.50, environmental impact weighted at 0.25, and the cost of the DG technology is also weighted at 0.25.

In this scenario, the overall priority ratio for the gas turbine is, photovoltaic and wind turbine is 0.244, 0.347, and 0.429 respectively, as shown in Table 5.18. In order words, the choice of DG for risk mitigation would be wind turbine.

Table 5. 15. Scenario 1

	Cost($/kW)	Risk Mitigation	Environmental Impact	Overall Priority
Criteria	0.333	0.333	0.333	
Gas Turbine	0.633	0.098	0.066	0.267
Photovoltaic	0.106	0.334	0.615	0.351
Wind Turbine	0.260	0.568	0.319	0.382

Table 5. 16. Scenario 2

	Cost($/kW)	Risk Mitigation	Environmental Impact	Overall Priority
Criteria	0.25	0.25	0.5	
Gas Turbine	0.633	0.098	0.066	0.216
Photovoltaic	0.106	0.334	0.615	0.418
Wind Turbine	0.260	0.568	0.319	0.366

Table 5. 17. Scenario 3

	Cost($/kW)	Risk Mitigation	Environmental Impact	Overall Priority
Criteria	0.25	0.5	0.25	
Gas Turbine	0.633	0.098	0.066	0.224
Photovoltaic	0.106	0.334	0.615	0.347
Wind Turbine	0.260	0.568	0.319	0.429

5.7 Analysis of Results

In this work, three reliability techniques and one multi-criteria decision tool are implemented. Analytical technique is first used to estimate the failure rate of load-points in feeder 4 of the IEEE RBTS-Bus 6. Failure mode and effect analysis is used to determine risk priority numbers (RPN) for the load-points assuming 0.04 to be the "Maximum Tolerable Risk" value. Having established the critical load-points of the network based on the load they serve, three DGs namely; gas turbine generator, photovoltaic solar system, and wind turbine are integrated into the network using the reliability block diagram technique. The integration of the DGs shows reduced risk level at the load-point by 2.76%, 3.5%2 and 3.68 for gas turbine generator, PV and WTG respectively from Table 5.2. Based on the risk mitigation level by the DGs, WTG may be selected to be the most suitable DG. However, DG selection in this study is not only about reliability or about risk mitigation so other criteria such as cost of the DG technology and their impact on the environment are also considered.

Analytic hierarch process is used to determine the most suitable DG among the three alternatives. Risk mitigation level, the cost of the DGs, and their effect on the environment are the main criteria used in this process. The results from the model synthesis show that, the gas turbine has the overall weighted priority of 0.419 followed by wind turbine and photovoltaic with priority ratios of 0.364 and 0.216 respectively. This means that, gas turbine generator is the preferred or most suitable distributed generator. Again, it can be deduced from Table 5.2 that the gas turbine is the least expensive DG but it also has the highest risk priority number, and this might contribute to it being the most suitable DG after the AHP implementation.

In order to determine which of the DGs may be the most suitable if other criteria are rated higher than the cost of the system, sensitivity analysis is performed. When all the criteria are equally weighted, wind turbine generator had the highest rated priority ratio of 0.382 followed by photovoltaic and gas turbine with priority ratios of 0.351 and 0.265 respectively. Again, when the risk mitigation criterion is rated at 50% and the other two criteria are 25%, wind turbine had a final priority of 0.429 followed by photovoltaic and the gas turbine with priority ratios of 0.347 and 0.224 respectively. Similarly, when the environmental impact of the DG implementation is rated 50% while keeping the cost and risk mitigation at 25%, the priority ratio of the photovoltaic, wind turbine and gas turbine are obtained as 0418, 0.366 and 0.216 respectively. Figure 5.2 shows how the various priority ratios of the DGs are related given the various weighted importance of the criteria for the sensitivity analysis.

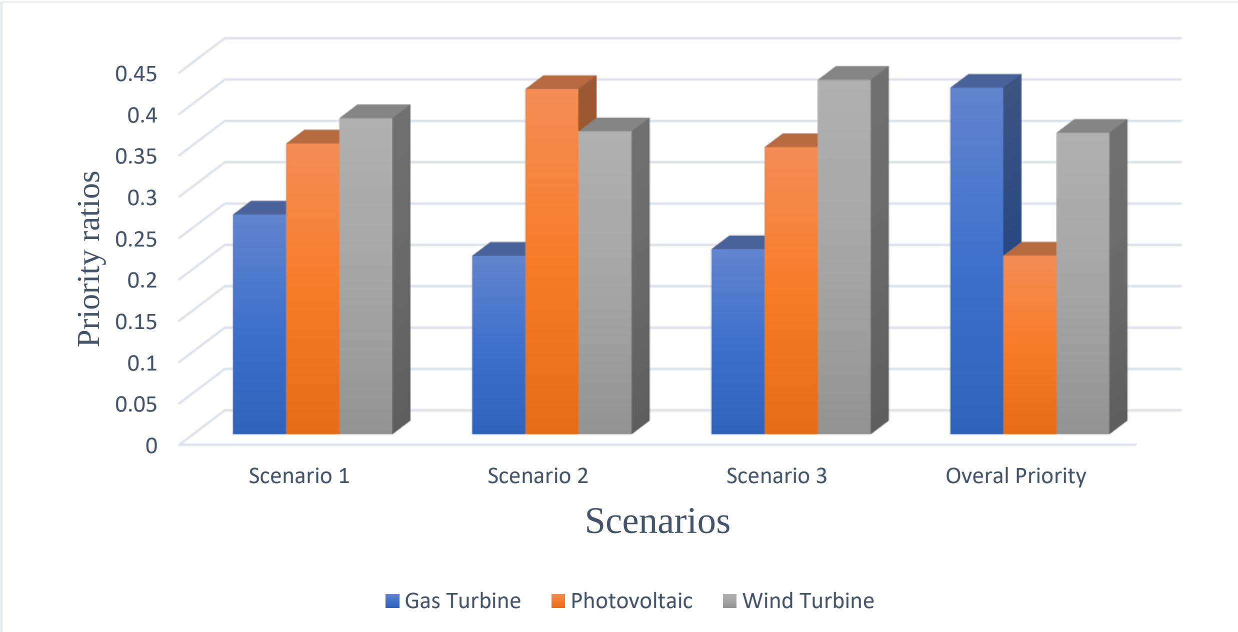

Figure 5. 3. Sensitivity analysis graph of the priority ratios for DGs

Based on the overall model synthesis and the sensitivity analysis, average final priority ratios are estimated for the alternative DGs as follows; 0.281 for gas turbine generator, 0.333 for the photovoltaic, and 0.385 for the wind turbine. With the overall average final priority ratio, it can be concluded that the wind turbine is the most suitable distributed generator for the study.

5.6 Summary

Analytic hierarchy process is used as the process to select the most suitable DG for the microgrid power system. The cost of the DG system, risk mitigation level, and the environmental impact of the DGs are used as the main criteria for the selection process. The process involved the use of pair-wise comparison of the criteria and the alternative DGs. The relative importance of the criteria is weighted and the pair-wise comparison matrix is developed. The matrix was used to estimate the final priority ratios of the criteria. Similarly, pair-wise comparison matrix was developed for the alternative DGs with respect to each of the criteria. From the priority ratio of both the criteria and the alternative DGs, the final priority ratio for the entire network is determined. The results show that, the overall priority ratio for the gas turbine generator is the highest, followed by the wind turbine and the photovoltaic. Which means that the gas turbine is the most suitable DG for the microgrid implementation. Sensitivity analysis is performed by varying the weighted importance of the criteria in three scenarios and average final priority ratios are estimated. With the overall average final priority ratio, wind turbine is considered the most suitable distributed generator.

Chapter 6

Conclusion and Future work

Several research work in risk analysis and reliability assessment in power systems are performed to identify the critical component of the network, quantify the average interruption of power supply to the consumer, and the cost of the interruption to both consumer and the utility provider. These are done to aid in maintenance and planning of future investment in the network. Other research works also focus on how the integration of distributed generators will reduce either risk level in the network or improve its reliability by forming microgrids

6.1. Conclusion

This work presented the application of reliability techniques such as analytic, FMEA/FMECA, and RBD together with AHP to evaluate the reliability of microgrid power systems with integration of DGs. This was implemented using the feeder 4, RBTS-Bus 6. The risk level was estimated in the form of failure probability using the failure rate of the load-points. The reliability technique used for this process was the analytical technique. The risk priority numbers were also estimated using FMEA by developing a risk matrix assuming ALARP to be 0.04. Reliability block diagram was also used to determine how much each DG reduces the risk level at the critical load-points LP-31, LP-33, LP-34, LP-37, and LP-40 in the network. The integration of the DGs shows that the gas turbine produced the most reduction of the risk level, followed by the photovoltaic and the wind turbine. Having established the percent reduction of the risk level by the integration of the DGs, analytic hierarchy process was used to select the most suitable DG among the alternatives.

With AHP application, the cost of the DG system, percent risk mitigation by the DGs, and the effect of DG implementation on the environment, are used as the criteria for selecting the most suitable DG. The results showed that gas turbine was the most suitable DG based on the weighted importance of the criteria. This is because the importance of the gas turbine was rated higher with respect to cost and risk mitigation criteria. Sensitivity analysis was performed to verify what the alternative DG could be, if the weighted importance of the criteria is varied. Three scenarios were considered for the sensitivity analysis: Scenario 1- all criteria were equally weighted; Scenario 2- Environmental impact weighted 0.50, the importance of both risk mitigation and cost of the DG weighted 0.25; Scenario 3- Risk mitigation importance is weighted 0.50, environmental impact weighted and the cost of the DG technology were both weighted at 0.25. Having performed the sensitivity analysis, a final average priority ratio was estimated. From these results, it was determined that the wind turbine generator would be the most suitable DG for the microgrid implementation based on the final average priority ratio after the sensitivity analysis.

6.2 Main Thesis Contribution

Combined application of reliability techniques and AHP for the reliability assessment of distribution power system containing a microgrid was implemented in this study. Conventional reliability assessment of microgrid power system estimate and express the reliability in terms of average reliability indices. This study presents another method of reliability evaluation using mostly risk assessment tools. The combination of the risk tools and the AHP also seeks to minimize the subjectivity of expert judgement in the AHP selection process. This is because this work used quantitative parameters in the AHP process instead of converting qualitative quantities into quantitative ones.

The main contributions of this thesis are the following;

1. Failure probability estimation of the load-points in the network using the annual average failure rate.
2. Building of risk matrix that was used to set the “Maximum Tolerable Risk” level.
3. The use of reliability block diagram to mitigate the risk level of the critical load-points. This was done with respect to the risk priority numbers (RPN) of the load-points
4. A step-by-step approach to the selection of the most suitable DG for a microgrid distribution system.

6.3 Future Work

The use of analytical technique of reliability in implementing this work makes it a bit straight forward and simple. Applying this to a bigger and complex network would be time consuming because it will involve lengthy calculation. Future work on this will be to develop MATLAB codes to estimate the failure probabilities and the risk mitigation level of the load-points. This will enable Monte Carlo Simulation implementation on MATLAB platform. With this, Monte Carlo Simulation procedure can be performed and be applied to complex and large network.

References

[1] G. Gharehpetian and S. Agah, Distribution Generation Systems: Design, operation and Grid Integration, Cambridge: Elservier Academic Press, 2017.

[2] W. H. Publication, "Economic Benefits of Increasing Electric Grid Reasilience to Weather Outages," President's Council of Economic Advisers and U.S Department of Energy, 2013.

[3] R. Billinton and L. Wenyuan, Reliability Assessment of Electric Power System Using Monte Carlo Methods, New York: Plenum Press, 1994.

[4] R. Billinton and R. N. Allen, Reliability Evaluation of Power Systems, Second ed, New York: Plenum Press, 1995.

[5] R. Billinton and R. N. Allen, Reliability Evaluation of Engineering Systems: Concept and Techniques, Second ed., New York: Plenum Press, 1992.

[6] R. Brown, Electric Power Distribution Reliability, Marcel Dekker, 2002.

[7] S. Chowdhury, S. Chowdhury and P. Crossley, Microgrids and Active Distribution Networks, Gateshead: Athenaeum Press Ltd, 2009.

[8] J. F. Manwell, J. G. MacGowan and J. L. Rogers, Wind Energy Explained: Theory, Design and Application, John Wiley & Sons Ltd, 2011.

[9] M. R. Patel, Wind and Solar Power Systems: design and operation, New York: CRC Press, 2006.

[10] W. Tong, Wind Power Generation and Wind Turbine Design, Southampton: WIT Press, 2010.

[11] H. L. Willis, Power Distribution Planning Reference Book, Second ed., New York: Marcel Decker, 2004.

[12] T. Funabashi, Integration of Distributed Energy Resources in Power Systems; implementation, Operation and Control, First ed., Elsevier Academic Press, 2016.

[13] Z. Bie, P. Zhang, G. Li, M. B. Hua and X. Wang, "Reliability Evaluation of Active Distribution System Including Microgrids," *IEEE Transaction of Power Systems*, vol. 27, no. 4, pp. 2342-2350, 2012.

[14] R. Billinton and R. Allen, Assessment of large Electric Power Systems, Kluwer Academic Publishers, 1988.

[15] I.E.A, "Key World Energy Statistics,," 2015.

[16] P. Wang and R. Billinton, "Reliability benefit analysis of adding WTG to a distribution system," *IEEE Transactions on Energy Conversion,* vol. 16, no. 2, pp. 134-139, 2001.

[17] A. P. Sanghvi, "Measurement and application of customer interruption costs/value of service for cost-benefit reliability evaluation: some commonly raised issues," *IEEE Transactions on Power Systems,* vol. 5, no. 4, pp. 1333-1344, November 1990.

[18] R. Karki, P. Hu and R. Billinton, "A Simplified Wind Power Generation Model for Reliability Evaluation," *IEEE Transaction on Energy Conversion,* vol. 21, no. 2, 2006.

[19] T. Adefarati and R. C. Bansal, "Reliability and economic assessment of a microgrid power system with the integration of renewable energy resources," *Applied Energy,* vol. 206, pp. 911-933, 2017.

[20] R. Billinton and P. Wang, "Reliability -network-equivalent approach to distribution-system-reliability evaluation," in *IEEE Proceedings: Generation, Transmission and Distribution,* 1998.

[21] R. N. Allen, R. Billinton, I. Sjamef, L. Geol and K. S. So, "Reliability Test System for Education Purpose-Basic Distribution System Data and Results," *IEEE Transaction on Power System,* vol. 6, no. 2, 1991.

[22] R. Billinton, S.Kumar, N. Chowdhury, K. Chu, K. Debnath, L. Goel, E. Khan, P. Kos, G. Nourbakhsh and J. Oteng-Adjei, "A Reliability Test System for Educational Purposes - Basic Data," *IEEE Trans on Power Systems,* Vols. PWRS-4, pp. 1238-1244, 1989.

[23] R. Billinton and S. Jonnavithula, "A Test for Teaching Overall Power System Reliability Assessment," *EEE Transaction on Power Systems,* vol. 14, no. 4, November 1996.

[24] R. Billinton and P. Wang, "Teaching distribution system reliability evaluation using Monte Carlo simulation," , vol. 14, no. 2, pp. , .," *IEEE Transactions on Power Systems,* vol. 14, no. 2, pp. 397- 403, May 1999.

[25] Y. M. Atwa, E. F. El-Saadany, M. M. A. Salama and R. Seethapathy, "Optimal Renewable Resources Mix for Distribution Systems Energy Loss Monimization," *IEEE Transaction on Power Systems,* vol. 25, no. 1, pp. 360-370, February 2010.

[26] S. Conti, R. Nicolosi and S. A. Rizzo, "Generalized Systematic Approach to Assess Distribution System Reliability with Renewable Distributed Generators and Microgrids," *IEEE Transactions on Power Delivery,* vol. 27, pp. 261-270, January 2012.

[27] S. Wang, Z. Li, L. Wu, M. Shahidehpour and Z. Li, "New Metrics for Assessing the Reliability and Economics of Microgrids in Distribution System," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2852-2861, 2013.

[28] H. Falaghi and M. Haghifam, "Distributed Generation Impacts on Electric Distribution Systems Reliability: Sensitivity Analysis," in *EUROCON 2005 - The International Conference on "Computer as a Tool*, Belgrade, 2005.

[29] Z. Li, Y. Yuan and F. Li, "Evaluating the reliability of island microgrid in an emergency mode," in *Proc. UPEC*, 2010.

[30] T. L. Saaty and L. G. Vargas, Models, Methods, Concepts & Applications of the Analytic Hierarchy Process, 2012.

[31] M. Brunnelli, Introduction to the analytic hierarchy process, Cham: Springer, 2015.

[32] M. Enrique and P. Milagros, Practical Decision Making using Super Decision v3: An Introduction to The Analytic Hierarchy Process, Springer Briefs in Operational Research, 2018.

[33] C. R. Algarin, A. P. Llannos and A. O. Castro, "An Analytical Hierarch Process Based Approach for Evaluating Renwable Energy Sources," *Internatiuonal Journal of Energy Economics and Policy*, vol. 7, no. 4, pp. 38 - 47, January 2017.

[34] J. C. Rojas-Zerpa and J. M. Yusta, "Application of multicriteria decision methods for electric supply planning in rural and remote areas," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 557-571, 2015.

[35] THE ANALYTIC HIERARCHY PROCESS-WHAT IT IS AND HOW IT IS USED, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0270025587904738. [Accessed 6 1 2019].

[36] "The Analytic Hierarchy Process," [Online]. Available: http://www.dii.unisi.it/~mocenni/Note_AHP.pdf.

[37] M. Bevilacqua and M. Braglia, "The analytic hierarchy process applied to maintenance strategy selection," *Reliability Engineering and System Safety*, vol. 70, pp. 71-83, 2000.

[38] R. K. Rietz and S. Suryanarayanan, "A Review of the application of analytic hierarchy process to the planning and operation of electric power microgrids," in *40th North American Power Symposium*, Calgary, 2008.

[39] M. Moderres, M. Kaminskiy and V. Kristov, Reliability Engineering and Risk Assessment, New York: Marcel Dekker, 1999.

[40] L. Wenyuan, Risk Assessment of Power Systems: Models, Methods and Applications, New York: Wiley IEEE Press, 2005.

[41] D. Smith, Reliability, Maintainability and Risk: Practical method for engineers, Fifth ed., Boston: Butterworth-Heinemann Publishers, 2000.

[42] T. Gonen, Electric Power Distribution Engineering, Third ed., Boca Raton: CRC Press, 2014.

[43] B. Dhillon, Reliability, Quality and Safety for Engineers, London: CRC Press, 2005.

[44] P. T. D. O'Connor and A. Kleyner, Practical Reliability Engineering, Fifth ed., Chichester: Wiley & Sons, 2012.

[45] C. E. Eebeling, An Introduction to Reliability and Maintainability Engineering, First ed., Boston: MCGraw-Hill, 1996.

[46] M. Cepin, Assessment of Power System Reliability: Methods and Applications, 2011.

[47] White Paper EPRI, Reliability of Electric Utility Distribution Systems, Palo Alto : EPRI, 2000.

[48] *Glossary of Terms Uses in NERC Reliability Standards,* NERC, 2014..

[49] "IEEE Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities," *IEEE Std 859-1987,* p. 1, 1988.

[50] EPRI RP-1356-1, "Development of Distribution System Reliability and Risk Analysis Models," vol. 2, August 1981.

[51] MIL-STD-721, "Definitions of Terms for Reliability and Maintainability," *2018,* April 16.

[52] N. Roberts, W. Vesely, D. Haasl and F. Goldberg, Fault tree handbook NUREG-0492, NRC, 1981.

[53] J. Faulin, A. A. Juan, S. Martorell and J. Ramirez-Marquez, Simulation Methods, for Reliability and Availability of Complex Systems, 2010.

[54] E. Zio, Monte Carlo Simulation Method for System Reliability and Risk Analysis, 2013.

[55] O. C. Ibe, Markov Processes for Stochastic Modeling, New York: Elsevier Academic Press, 2009.

[56] P. Thodi, F. I. Khan and M. R. Haddara, "The Development of Posterior Probability Models in Risk-Based Integrity Modeling," *Society for Risk Analysis,* 2010.

[57] Product Quality Research Institute, "Failure Moded and Effect Analyis," Risk Management Training Group, 2008.

[58] M. Shafiee and F. Dinmohammadi, "An FMEA-Based Risk Assessment Approach for Wind Turbine Systems: A Comparative Study of Onshore and Offshore," *Journal of Energies,* vol. 7, pp. 619-642, February 2014.

[59] K. O. Kim and M. J. Zuo, "General model for the risk priority number in failure mode and effect analysis," *Reliability Engineering & System Safety*, vol. 169, pp. 321-329, 2018.

[60] R. Y. Rubinstein and D. P. Kroese, Simulation and the Monte Carlo Method, Second ed., New Jersey: Wiley Series, 2008.

[61] T. Koski and J. M. Noble, Bayesian Networks: An Introduction, John Wiley & Sons Ltd, 2009.

[62] R. E. Neapolitan, Learning Bayesian Networks, New Jersey, Pearson Prentice Hall, 2004.

[63] H. Langsetha and L. Portinale, ", "Bayesian networks in reliability," *Reliability Engineering and System Safety,* vol. 92, no. 1, pp. 92-108, January 2007.

[64] L. Gao, C. L. Y. Zhou and L. Huo, "Reliability Assessment of Distribution Systems with Distributed Generation based on Bayesian Networks," *Engineering Review,* vol. 34, no. 1, pp. 55 - 62, 2014.

[65] W. Chenshan and X. Yingua, "Applying Bayesian Network to Distribution Reliability Analysis," in *EEE Region 10 Conference*.

[66] D. C. Yu, T. C. Nguyen and P. Haddawy, "Bayesian network model for reliability assessment of power systems," *IEEE Transactions on Power Systems*, vol. 14, no. 2, pp. 426 - 432, 1999.

[67] C. A. Smith, M. D. Donovan and M. J. Bartos, "Reliability Survey of 600 - 800 kW Diesel and Gas Generators," *IEEE TRansaction on Industry Application,* vol. 26, no. 4, 1990.

[68] S. Pfaffel, S. Faulstich and K. Rohrig, "Performance and Reliability of Wind Turbine: A Review," *Energies,* November 2017.

[69] D. C. Jordan, T. J. Silverman, J. H. Wohlgemuth, S. R. Kurtz and K. T. VanSant, "http://nrel.gov," National Renewable Energy Laboratory, April 2017. [Online]. Available: https://www.nrel.gov/news/program/2017/failures-pv-panels-degradation.html. [Accessed 27 January 2019].

[70] LEIDOS ENGINEERING, "Capital Cost Estimates for Utility Scale Electricity Generating Plants," Energy Information Administration Office of Electricity, Coal, Nuclear, and Renewables Analysis, 2016.

Appendix A

The Roy Billinton Test System (RBTS) is a single line diagram of distribution systems developed at the University of Saskatchewan power system research group led by Prof. Roy Billinton. It was designed for education purposes in teaching overall reliability of power systems. The RBTS is a 6 bus test system with five load buses (bus 2 – bus 6) [19]. Figure A.1 shows the distribution network at bus 6 which is considered for this study.

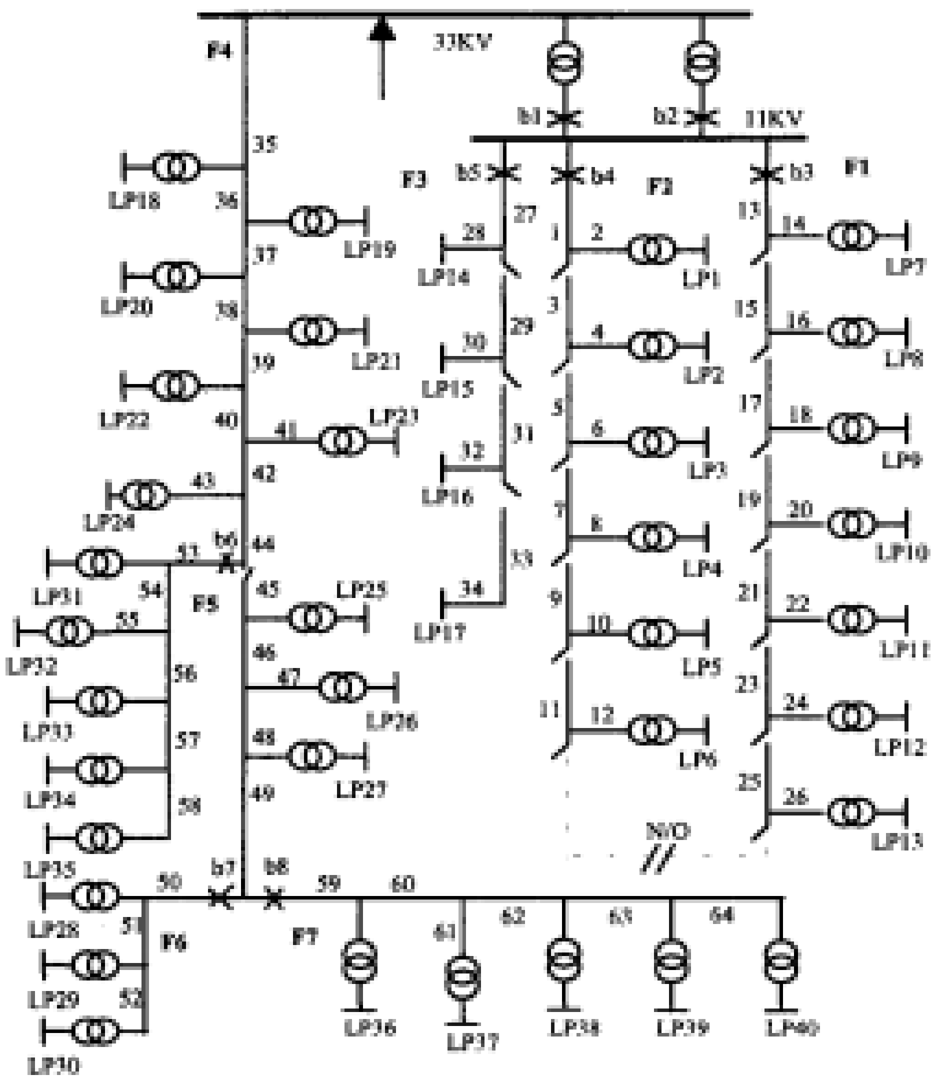

Figure A. 1. Distribution system of the IEEE RBTS Bus 6 [20]

The distribution network at bus 6 (Figure A.1) is a typical rural/urban network with agricultural, small industrial, commercial and residential customers and government institutions.

Appendix B

This section of the thesis present how the reliability indices such as the average failure rate (λ), average annual outage time (U), and repair time (r) for the load-points in the network are calculated. The reliability indices are calculated with parameters from Table 4.1 and Table 4.2. First, the equivalent indices for the subfeeders F5, F6, and F7 are calculated. The failure rate of the load-point that may be affected due to a failure of the section of the transmission has each section of the line's length multiplied by the failure rate of the line. The product (length of transmission line section multiplied by the lines' failure rate) of which is summed up to form the average failure rate of the load-point [3, 4, 6, 14, 46]. The procedure is presented in Table B1, Table B2, and Table B3. Having calculated the equivalence of the subfeeders, the network in Figure 4.1 is transformed into Figure 4.2.

Table B. 1. Reliability indices for subfeeder F5

Calculation of Reliability Indices for equivalent components in subfeeder (F5)			
Component	$\lambda eq\ 5$	r	U
53	0.065 x 3.2 = 0.208	5	0.208 x 5 = 1.04
54	0.065 x 1.6 = 0.104	5	0.104 x 5 = 0.52
56	0.065 x 2.8 = 0.182	5	0.182 x 5 = 0.91
57	0.065 x 2.5 = 0.163	5	0.163 x 5 = 0.813
58	0.065 x 3.2 = 0.208	5	0.208 x 5 = 1.04
Total	0.865	5	4.323

Table B. 2. Reliability indices for subfeeder F6

Calculation of Reliability Indices for equivalent components in subfeeder (F6)			
Component	$\lambda eq\ 6$	r	U
50	0.065 x 2.8 = 0.182	5	0.182 x 5 = 0.91
51	0.065 x 3.2 = 0.208	5	0.208 x 5 = 1.04
52	0.065 x 2.5 = 0.163	5	0.1625 x 5 = 0.813
Total	0.553	5	2.763

Table B. 3. Reliability indices for subfeeder F7

Calculation of Reliability Indices for equivalent components in subfeeder (F7)			
Component	λeq 7	r	U
59	0.065 x 2.8 = 0.182	5	0.182 x 5 = 0.91
60	0.065 x 2.5 = 0.163	5	0.1625 x5 = 0.813
62	0.065 x 1.6 = 0.104	5	0.104 x 5 = 0.52
63	0.065 x 3.2 = 0.208	5	0.208 x 5 = 1.04
54	0.065 x 2.8 = 0.182	5	0.182 x 5 = 0.91
Total	0.839	4.249	3.563

The subfeeders (F5, F56, and F7) of the network are replaced with their equivalent reliability indices calculated as in Table B.1, Table B.2, and Table B.3 respectively. This transforms the network in Figure 4.1 into a simple radial network in Figure 4.2, from which the reliability indices for the entire network is calculated. The calculation procedure is similar but the indices of equivalent components are added to the respective load-points connected to the subfeeders. A transformer failure rate of 0.015 f/year is also added. The result is presented in Table B.3 – Table B.7

Table B. 4. Reliability indices for LP 18 – LP 21

Calculation of Reliability Indices without Distributed Generators												
Component	Load Point 18			Load Point 19			Load Point 20			Load Point 21		
35	λ	r	U	λ	r	U	λ	r	U	λ	r	U
36	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
37	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813
38	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
39	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
40	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
42	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813
44	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
45	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
46	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208
48	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182
49	0.228	1	0.228	0.228	1	0.228	0.228	1	0.228	0.228	1	0.228
24	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104
Lateral Distributors	0.015	200	3	0.015	200	3	0.015	200	3	0.015	200	3
41												
43												
47												
55												
61												
λeq												
Total	1.673	5.0233	8.402	1.673	5.0233	8.402	1.673	5.0233	8.402	1.673	5.0233	8.403

Table B. 5. Reliability indices for LP 23 – LP 26

Calculation of Reliability Indices without Distributed Generators												
Component	Load Point 23			Load Point 24			Load Point 25			Load Point 26		
35	λ	r	U	λ	r	U	λ	r	U	λ	r	U
36	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
37	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813
38	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
39	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
40	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
42	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813
44	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
45	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
46	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	5	1.04
48	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	5	0.91
49	0.228	1	0.228	0.228	1	0.228	0.228	1	0.228	0.228	5	1.138
24	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	5	0.52
Lateral Distributors	0.015	200	3	0.015	200	3	0.015	200	3	0.015	200	3
41												
43	0.039	5	0.195									
47				0.0488	5	0.244						
55										0.039	5	0.195
61												
λeq												
Total	1.713	5.0228	8.597	1.721	5.0227	8.645	1.675	5.0233	8.402	1.713	6.709	11.483

Table B. 6. Reliability indices for LP 27 – LP 30

Calculation of Reliability Indices without Distributed Generators												
Component	Load Point 27			Load Point 28			Load Point 29			Load Point 30		
35	λ	r	U	λ	r	U	λ	r	U	λ	r	U
36	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
37	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813
38	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
39	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
40	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
42	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813
44	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
45	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
46	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	5	1.04
48	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	5	0.91
49	0.228	1	0.228	0.228	1	0.228	0.223	1	0.228	0.228	5	1.138
24	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	5	0.52
Lateral Distributors	0.015	200	3	0.015	200	3	0.015	200	3	0.015	200	3
41												
43												
47												
55												
61												
λeq				0.553	5	2.763	0.553	5	2.763	0.553	5	2.763
Total	1.673	5.0233	8.402	2.225	5.0175	11.164	2.225	5.0175	11.164	2.225	6.315	14.05

Table B. 7. Reliability indices for LP 31 – LP 34

Calculation of Reliability Indices without Distributed Generators												
Component	Load Point 31			Load Point 32			Load Point 33			Load Point 34		
35	λ	r	U	λ	r	U	λ	r	U	λ	r	U
36	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
37	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813
38	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
39	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
40	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
42	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813	0.163	5	0.813
44	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
45	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
46	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208	0.208	1	0.208
48	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182	0.182	1	0.182
49	0.228	1	0.228	0.228	1	0.228	0.228	1	0.228	0.228	1	0.228
24	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104	0.104	1	0.104
Lateral Distributors	0.015	200	3	0.015	200	3	0.015	200	3	0.015	200	3
41												
43												
47												
55				0.052	5	0.26						
61												
λeq	0.865	5	4.323	0.865	5	4.323	0.865	5	4.323	0.865	5	4.323
Total	2.537	5.0153	12.724	2.589	5.0151	12.984	2.537	5.0154	12.724	2.537	5.0154	12.724

Table B. 8. Reliability indices for LP 35 – LP 38

Calculation of Reliability Indices without Distributed Generators												
Component	Load Point 35			Load Point 36			Load Point 37			Load Point 38		
35	λ	r	U	λ	r	U	λ	r	U	λ	r	U
36	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
37	0.163	5	0.813	0.1625	5	0.813	0.163	5	0.813	0.163	5	0.813
38	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
39	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
40	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
42	0.163	5	0.813	0.1625	5	0.813	0.163	5	0.813	0.163	5	0.813
44	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
45	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293	0.0585	5	0.293
46	0.208	1	0.208	0.208	5	1.04	0.208	5	1.04	0.208	5	1.04
48	0.182	1	0.182	0.182	5	0.91	0.182	5	0.91	0.182	5	0.91
49	0.228	1	0.228	0.2275	5	1.138	0.228	5	1.138	0.228	5	1.138
24	0.104	1	0.104	0.104	5	0.52	0.104	5	0.52	0.104	5	0.52
Lateral Distributors	0.015	200	3	0.015	200	3	0.015	200	3	0.015	200	3
41												
43												
47												
55												
61							0.0488	5	0.244			
λeq	0.865	5	4.323	0.839	5	4.193	0.839	5	4.193	0.839	5	4.193
Total	2.537	5.0154	12.724	2.511	6.16487	15.48	2.560	6.143	15.724	2.511	6.165	15.48

Table B. 9. Reliability indices for LP 39 – LP 40

Calculation of Reliability Indices without Distributed Generators						
Load Point 39			Load Point 40			
λ	r	U	λ	r	U	
0.182	5	0.91	0.182	5	0.91	
0.163	5	0.813	0.163	5	0.813	
0.104	5	0.52	0.104	5	0.52	
0.0585	5	0.293	0.0585	5	0.293	
0.104	5	0.52	0.104	5	0.52	
0.163	5	0.813	0.163	5	0.813	
0.104	5	0.52	0.104	5	0.52	
0.0585	5	0.293	0.0585	5	0.293	
0.208	5	1.04	0.208	5	1.04	
0.182	5	0.91	0.182	5	0.91	
0.228	5	1.138	0.228	5	1.138	
0.104	5	0.52	0.104	5	0.52	
0.015	200	3	0.015	200	3	
0.839	5	4.193	0.839	5	4.193	
2.511	6.165	15.48	2.511	6.165	15.48	