Industrial Power Distribution System Reliability Assessment utilizing Markov Approach

By

Oscar R. Guzman-Rivera

A engineering project submitted in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2010

Approved by:

_______________________________ _________________
Efraín O'Neill-Carrillo, PhD. Date
Member, Graduate Committee

_______________________________ _________________
Lionel Orama Exclusa, PhD. Date
Member, Graduate Committee

_______________________________ _________________
Andrés Díaz, PhD. Date
President, Graduate Committee

_______________________________ _________________
Pedro Vasquez, PhD. Date
Representative of Graduate Studies

_______________________________ _________________
Hamed Parsiani, PhD. Date
Chairperson of the Department

ABSTRACT

A method to perform power system reliability analysis using Markov Approach, Reliability Block Diagrams and Fault Tree analysis has been presented. The Markov method we use is a state space model and is based on state diagrams generated for a one line industrial power distribution system. The Reliability block diagram (RBD) method is a graphical and calculation tool used to model the distribution power system of an industrial facility. Quantitative reliability estimations on this work are based on CARMS and Block Sim simulations as well as state space, RBD's and Failure Mode analyses.

The power system reliability was assessed and the main contributors to power system reliability have been identified, both qualitatively and quantitatively. Methods to improve reliability have also been provided including redundancies and protection systems that might be added to the system in order to improve reliability.

RESUMEN

En este Proyecto de Ingeniería se presenta un método para hacer estudios de confiabilidad en sistemas de distribución de potencia industrial utilizando el método de Markov, Diagramas de Bloque de Confiabilidad y Análisis de fallas. El método de Markov que se utiliza es un modelo de estado espacial basado en la generación de diagramas de estados para un diagrama mono lineal del sistema de distribución de potencia de una planta industrial. El método de diagramas de bloque de confiabilidad es una herramienta gráfica y matemática utilizada para modelar el sistema de distribución de potencia de una facilidad industrial. Las proyecciones cuantitativas de confiabilidad en esta tesis se basan en simulaciones hechas con CARMS y Block Sim como también análisis de estados espaciales, diagramas de bloque de confiabilidad y Análisis de Fallas.

La confiabilidad de nuestro sistema de potencia fue evaluada y los contribuyentes principales a la confiabilidad de este sistema fueron identificados, cuantitativamente y cualitativamente. Métodos para mejorar la confiabilidad como redundancias y sistemas de protección han sido proveídos.

To GOD our savior for giving me illumination and understanding, because everything that has happened in my life has been his will. To my family, for encouraging and believing in me, for all their unconditional support and advice over the past years and for always be there when I most needed it.

ACKNOWLEDGEMENTS

There were a lot of people that helped me through the journey of completing my Master's degree. I have to admit that without the enthusiasm and inspiration of my advisor, Dr. Andrés Díaz, this engineering project would not have been possible. He has been not only an advisor to me but a great friend. I have to thank all my friends for their invaluable guidance through my research and course work. Throughout my engineering project-writing period, they provided encouragement, sound advice, good teaching, good company, and lots of good ideas. I would have been lost without them.

I would like to thank the many people who have taught me engineering through my entire bachelor and masters degree: all my undergraduate professors, (especially Dr. Agustin Irizarry, Dr. Jose Cedeño and Dr. Lionel Orama), my Alabama Power Co-workers (especially Joel A. Tuttle and Ray D. Giroux), and finally my graduate teachers (especially Dr. Efrain O'Neill Carrillo, Dr. Lionel Orama Exclusa and Dr. Andres Diaz). For inspiring me to pursue my masters and always giving me good advice.

I am indebted to my many student colleagues for providing a stimulating and fun environment in which to learn and grow. I am especially grateful to Christian E. Bosque, Edwin Berrios-Galarza, Damian Galarza Torres, Luisa Feliciano, Rene Martinez-Cid and Enid Serrano at the University of Puerto Rico.

I am grateful to the secretaries of the Electrical Engineering Department (especially Sandra Montalvo) for help the department to run smoothly and for assisting me in many different ways.

Finally, I would like to give all my gratitude to my parents, my extended family, and to my fiancée Alexandra Litchfield-Santana. These people mean the most to me because they give me all their support and all their unconditional love and the journey was very pleasant with their presence by my side.

Table of Contents

Table List

Tables **Page**

Figure List

Figures **Page**

1 INTRODUCTION

Due to recent improvement on the India's Brewery company a complete redesign of its power distribution system has been performed. Then, a complete reliability analysis should be performed on the plant in order to verify that this new design is meeting company's requirements. Remember that by not providing the necessary redundancies in a system, possible failures can lead to power outages that are translated to thousands of dollars in losses depending on how critical the failure is. Outages have impacted our economy, as well as our society; thousands of dollars are lost every time an industry runs out of power.

For a Brewery company to succeed in today's highly competitive and technologically complex environment, it is important that it knows the reliability of its beer production. It also must be capable of control it in order to deliver production at an optimum reliability level. This minimizes the company costs of its production without compromising reliability and quality. The Reliability of the company's power distribution system should be known to avoid catastrophic events that could imply loss of property, loss of income, or worst, loss of life.

Reliability plays an important part in the analysis and design of electrical systems, especially when we are talking big scale as it is with industrial or commercial power system design. An Industrial Reliability Assessment is based on the results of analyses from computer programs and data that belong to the performance results of the power system in the field. Considerations of two important aspects, quality and continuity of supply, along with other important factors are normally referred to as reliability assessment. The data produced by these assessments are utilized to accurately measure and improve the reliability of the system being analyzed, in this case the distribution power system of an industry. This is very important because today's market drive a constant push for cost reduction and better efficiency of the systems.

1.1 Motivation

The availability of energy distribution systems is significantly impacted by AC mains power quality. The degree to which power quality affects power systems depends on different factors such as the quality of the electrical power, the downtime caused by factors unrelated to power and the ability of the system to recover from power outage. This problems leads to losing electric power service which has major economic and social impacts on both the utility supplying electric energy and the end users of electric service. Customers won't tolerate an on-off relationship. For this reason reliability analyses need to be run on every power distribution system in order to ensure system uptime and prevent outages. Major power outage impacts the economy in a very bad way. Therefore, maintaining a reliable power supply is a critical issue for power systems design and operation.

The design of reliable industrial and commercial power distribution systems is important because of the high cost associated with power outages. It is necessary to consider the cost of power outages when making design decisions for new power distribution systems as well as to have the ability to make quantitative "cost-versus-reliability" trade-off studies [1]. The quantitative reliability methods permit reliability indexes for any electric power system to be computed given the reliability performance of the constituent components of the system. Thus, alternative system designs can be studied to evaluate the impact on service reliability, system availability and cost of changes in component reliability, system configurations, or system operating policies including maintenance practices. Reliability plays an important role in the analysis and design of electrical systems. Reliable systems reduce ownership cost, it reduce the dependence on spare parts, and the need for support personnel [11].

1.2 Objective

The main objective of this project is to perform a complete reliability analysis on the power distribution radial system of the India Brewery Company in Mayaguez, Puerto Rico. The scope of this engineering project is to provide accurate reliability data of India's power distribution system utilizing Markov process techniques, Reliability Block Diagrams (RBD's) and Fault Tree Analyses (FTA's) as a mean to provide accurate results. Since the Reliability Block Diagram approach outputs an approximate measure of what the real reliability number should be, the same is used to provide graphical understanding of our complete system. The Reliability Block Diagram method will also serve as an aid to compare results with the ones obtained with Markov (state diagram) techniques which provide more accurate reliability data. This way it could be determined what improvements could be done on India's Brewery plant power distribution system in order to make the system more reliable.

On the other hand the development of these reliability analyses will provide new opportunities for other students to develop power system reliability skills by engaging in a real life collaborative design experience. In addition, this project can be the source of challenging projects and the step stone to move forward to new technologies that could make our power distribution systems more reliable and more efficient.

1.3 Literature Review

The design of reliable industrial and commercial power systems is of considerable interest to many people. Prior to 1962, a qualitative viewpoint was taken when attempting to achieve this objective. The need for a quantitative approach was first recognized in the early 1960s when a small group of pioneers led by W. H. Dickinson organized an extensive AIEE survey of the reliability of electrical equipment in industrial plants [1]. During that same year The Westinghouse Electric Corporation and Gas Company introduced the concept of a fluctuation environment to describe the failure rate of transmission systems components. After New York power blackout in 1965, the industry established the North American Electric Reliability Council (NERC) to develop guidelines and procedures for preventing those kind of incidents, increasing the reliability of power distribution networks and reducing the economical impact as well.

Reliability assessment in electrical power systems makes use of a variety of mathematical methods. Recent publications have focused on finding new methods to perform reliability assessments on power systems. The development of power distribution system subject to reliability considerations is based on a balanced between designing cost and the economic damage resulting from power outages. Inspired with this premise, Kobi Yahaw, in his paper titled "Reliability Assessment and Performance Based Incentive on Power Distribution Systems" has performed a reliability analysis on the Israeli power distribution system, basing his reliability estimations on Monte-Carlo Simulations [2]. The Monte Carlo method is a method that involves random numbers and probability to solve problems; it is widely used to determine the probability of complex systems. In system reliability this method generates random failure times and from each components failure distribution. The overall system reliability is then obtained by simulating system operation and empirically calculating the reliability values for a series of time values. The Monte Carlo method mentioned above is suitable for heterogeneous distribution companies, which have a large variety of power characteristics. But, this sequential Monte Carlo simulations, although flexible and with high reliability potential, is often not an option because of its extreme computational demand. This method should only be seen as a last resource method or for checking results when developing faster methods.

State Space model for electrical power systems made by independent semi-Markov components have also been proposed recently. With this method restoration times can have a non exponential distribution, thus obtaining a more realistic reliability characterization [3]. Here a state space model was employed for the analytical calculations of Mean Time between Failure (MTBF) and Mean Time to Repair (MTTR) for a system made up of independent semi Markov components. In paper [3] this model was applied to the reliability assessment of an uninterruptible power supply (UPS), but this same model could also be useful for the electrical power distribution system. This state space model made by independent semi Markov components allows a complete assessment of the electrical power system reliability. The main objective of this is to derive some benefits by the investments aimed at increasing the reliability thanks to the reduction of the outage cost. Figure [2-1] shows that the optimum reliability levels are achieved by minimizing the total costs.

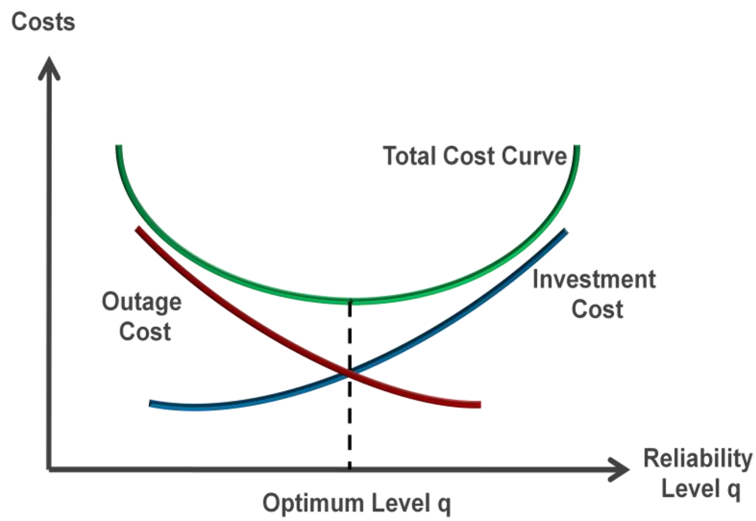


Figure 1-1 Graph of the optimum reliability level minimizing the total cost. Taken from [3]

There are studies that propose a special kind of semi Markov model which uses Weibull distributions for all stochastic durations. This model contains the homogenous Markov model as a subset, enables bell shape distributions and may be used in various analytical and non-sequential reliability assessments methods [4]. An example of a three state Weibull Markov model is shown in figure [2-2]. Any homogenous Markov model can be converted to a Weibull Markov model. But, using a pure homogenous Markov model has the advantage that a system built with homogenous Markov components (as almost all power distribution systems are built) is again a homogenous Markov model. Then, no transformations will be needed and all reliability calculations are easier.

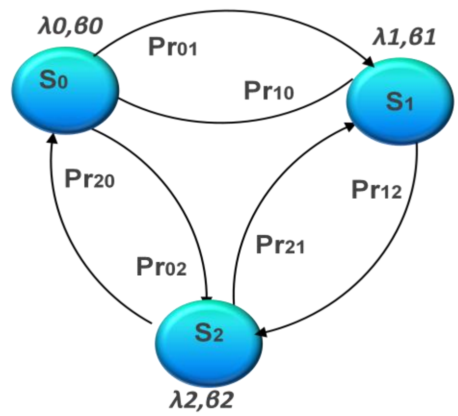


Figure 1-2 Three State Weibull Markov model with parameters. Taken from [4]

Each of these methods limits or enables the next one. A stochastic model that describes only the probability of the possible states for the power system components will disable a sequential Monte Carlo analysis. The same way a state enumeration or non sequential method will disable a transient analysis of the system. For this reason the most commonly used stochastic model is the Markov model which uses the negative exponential distribution to model all stochastic durations.

Other methods such as Reliability Block Diagrams have also been explored. Paper [5] describes the approach of simulating reliability using reliability block diagrams (RBD). RBD is a combinatorial model that shows an abstract view of the system redundancies and provides ease of reliability evaluation. This method has been found to be a practical reliability modeling method for industrial and commercial power systems. Knowing all this is not difficult to determine that the best approach to analyze our system will be using Markov model and RBD method as we state on this engineering project.

1.4 Summary of Following Chapters

Chapter 2 develops the necessary background in basic reliability concepts. Basic Reliability definitions such as Failure rates, Mean Time Between failures and Mean Time to repair all the way through system availability concepts are covered in this chapter along with basic Reliability modeling techniques such as Markov Modeling. Chapter 3 deals with the Reliability Analysis of an industrial distribution radial system applying different techniques such as Markov and Reliability Block Diagrams (RBDs). Conclusions and future work are presented in chapter 4.

2 THEORETICAL BACKGROUND

2.1 Basic Concepts of Reliability Theory

The basics principles of reliability analysis concepts applied to industrial and commercial power distribution systems will be presented through this chapter. In order to have a better understanding of the reliability concepts some basics definitions will described.

2.1.1 Failure Rate

Failure rate is the frequency with which an engineered system or component fails. It is generally expressed in failures per hour and often denoted by the Greek letter λ (lambda). It is important to mention that a failure in a power system is defined as any trouble with a power system component that causes any of the following problems to occur:

- Partial or complete plant shutdown or below-standard plant operation.
- Unacceptable performance of user's equipment.
- Operation of the electrical protective relaying or emergency operation of the plant electrical system.
- De-energization of any electric circuit or equipment.
- A power interruption or loss of service.

- A deviation from normal voltage or frequency outside the normal utility profile.

2.1.2 Mean Time between Failure (MTBF)

MTBF is a basic measure of reliability for repairable items. It can be described as the number of hours that pass before a component, assembly or system fails. It is a commonly used variable in reliability and maintainability analyses. MTBF can be calculated as the inverse of the failure rate for constant failure rate systems. Refereeing to figure [2-3] the MTBF is the sum of the operational periods divided by the numbers of observed failures as seen on equation 2.1.

$$\boldsymbol{MTBF = \frac{\sum(downtime - uptime)}{number\ of\ failures}}$$ **Equation 2.1**

A graphical explanation of this equation it is seen on figure [2-1]. This figure shows that the mean time between failures equals the down time minus the uptime of a system or component.

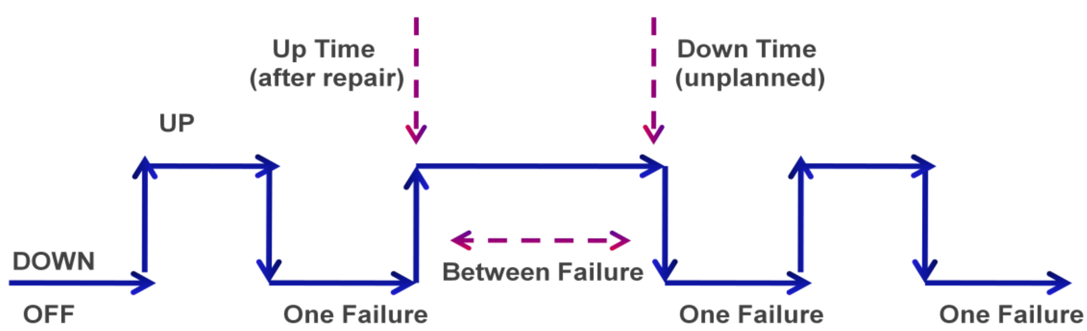


Figure 2-3 MTBF=Downtime-Uptime.

2.1.3 Mean Time to Failure (MTTF)

MTTF is a basic measure of reliability for non-repairable systems. It is the mean time expected until the first failure of a piece of equipment. MTTF is a statistical value and is meant to be the mean over a long period of time and large number of units. For constant failure rate systems, MTTF is the inverse of the failure rate. For example if failure rate is given in failures per million hour, then the MTTF will be equal to 1,000,000/Failure Rate for components with exponential distributions. From the last two definitions we can deduct that the MTBF should be used only in reference to repairable items, while MTTF should be used for non-repairable items. However, MTBF is used for both, repairable and non-repairable items.

2.1.4 Mean Time to Repair (MTTR)

MTTR or Mean Time to Repair represents the average time taken to put a defective components or system back in working order. It is a measure of the maintainability of the system and predicts the average amount of time required to get the system to work again in case of a system failure. The MTTR can also be used interchangeably with the Mean Corrective Time (MCT) because only corrective maintenance items are considered in the MTTR calculations. It can be estimated by dividing the summation of repair times by the number of repairs, and therefore, it is basically the average repair time.

$$\boldsymbol{MTTR = \frac{\sum(repair\ times)}{number\ of\ repairs}} \qquad \textbf{Equation 2.2}$$

2.1.5 Repair Time

The repair time of a tailed component or the duration of a failure is the clock time from the occurrence of the failure of a component to the time when the component is restored to service, either by repair of the failed component or by substitution of a spare component for the failed component. The repair time is also called the duration of a failure. It includes time for diagnosing the trouble, locating the failed component, waiting for parts, repairing or replacing, testing, and restoring the component to service. It is not the time required to restore service to a load by putting alternate circuits into operation. The terms “repair time” and “forced outage duration” are often used synonymously.

2.1.6 System Availability

Availability of a system is the degree in which a system or equipment is operable and in a committable state. It is the long term average fraction of time that a component or system is in service and satisfactorily performing its intended function [1]. System availability is calculated by modeling the system as an interconnection of parts in series and parallel. The following rules are used to decide if components should be placed in series or parallel.

- If failure of a part leads to a combination that becomes inoperable, the two parts are considered to be operating in series.
- If failure of a part leads to the other part taking over the operations of the failed part, the two parts are considered to be operating in parallel.

Figure [2-4] shows two block diagrams corresponding to the availability in series.

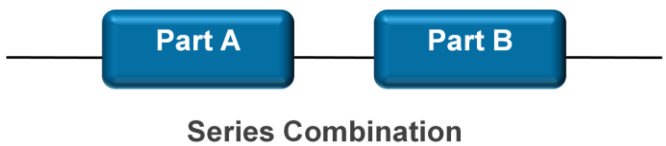


Figure 2-4 Series Availability.

As stated above, two parts A and B are considered to be operating in series if failure of either of the parts results in failure of the combination. The combined system is operational only if both parts A and B are available. Then it follows that the combined availability is a product of the availability of the two parts. The combined availability is shown by equation 2.3 below:

$$A_v = A_A * A_B \qquad \textbf{Equation 2.3}$$

The implications of the above equation are that the combined availability of the two components in series is always lower than the availability of its individual components.

The other case is when we have the availability in parallel. Figure [2-5] shows a block diagram representing the availability in parallel where component A and B are the same.

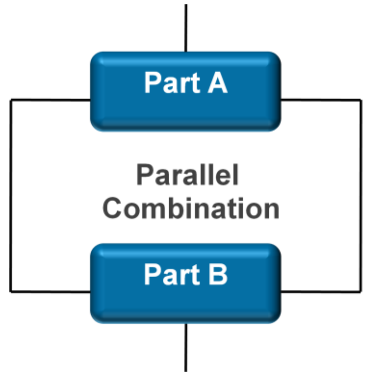


Figure 2-5 Parallel Availability.

As stated above, two parts are considered to be operating in parallel if the combination is considered down or failed when both components fail. The combined system is operational if either is available. Then it follows that the combined availability is:

$$A_v = 1 - (1 - A_A)^2 \qquad \textbf{Equation 2.3}$$

The implications of the above equation are that the combined availability of two components in parallel is always much higher than the availability of its individual components. Once the MTBF and the MTTR of a system are known, the availability of the system can be calculated using the following formula:

$$A_v = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \qquad \textbf{Equation 2.4}$$

2.2 Fundamentals of Power Systems Reliability Evaluation

To perform a quantitative reliability evaluation in electric power systems it is important to define some basic reliability terms, discuss useful measures of basic reliability with the basic data needed to compute this numbers, and describe a procedure for system reliability analysis including computations of quantitative reliability indexes. The quantitative reliability methods permit reliability indexes for any electric power system to be computed given the reliability performance of the constituent components of the system. Thus, alternative system designs can be studied to evaluate the impact on service reliability, system availability and cost of changes in component reliability, system configurations, or system operating policies including maintenance practices.

2.2.1 Systems Reliability Indexes

Terms previously defined in section 2.1 are commonly used in the survey of reliability of electric equipment in industrial plants. The basic system reliability indexes that have proven to be the most useful and meaningful in power distribution system designs are [17]:

- Load interruption frequency
- Expected duration of load interruption events
- Total expected (average) interruption time per year (or other time period)
- System availability or unavailability as measured at the load supply point in question
- Expected demanded, but unsupplied, energy per year

It should be noted here that the disruptive effect of power interruptions is often non-linearly related to the duration of the interruption. Thus, it is often desirable to compute not only an overall interruption frequency but also frequencies of interruptions categorized by the appropriate durations.

2.2.2 Method for System Reliability Evaluation

The method called *minimal-cut-set* is believed to be well suited to the study and analysis of electric power distribution systems. An important feature of this method is that systems weak points can be identify focusing design attention on those sections or components of the system that contribute most to service unreliability.

The procedure for system reliability evaluation is outlined as follow:

- Assess the service reliability requirements of the loads and processes that are to be supplied and determine the appropriate service interruption definition or definitions.
- Perform a failure modes and effects analysis (FMEA) identifying and listing those component failures and combinations of component failures that result in service interruptions and that constitute minimal cut-sets of the system.
- Compute the interruption frequency contribution, the expected interruption duration, and the probability of each of the minimal cut-sets of last step.

- Combine the results of step jus mentioned to produce system reliability indexes.

2.2.3 Failure Mode and Effect Analysis (FMEA)

A failure modes and effects analysis (FMEA) is a procedure for analysis of potential failure modes within a system for classification by severity or determination of the effect of failures on the system. The FMEA for power distribution systems takes into consideration the determination and listing of those component outage events or combinations of component outages that result in an interruption of service at the load point being studied according to the interruption definition that has been adopted. This analysis must be made in consideration of the different types and modes of outages that components may exhibit and the reaction of the system's protection scheme to these events. The primary result of the FMEA as far as quantitative reliability evaluation is concerned, is the list of minimal cut-sets it produces.

An important non-quantitative benefit of the FMEA is the systematic thought process and investigation that it requires. Often weak points in system design will be identified before any quantitative reliability indexes are computed. Thus, the FMEA is a useful reliability design tool even in the absence of the data needed for quantitative evaluation.

The FMEA and the determination of minimal cut-sets are most efficiently conducted by considering first the effects of outages of single components and then the effects of overlapping outages of increasing numbers of components. Those cut-sets containing a single component are termed *first-order cut-sets*. Similarly, cut-sets containing two components are termed *second- order cut-sets,* etc. In theory the FMEA should continue until all the minimal cut-sets of the system have been found. Since most power distribution systems have at least some first-order minimal cut-sets, the analysis can usually be terminated after the second-order minimal cut-sets have been found.

2.3 Basic Reliability Models

Let's start defining what a reliability model is. A reliability model is simply a mathematical and graphical representation of the system reliability characteristics. In order to perform reliability modeling, there is need to be familiar with the failure modes and their effect on the system as well as the failure rates on the individual components. This section provides a brief overview of some of the different models used in reliability analysis.

2.3.1 Reliability Models

Reliability models support systems design and are used to:

- *Set the requirements*: reliability modeling help in the evaluation process when doing a design conceptualization.

- *Predict reliability of different configurations*: Alternative design configurations are analyzed using reliability modeling technique to later choose the most promising and reliable configuration.
- *Identify weak points in the system*: If the system does not meet reliability requirements a reliability analysis is performed to determine the unreliable components.
- *Support cost effective trade-off*: Reliability models are used to predict the number of failures in each component.

Now that some of the reliability models used have been mention, different types of reliability models such as parts-count, combinatorial and Markov models will be described.

2.3.2 Parts Count Model

A parts-counts reliability model is mainly used to estimate the reliability of a non-redundant component or assembly. To execute this type of reliability model a basic assumption needs to be made. The assumption is that only a single failure of a component or assembly will cause system failure. Parts-count model is also known as the serial model. It is also used in redundant systems design to estimates failure rates for the individual system components.

The part count model requires the following steps:

- Obtain a complete part list.

- Determine or estimate stresses for each part.
- Select the failure rate source (Telcordia, Belcore, Mil_HDBK-217).
- Determine the appropriate failure rate for each part.
- Determine subsystems failure rates by adding all its components failure rates.
- Compute reliability for a specified mission or life time of the system.

Since part count reliability modeling is considered a series model as it was mentioned earlier, if there is a system consisting of N series components in which the failure of a component will cause failure, this failure will be given by the next equation:

$$\boldsymbol{R(t) = R_1(t) * R_2(t) \ldots R_N(t)} \qquad \textbf{Equation 2.5}$$

Where $\boldsymbol{R(t)}$ is the system reliability and $\boldsymbol{R_i(t)}$, ***i=1,2,3,...N***, are the components reliabilities. If the components have exponential failure densities, then:

$$\boldsymbol{R(t) = exp(-\textstyle\sum_{i=1}^{n} \lambda_i t) = e^{-\lambda t}} \qquad \textbf{Equation 2.6}$$

where

$$\boldsymbol{\lambda = \lambda_1 + \lambda_2 + \lambda_3 + \cdots \lambda_N} \qquad \textbf{Equation 2.7}$$

2.3.3 Combinatorial Model

Combinatorial reliability models include reliability block diagrams (RBD’s), Fault Tree Analysis (FTA), and success trees. These models are applicable to simple systems and are based on perfect spare component switching assumptions.

Combinatorial models have serious limitations because they cannot be used to model system repairs or dynamic reconfiguration of the system.

2.3.4 Reliability Block Diagrams (RBD's)

A major advantage of using RBD approach is the ease of reliability evaluation. A reliability block diagram is used to show an abstract view of the system. For example figure [2-6] shows a system consisting of two parallel redundancies followed by three series redundancies. The two block named X are connected in parallel and conform a parallel redundancy while the two following blocks named Y and Z are connected in series, conforming a series redundancy.

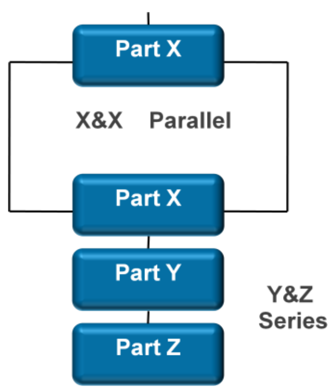


Figure 2-6 System consisting of parallel and series redundancies.

It is important to mention that reliability block diagrams cannot always provide the required reliability and fail-safety information that is needed to design fault tolerant systems. The problem arises because RBD's can only represent two states per component (good or failed), whereas the redundancy analysis usually required the representation of multiple states. One of the drawbacks of using reliability block diagram as a modeling tool is that it is not capable of handling time dependant redundancy configurations, such as standby with switch and load sharing. Some of the advantages of using reliability block diagrams is its simplicity and easy of evaluation. It can be used as a starting point in reliability analysis.

2.3.5 Fault Tree Analysis (FTA)

The Fault tree analysis is a graphical model. A fault tree analysis will let the user know which combinations of a component failure will result in a system failure. Fault trees are composed of events and logical event connectors such as AND-gates and OR-gates. Each events node's sub-events are the necessary pre-conditions that could cause this event to occur [27]. Figure [2-7] shows a fault tree diagram for a parallel system consisting of two components. From the figure it can be seen that both components (A and B) needs to fail in order to have a system failure. If we were to represent a series combination of component then an OR-gate logic gate should be used instead.

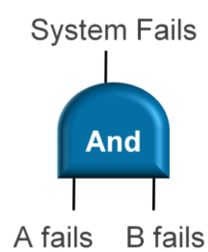


Figure 2-7 FTA diagram for a parallel configuration.

The advantage of using FTA method is that the user can clarify fault processes and fault propagations in the system. FTA also provides a method to:

- Calculate unreliability and unavailability

- Analyze uncertainty and Sensitivity
- Analyze common cause failure
- Produce minimal cut sets
- Define events failure modes
- Determine the important of elements in a system.

Although the Fault Tree Analysis is very useful it also has certain limitations. Some of its limitations are:

- Time exposure: FTA does not allow an easy representation of different equipment configurations during different mission times.
- Severity of faults: FTA does not support inclusion or exclusion of specific faults.
- Fault sequence: FTA not able to represent distinguish sequence of specific faults in a multiple fault situation.
- Duplication of faults: Same fault may appear in different parts of the fault tree, if the problem is not corrected erroneous results may be obtained.
- Fault propagation in the system: FTA not suitable for the representation of dynamic configurations.
- Repair and maintenance: Repair and maintenance cannot be expressed using fault tree representation.

2.3.6 Markov Model Overview

Markov analysis provides the means for analyzing the reliability and availability of systems whose components have strong dependencies. A Markov analysis looks at a sequence of events, and analyzes the tendency of one event to be followed by another. It considers system states and the possible transition between these states. The basic assumption in this process is that is memory less, this mean that the transition probabilities are determined only by the present state and not by the history. Using this model the user is able to generate a new sequence of random but related events, which will look similar to the original.

To represent system states, Markov model use state transition diagrams (STD). The state transition diagram identifies all the discrete state of the system and the possible transitions between those states. In Markov process the transition frequencies between states depends only on the current state probabilities and the constant transition rates between states. The transitional probabilities between states are a function of the failure rates of the various system element failures. A set of first order differential equation will equal the number of states of the model. Then the mathematical problem when doing Markov Modeling is to solve the equation below:

$$\boldsymbol{P} = [\boldsymbol{A}]\boldsymbol{P} \qquad \textbf{Equation 2.8}$$

Where $\dot{\underline{P}}$ and $\underline{P}$ are vectors of dimension nx1, [A] is a matrix of dimension m x m and then 'n' denotes the number of states in the system. The solution of this equation will be:

$$\mathbf{P} = \mathbf{exp}[\mathbf{A}]\,\mathbf{t} * \mathbf{P}(\mathbf{0}) \qquad \textbf{Equation 2.9}$$

Where exp [A] t is a matrix of dimension n x n and P (0) is the initial probability vector describing the initial state of the system. In order to solve for the matrix exp [A] t, two approaches can be used, the first one will be to solve this matrix using the Eigen value method and the second will be to compute an infinite series.

To demonstrate how the Markov model equations are developed, it can be assume to have a system that is made up of two elements. Each element has two mutually exclusive states (good and failed). Each states of the model are generated with elements being either good or failed. The probabilities associated to transition from state to state are a function of the element failure rates. Transitional probabilities of elements with constant failure rates can be approximated by $\lambda*\Delta t$. The probability in Δt associated to the element failure can be neglected.

Markov differential equation is developed by describing the probability associated with each of the states at a time interval $t + \Delta t$ as function of the state of the system at a time t. Basically, the probability of being in state two at certain time t and not making any state transition during Δt time, is equal to the probability of being in state one at some point defined by $t + \Delta t$. All this can be expressed by the next equation:

$$\mathbf{P_2(t + \Delta t) = P_2(t)(1 - \lambda_2 * \Delta t)} \qquad \textbf{Equation 2.10}$$

The other state probabilities are generated using the same concept and all this process results in the following equations:

Rearranging

$$\mathbf{P_1(t + \Delta t) = P_1(t)[1 - (\lambda_1 + \lambda_2) * \Delta t]}$$
$$\mathbf{P_2(t + \Delta t) = P_1(t)\lambda_1 \Delta t + P_2(t)(1 - \lambda_2 \Delta t)]}$$
$$\mathbf{P_3(t + \Delta t) = P_1(t)\lambda_2 \Delta t + P_3(t)(1 - \lambda_1 \Delta t)]}$$
$$\mathbf{P_4(t + \Delta t) = P_2(t)\lambda_2 \Delta t + P_3(t)\lambda_1 \Delta t + P_4(t)}$$

Taking the limit as $\Delta t \rightarrow 0$

$$\mathbf{dP_1(t)/dt = -(\lambda_1 + \lambda_2)P_1(t)}$$
$$\mathbf{dP_2(t)/dt = \lambda_1 P_1(t) + \lambda_2 P_2(t)}$$
$$\mathbf{dP_3(t)/dt = \lambda_2 P_1(t) + \lambda_1 P_3(t)}$$
$$\mathbf{dP_4(t)/dt = \lambda_2 P_2(t) + \lambda_1 P_3(t)}$$

$$\begin{bmatrix} \mathbf{dP_1(1)/dt} \\ \mathbf{dP_2(1)/dt} \\ \mathbf{dP_3(1)/dt} \\ \mathbf{dP_4(1)/dt} \end{bmatrix} = \begin{bmatrix} \mathbf{-(\lambda_1 + \lambda_2)} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{\lambda_1} & \mathbf{-\lambda_2} & \mathbf{0} & \mathbf{0} \\ \mathbf{\lambda_2} & \mathbf{0} & \mathbf{-\lambda_1} & \mathbf{0} \\ \mathbf{0} & \mathbf{\lambda_2} & \mathbf{\lambda_1} & \mathbf{0} \end{bmatrix} * \begin{bmatrix} \mathbf{P_1(t)} \\ \mathbf{P_2(t)} \\ \mathbf{P_3(t)} \\ \mathbf{P_4(t)} \end{bmatrix}$$

Or P = [A] P where [A] represents the state transition matrix. The important thing here is to note that the analyst only needs to generate the states and the transition between states as defined by the element failure rate.

These Markov state diagrams contain sufficient information for developing the state equations. For example in a parallel system consisting of two components, A and B, it can be defined the system states mentioned in table 2.1.

Table 2.1 Table 2.1 Parallel configuration state description

State	Description
S1	System fully operational
S2	Component A has failed, B still operational
S3	Component B has failed, A still operational
S4	Both components have failed, system has failed

The corresponding Markov Diagram is shown in figure [2-8]. This figure shows the four states mention in table 2.1 with its respect transition reliability numbers or failure rates. Lambda A and Lambda B are the components (A and B) failure rates.

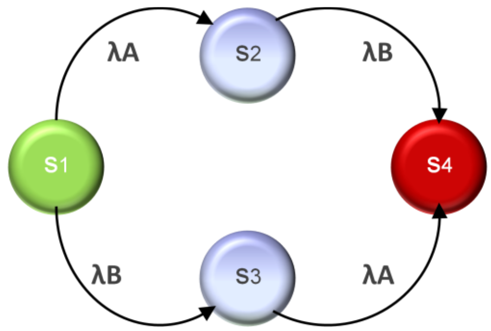


Figure 2-8 State diagram for a parallel configuration.

The advantages of using Markov model with state transition diagram is that it can be used in those situations where all failure rates statistics are not available. Also a state diagram is more accurate than the reliability block diagram because it can represent more systems states and component failure dependency.

The major drawback of this method is that Markov diagrams for large systems are huge, complicated and difficult to construct.

2.4 Markov Process Fundamentals

There are four different Markov Processes, classified according to the state-space and time characteristics. These processes are summarized in table 2.2 shown below. A detailed description of each process is provided in this section.

Table 2.2 Table 2.2 Markov Process Types

Type	Acronym	Sate-Space	Time Space
1	DSMC	Discrete	Discrete
2	DSMP	Discrete	Continuous
3	CSMC	Continuous	Discrete
4	CSMP	Continuous	Continuous

2.4.1 Discrete Time, Discrete State Markov Model

The Discrete Time, Discrete State model is represented by discrete transition matrices, specifying fixed transition probabilities. In probabilistic systems it is possible that as a result of a particular event it can be expected several different outcomes. If we were dealing with a stationary process then we can assign distinct transitional probabilities to each of the possible outcomes. The sum of these transitional probabilities will equal unity.

The events resulting from an experiment can be considered as further experiments. Then a sequence of these experiments is called a stochastic process. When the transitional probabilities to the next state are dependent only on the preceding experiment, this stochastic process is called the discrete Markov process or Markov chain. Basically a Markov chain means that future states depends only on the present state and are independent of past states. Discrete Markov systems are defined by a set of states with a matrix of associated probabilities going from one state to another. Being a stochastic process means that all state transitions are probabilistic and not deterministic.

Since we have fixed transition probabilities, the implication is that we are working with fixed time intervals and discrete events. Unfortunately, many redundancy configurations cannot be easily modeled using the fixed time interval scheme, because a random change of state during this time interval may be experienced.

2.4.2 Continuous Time, Discrete State Markov Model

The Continuous Time, Discrete State Markov Model is the most important class of Markov Model. The different of this model compared to the previous one is that now time is assuming a continuous range of values. Instead of letting transitions occur between discrete times, now transitions occur in a very short period of time.

2.4.3 Discrete Time, Continuous State Markov Model

The Discrete Time, Continuous State model is applicable if there are discrete changes in time in an environment where the states of the system are continuous over the specified range. But, since numerical data are seldom available, and the solution of the resulting partial differential equations is more complex, multiparameter modeling and computation remains a difficult problem.

2.4.4 Continuous Time, Continuous State Markov Model

The conventional diffusion equation fall under the Continuous Time, Continuous State model. In reliability we work with fully operational systems or failed systems. When we introduce degraded operability it is easy to think about the continuity of physical states in which the system can exist. The problem with this approach is that the evaluation of these equations represents a greater cost.

3 Methodology

This reliability analysis for industrial facilities is based on India's Brewery power distribution system. A One Line Diagram provided by this industry has been used to perform this reliability assessment. The complete India's Brewery One Line Diagram for its power distribution system is shown in Appendix A. In order to simplify our analyses the system has been subdivided in two sections, the first section correspond to 2500 KVA Substation and the second to a 4200 KVA Substation. The First step to start this analysis is to carefully analyze all components and the interconnections between them as well as the reliability data. A complete components list for this system is put together and is shown in Appendix B. This Reliability Assessment will begin with a Failure Mode Effect Analysis for each distribution power system section. This analysis is intended to determine possible flaws in the system and provide possible solutions to the problem. After the FMEA is complete, there is a need to use other computer based tools such as CARMS and BlockSim; with these tools several analyses and tests are run in order to acquire sufficient reliability data. Among the analysis performed we have the discrete space, continuous time Markov modeling using CARMS and the Reliability Block Diagram Analysis using BlockSim.

3.1 Reliability Assessment Methodology

3.1.1 Reliability Predictions and Failure Rate data

As we just mentioned, the first step is to gather all reliability data from each system component. When actual component failure rate data is not available, standards based reliability prediction is used to evaluate design feasibility, compare design alternatives, identify potential failure areas and track reliability improvements. Table 3.1 and table 3.2 below show all systems components for sections I and II with its correspondent failure rates data. Most of the failure rates shown on the table are based on the IEEE 497 Standard.

Table 3.1 Table 3.1 India's Brewery Component and Failure Rate Data for Section I

SYSTEM: 2500KVA SUBSTATION NONE LINE DATE: 07/20/2009

IDENTURE LEVEL: 1 & 2

REFERENCE DRAWING: E1-01-REV 71409

IND LEV	ID #	ITEM/FUNCTIONAL IDENTIFICATION	RATINGS	FAILURE RATE (λp)	ITEM DESCRIPTION
1	T-1	Transformer	38KVΔ , 2500KVA , 480VΔ	0.0059	Δ-Δ Main Power Transformer supply power to distribution system.
1	EM1.2	Transformer Meter	2500KVA	0.00036	2500KVA Transformer Meter.

1	DS-1	Outdoor Switch Bvoard (65 KAIC)	480V, 3Φ, 3W, 4000 Amp Main Bus	0.023602	Non Walk-in Outdoor switchboard-sloped roof. 480V, 3Φ, 3W, 4000 Amp Main Bus, Ground Bus Cutler Hammer Power Line I. Switchboard 100% rated low voltage power. Circuit Breakers individually mounted distribution devices. Stainless steel enclosure.
2	DS 840	Circuit Breaker	4000AF / 4000 AT (LSI)	0.003	Protects 65 KAIC from high current
2	MP-1	Metering Package	-	0.00036	Connected to a Current Transformer. Measure current and voltage from the 65 KAIC switchgear.
2	CB-1	Circuit Breaker	1600AF / 1200AT	0.003	Protects KHS Can line Switchboard from high current
2	CB-2	Circuit Breaker	1600AF / 1200AT	0.003	Protect KHS Bottle Line from high current
2	CB-3	Circuit Breaker	800AF / 400AT	0.003	(MCC) Bottling Building and New Tunnel
2	CB-4	Circuit Breaker	1600AF / 1200AT	0.003	Protect Outdoor Power Panel WWTP, APT 2000 Amps from high current
2	CB-5	Circuit Breaker	800AF / 600AT	0.003	Protect Air compressors panel at refrigeration building
2	CB-6	Circuit Breaker	800AF / SPACE	0.003	Protect New PF Correction Capacitor from high current
2	EM10.1	Line Meter	-	0.00036	Can Line Meter
2	EM9.1	Line Meter	-	0.00036	New Glass Line Meter
2	EM12.5	Power Meter	-	0.00036	CB Lightning and Power meter
2	EM4.1	Transformer Meter	2500KVA	0.00036	Air compressor (#2 & #3) at 2500KVA transformer meter
2	BS-1	Bus Bar	4000 Amo Main bus	0.000802	Provides power to loads connected to it
1	PFCC	Capacitor	-	0.17443	Power Factor Correction

					Capacitor
1	EM10.2	Line Meter	-	0.00036	Measures power from the New Keg plant Swicthgear
1	KP	Switchgear	-		Keg Plant Switchgear
2	CB-8	Circuit Breaker	50A / 3	0.0023	Protects AVQ1-Q10 KZE KEG Liner from high current
2	CB-9	Circuit Breaker	40A / 3	0.0023	Protect AVQ1-Q14 KEG Line from high current
2	BS-2	Bus Bar	480V, 1200A	0.000802	Provides power to loads connected to it
1	WWTP,ATP	Switchgear	-		Switchgear for WWTP and ATP from high
2	CB-10	Circuit Breaker	1200A / 3	0.003	Protect swicthgear line bus
2	CB-11	Circuit Breaker	600A / 3	0.0023	Protect WWTP
2	CB-12	Circuit Breaker	250A / 3	0.0023	Protect ATP
2	BS-3	Bus Bar	480V, 1200A	0.000802	Provides power to WWTP and ATP loads
1	EM11.1	Meter	-	0.00036	WWTP Machinery and Lightning Equipment Meter
1	EM12.7	Meter	-	0.00036	Supply Chain Lightning And Power Meter
1	L-X	Lines	-	0.00923	Interconnecting Lines (failure rate is per 1000 ft)
1	TR-X	Line Terminations	-	0.00127	Line Terminations

Table 3.2 India's Brewery Component and Failure Rate Data for Section II

SYSTEM: 4200KVA SUBSTATION NONE LINE DATE: 07/20/2009

IDENTURE LEVEL: 1 & 2

REFERENCE DRAWING: E1-01-REV 71409

IND LEV	ID #	ITEM/FUNCTIONAL IDENTIFICATION	RATINGS	FAILURE RATE (λp)	ITEM DESCRIPTION
1	T-2	Transformer	38KVΔ , 3000 / 4200KVA , 480Y / 277V , Z=6.5%	0.0059	Δ-Y Main Power Transformer supply power to distribution system.

1	EM1.1	Transformer Meter	4200 KVA	0.00036	4200 KVA Transformer Meter
1	CB-13	Circuit Breaker	3000A / 3P	0.003	Protects 3000Amps ATS from high current
1	CB-14	Circuit Breaker	1000A / 3P	0.003	Protects existing Brew House Swicthboard (65 KAIC)
1	ATS	Swicth	3000A	0.03187	Switch between standby generator and CU bus Bars
1	CB-16	Circuit Breaker	-	0.003	Protects 2000 KVA Standby Generator
1	SG	Standby Generator	2000 KVA	0.63299	Standby Diesel Generator
1	CB-15	Circuit Breaker	400A / 3P	0.0023	Protects power transformer
1	PFC	Power Factor Capacitor	840 KVAR	0.17443	Provides Power Factor Correction
1	CB-17	Circuit Breaker	2000A / 3P	0.003	Protects Grasso Switchboard
1	BS-4	Bus Bar	-	0.000802	Provides power to 1600 Amps main switchboard and Grasso Switchboard
1	MLS	Swicthboard	1600A	0.006102	1600A Main Lugs switchboard non walk-in outdoor. Satinless steel enclosure.
2	BS-5	Bus Bar	-	0.000802	Provides Power to compressor #1, dryer #1 in refrigeration building and boiler room.
2	CB-18	Circuit Breaker	1200A / 3P	0.003	Protects Compresor 1 and Atlas 1 in the refrigeration building
2	CB-19	Circuit Breaker	400A / 3	0.0023	Protects Boiler Room
1	EM2.1	Meter	-	0.00036	Grasso Refrigeration Utility Meter
1	EM6.1	Meter	-	0.00036	Steam Generation Utility Meter
1	GS	Swicthboard	-		Grasso Switchboard
1	BHS	Switchboard	65 KAIC	0.024502	Existing Brew House Switchboard (65 KAIC)
2	BS-6	Bus Bar	-	0.000802	Provides power to loads connected Brewhouse 65 KAIC Switchboard
2	CB-20	Circuit Breaker	-	0.0023	Protect entire Brew House switchboard
2	CB-21	Circuit Breaker	800A / 3	0.003	Protects Old Keg Plant. Shall be eliminated once the NBB Starts
2	CB-22	Circuit Breaker	100A / 3	0.0023	Protect Brew House equipment. Will remain until the decomission of line #1 and #2 and the Keg Plant.

2	CB-23	Circuit Breaker	300A / 3	0.0023	Protect Brew House Lightning. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-24	Circuit Breaker	150 / 3	0.0023	Protect Grain Storage Silos. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-25	Circuit Breaker	-	0.0023	Protect WT Lightning panel. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-26	Circuit Breaker	-	0.0023	Protects supply chain warehouse. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-27	Circuit Breaker	-	0.0023	Protect Technical Services. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-28	Circuit Breaker	-	0.0023	Protect Engineering Offices. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-29	Circuit Breaker	-	0.0023	Protect Administration Offices. Will remain until the decomission of line #1 and #2 and the Keg Plant.
1	EM7.1	Meter	-	0.00036	Brew House Equipment and Machinery Meter
1	EM12.3	Power Meter	-	0.00036	Brew House Lightning and Power Meter
1	EM12.9	Power Meter	-	0.00036	Grain Storage Silos and Lightning and Power Meter
1	EM12.2	Power Meter	-	0.00036	WT Lightning and Power Meter
1	EM12.7	Power Meter	-	0.00036	Supply Chain Lightning and Power Meter
1	EM12.10	Power Meter	-	0.00036	Engineering Lightning and Power Meter
1	EM12.10	Power Meter	-	0.00036	Engineering Lightning and Power Meter
1	EM12.1	Power Meter	-	0.00036	RB Lightning and Power Meter
1	42-SG	Swicthgear	42 KAIC	0.021722	42 KAIC Switchgear
2	BS-7	Bus Bar	-	0.000802	Provides Power lo loads connected to the 42 KAIC Switchboard

2	CB-30	Circuit Breaker	150 / 3	0.0023	Protects Infirmary Cooperative Main Gate
2	CB-31	Circuit Breaker	-	0.0023	Protects LP-TF-02 BMS Future
2	CB-32	Circuit Breaker	150 / 3	0.0023	Protects PP-RB and LP-CB
2	CB-33	Circuit Breaker	400 / 3	0.0023	Protects Haffmans CO2 Recovery Plant Refrigeration Building
2	CB-34	Circuit Breaker	500 / 3	0.0023	Protects Filtration Building Ziemann Power Panel
2	CB-35	Circuit Breaker	400 / 3	0.0023	Protects Water Treatment Ziemman Power Panel
2	CB-36	Circuit Breaker	150 / 3	0.0023	Protects LP-FB
2	CB-37	Circuit Breaker	50 / 3	0.0023	Protects MIS & Phone Switchboard Future
2	EM1.13	Meter	-	0.00036	Main gate Meter
2	EMXXX	Meter	-	0.00036	BMS Futute Meter
2	EM3.1	Meter	-	0.00036	CO2 Recovery and Distribution Utility Meter
2	EM8.1	Meter	-	0.00036	Filtration Equipment Meter
2	EM5.1	Meter	-	0.00036	New Water Treatment Plant Meter
2	EM12.4	Power Meter	-	0.00036	FB Lightning and Power Meter
2	EM12.13	Meter	-	0.00036	MIS and Phone Swicthboard Meter
1	EM12.1	Meter	-	0.00036	RB Lightning and Power Meter
1	EM12.5	Meter	-	0.00036	CB Lightning and Power Meter
1	EM14.2	Transformer Meter	-	0.00036	Air Compressor Transformer Meter
1	REF-S	Swicthboard	-	0.007702	ATLAS COPCO in Refrigeration Building
2	BS-8	Bus Bar	-	0.000802	Provides power to compressor #1, dryer #1 in refrigeration building.
2	CB-38	Circuit Breaker	400 / 3	0.0023	Protects Refrigeration Building Switchboard
2	CB-39	Circuit Breaker	250 / 3	0.0023	Protects Compresor #1
2	CB-40	Circuit Breaker	50 / 3	0.0023	Protects Dryer #1
1	L-X	Lines	-	0.00923	Interconnecting Lines
1	TR-X	Line Terminations	-	0.00127	Line Terminations

3.1.2 Failure Mode Effect Analysis (FMEA)

The next step is to think about all failure modes that could possibly affect this power system. The failure mode effect analysis (FMEA) is performed here to determine potential failure modes within the power system design. The idea is to address those issues on the early stages of the design, therefore enhancing reliability through the design process. Since India brewery power distribution system is undergoing several design changes during these days, it is considered important to perform a failure mode analysis on those new designs.

In order to start this analysis we used the template shown in figure [3-1] and followed several steps described in this section.

FAILURE MODE AND EFFECT ANALYSIS

SYSTEM: ______________ DATE: ______________
IDENTURE LEVEL: ______________ SHEET: ______________
REFERENCE DRAWING: ______________ COMPILED BY: ______________
MISSION: ______________ APPROVED BY: ______________

IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION	FUNCTION	FAILURE MDOES AND CAUSES	MISSION PHASE/ OPERATIONAL MODE	FAILURE EFFECT			COMPENSATING PROVISIONS	SEVERITY CLASS	COMMENTS /REMARKS
					LOCAL EFFECTS	NEXT HIGHER EFFECT	END EFFECTS			

Figure 3-1 Failure Mode Effect Analysis (FMEA) Template

First, an identification number has been assigned to each component in the design to facilitate their location. Then, we proceed to list the items with its functions. In this case the items are components so they are listed in a logical manner under the subsystem. It is important to understand the process and it functions to simplify the analysis. After that, all failure modes and causes are identified for each component. A failure mode is an event which initiates the physical process of deterioration that will end in a failure. A failure cause is basically defined as a design weakness that might result in that failure. The failure modes and its potential causes are identified and documented on the FMEA spreadsheet (shown in Appendix C). After identifying all potential failure modes, a probability factor known as the alpha number is assigned to each failure mode. This number tells us how likely that failure can occur. Figure [3-2] presents a FMEA portion for one component (In this case a power transformer). From this example it can be seen that a transformer can fail in three main different ways; open, short or parameter change. And it can also be seen that each failure mode has an alpha number assigned to it. This alpha number as we said represent the probability of occurrence for that specific failure mode. The alpha number should add to one for each component analyzed.

ID NUMBER	ITEM/FUNCTIONAL IDENTIFICATION	FUNCTION	FAILURE RATE (λp)	FAILURE MODES AND CAUSES	FAILURE MODE RATIO (α)
T-1	Transformer	Δ-Δ Main Power Transformer supply power to distribution system.	0.0062	Fails Open	0.42
T-1	Transformer	Δ-Δ Main Power Transformer supply power to distribution system.	0.0062	Fails Short	0.42
T-1	Transformer	Δ-Δ Main Power Transformer supply power to distribution system.	0.0062	Parameter change	0.16

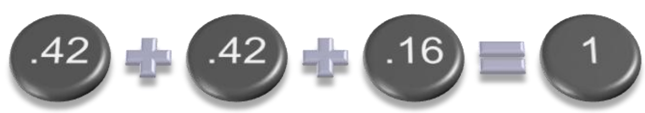


Figure 3-2 FMEA portion example to show alpha numbers must add to one.

After gathering all this data, a list of failure mode effects is created. In other words, for each failure mode an ultimate effect is determined. A failure effect is the consequence a failure mode has on the operation, function or status of an item. Also a numerical ranking is specified for the severity of each effect. In this case we use the ranking scheme listed in table 3.3. The intent of the ranking is to help us determined whether a failure would be a minor nuisance or a catastrophic occurrence that could imply loss of production.

Table 3.3 Table 3.3 Severity Classification Definition

Severity Class	Severity Definition
I - Catastrophic Failure	May cause death or system loss.
II - Critical Failure	May cause severe injury, major property damage, or major system damage which will result in a mission loss.
III - Marginal Failure	May cause minor injuries, minor property damage, and minor system damage which will result in delay or loss of availability or mission degradation.
IV - Minor Failure	Not serious enough to cause injury, property damage, or system damage, but will result in unscheduled maintenance and repair.
V - Non Effect Failure	A failure that does not affect the system in any way because is a failure of a component that is not mission critical.

Then we proceed to identify the compensating provisions which are the redundant component provided in order to avoid those failure modes. Finally, to complete the FMEA we have determined the recommended actions to address potential failures that might be critical.

3.1.3 FMECA Analysis Results

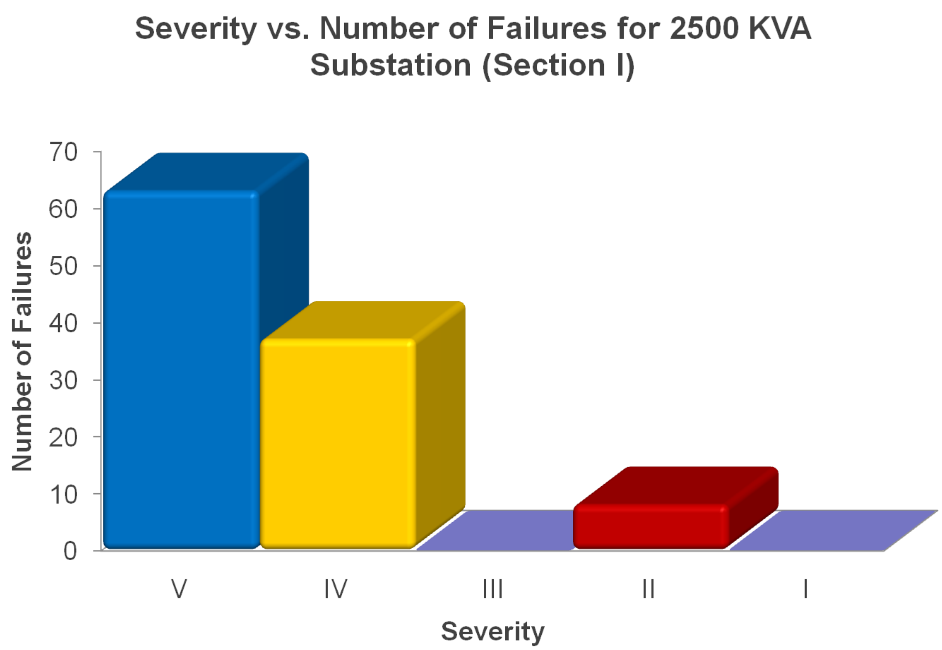


Figure 3-3 FMEA Severity vs. Number of Failures for 2500 KVA Substation.

From the Failure Mode Effect Analysis we have obtained several results. The first sets of results are presented in figure [3-3] above and figure [3-4] below. Figure [3-3] is a graphical representation of the failure modes and criticality distribution for the 2500 KVA substation (Section I). This helps us understand the reliability behavior of the system in terms of failure criticality. In other words, this shows how many failures are causing critical effects that are not being mitigated. Recall from table 3.3 the severity definitions, failures with severity below three needs to be targeted and there is a need to provide some kind of redundant or standby configuration to mitigate them. From this figure it can be seen that for the 2500 KVA Substation we have 63 failures with criticality V, 37 with severity level IV, 8 with severity II and zero failures with severities III or I.

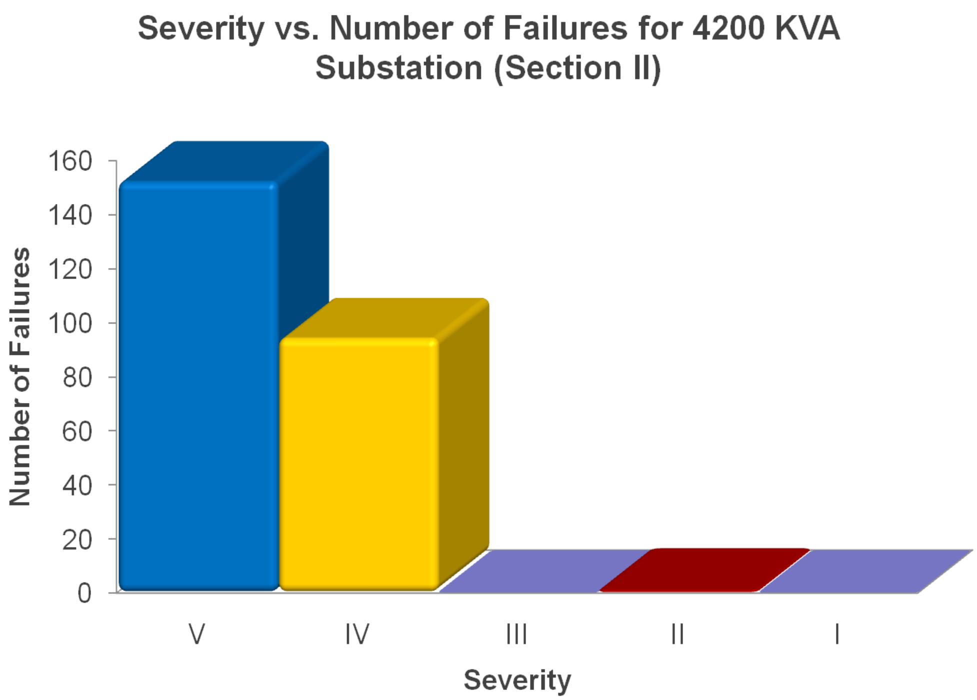


Figure 3-4 FMEA Severity vs. Number of Failures for 4200 KVA Substation.

The same way figure [3-4] is a graphical representation of the failure modes and severity distribution for the 4200 KVA substation (Section II). From this figure it can be seen that for the 4200 KVA Substation we have 152 failures with severity levels V, 94 with severity IV, 1 with criticality II and zero failures with criticalities III or I. For the 4200KVA there are some failures that might cause damage or partial loss on the system, that correspond to a severity level III. This severity is not reflected here because the system provides redundancy to mitigate them so they are now severity level IV. The idea of these plots is to target those failures causing severities lower than three and provide with design changes in order to mitigate those failures.

3.1.4 Markov State Diagram Analysis

Since we now know that it is not practical and highly difficult to state all differential equations for all subsystems we proceed to find a tool that help us in the process of calculating the reliability number for a Markov system. We have chose CARMS software to perform this task. Figure [3-5] below shows the conventional Markov Model Method vs. CARMS approach. As it is seen from figure [3-5] it is much easier to use CARMS approach since it avoids the need to solve differential equations and the need to look for a tool to obtain graphical and statistical results.

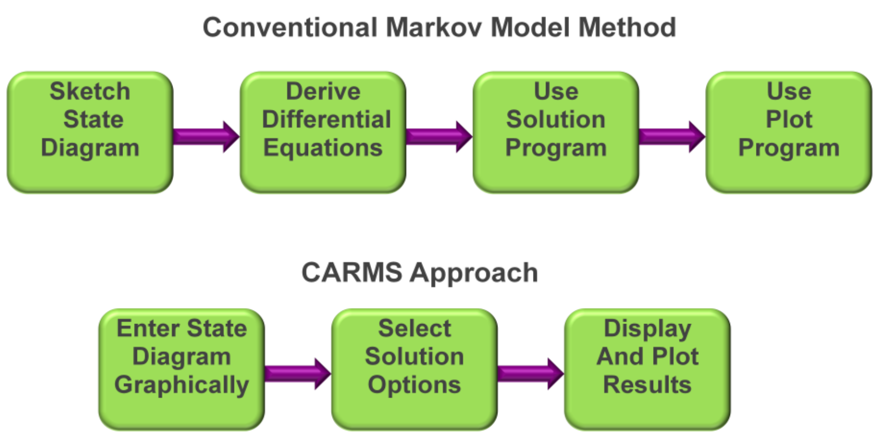


Figure 3-5 Approaches to creating Markov model.

3.2 BlockSim Software Analysis

Now we will proceed to perform a series of simulations using BlockSim Software. BlockSim allows us to perform complex system reliability, maintainability and availability analysis and optimization using reliability block diagram (RBD) approach, a fault tree diagram (FTD) approach or a combination of both. BlockSim allows us to analyze India's brewery power distribution systems to obtain approximate system reliability results, to calculate the optimum scenario to meet systems reliability goals and to obtain systems reliability, availability and throughput results to discrete event simulations.

It is necessary to understand that the RBD method has certain limitations. This is because the RBD method cannot always provide the required reliability and fail safety information that is required to perform fault tolerant system studies. One of the drawbacks that we need to recognize is that RBD method only represent two states per component (i.e. good and failed), whereas redundancy analysis usually requires the representation of multiple states. For example, reliability block diagrams are incapable of handling time dependent redundancy configurations, such as stand by with switching, load sharing, and many others. It is seen how difficult is to track up the logic of the system design with this method. Calculation using RBD approach were used because is very simple, understandable, well known and usually easy to evaluate. Also this method is used as an initial starting point in reliability analysis and as a reference to compare with Markov method results.

3.2.1 BlockSim Simulation and Results

To start the reliability analysis using this tool we have already drew the blocks and has defined them with the reliability characteristics of each component of the system. Then, these blocks are configured into a reliability block diagram (RBD) that represents the reliability wise configuration. These block diagrams for all sections comprehending our system are presented in Appendix A. Each of the RBD diagrams is analyzed in order to determine the reliability function of the entire system. This analysis is then used to create plots that will be presented and explained throughout this section.

As a first approach to this analysis the exponential failure distribution has been used. This distribution is a good approximation for the long flat portion of the bathtub curve (refer to Figure [3-6]). The majority of the component or the system lifetime is located on that portion of the bathtub curve; therefore this justifies the frequent use of the exponential distribution, where early failure and wear out has not been taken into consideration. Frequently, a curve is mathematically approximated by piecewise straight lines which make calculations a lot easier. In our case the failure rate curve is approximated by constant rates that are the average of the actual changing rate during the respective time duration. Based on that fundamental theory we can approximate any bathtub curve by exponential distribution segments. It's important to explain every plot obtained using this model in order to have good understanding and to better compare with Markov method.

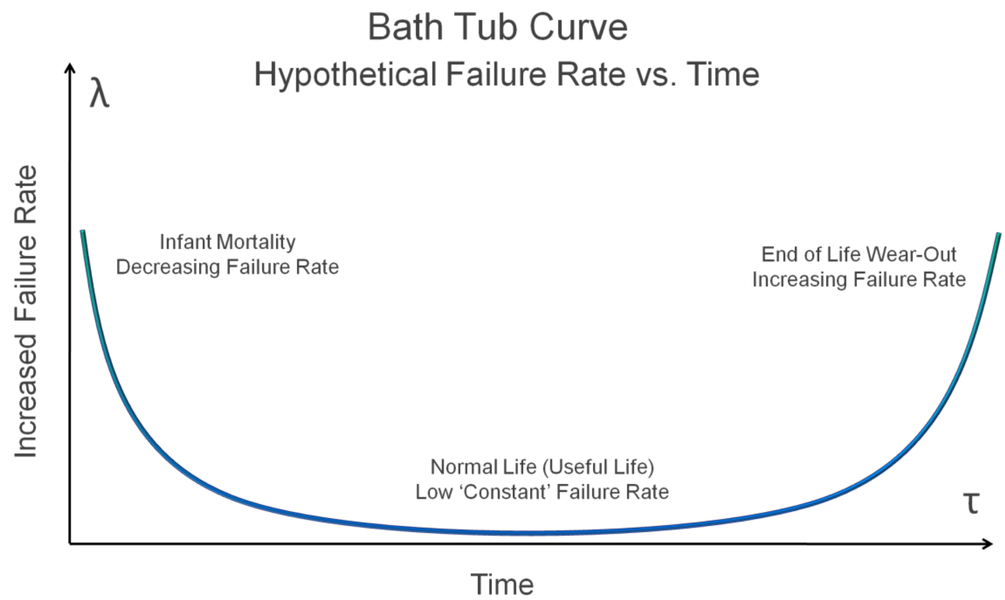


Figure 3-6 Bath Tub Curve

The first set of plots (figure [3-7] to figure [3-8]) corresponds to the analysis of the 2500 KVA substation excluding the failure rate of the utility. Since the utility is not part of the India's power distribution systems design. This has been done to analyze the impacts of the system component failure rates without the effect of the utility failure rate. The utility failure rate is so big that all other failure rates get buried in it and is difficult to see the real impact of the system components alone. Figure [3-7] tells us how reliable 2500 KVA substation supplied power is through time (excluding the effect of the utility failure rate). At year zero we have a reliability value of one because at the beginning of the system's life the reliability is basically perfect. As years pass by it can be seen and exponential decreased in the reliability value of the system such that at year 50 the reliability has decreased 30%. If we were to improve this numbers we need to add repair procedures for each component as well as to add redundancies in critical areas of the system. Figure [3-8] show the unreliability vs. time plot for the 2500 KVA which tells us how unreliable this power system is as time goes by. As it can be seen from figure [3-8], the unreliability of the system at zero years is zero; this is because at zero years the power system is supposed to be perfectly reliable. Through the years the unreliability of the system increased to the point that in 50 years the unreliability of the system has increased exponentially to 70%. If we combined how much our reliability has decreased in 50 years and how much the unreliability has increased in 50 years we have 100% of the total probabilistic distribution of the system. This is another way to prove that the reliability and unreliability complements each other (Unreliability = 1-Reliability).

The next set of plots (from figure [3-9] to figure [3-10]) corresponds to the same 2500KVA substation but this time including the effect of the utility failure rate. Figure [3-9] is a plot of reliability vs. time of this section with utility included in the analysis. As it can be seen from this figure the reliability of the system decrease exponentially over time and the system becomes completely not reliable after 3 years. If we compare this plot to the one excluding the utility we can appreciate the big impact that the utility failure rate has on the system. With the utility failure rate on the analysis the system become completely unreliable after three years while if we exclude the utility from the analysis it can be seen from figure [3-7] that the system becomes unreliable after fifty years. This is due to the failure rate of the utility which reliability value lays around 1.95, when the average failure rates of the others are in the order of .006. The next plot to discuss here will be the unreliability vs. time plot for the 2500 KVA substation including utility. One of the characteristics of the system unreliability curves is the constant increase with time. For example, from figure [3-10] it can be seen that when the time goes from t=.5 to t=1year the system is 23% less reliable. To suppress the continue increase of the unreliability curves we must provide preventive and corrective maintenance to the system. This has not been considered for this engineering project since that portion of the analysis belongs to a maintainability analysis. Basically these curves tell us how many years will take for the system to collapse if no maintenance is required. It can be seen from section one that the Utility will fail completely in 2.5 years. If power generation from utility is lost; then all distributed power will be lost to all load points. This event will induce a decrease in the overall reliability of the power distribution system. By providing standby redundancies to the system, if the utility fails completely we can make our system to last an additional 2.5 years. This will increase the reliability of the system, therefore decreasing the unreliability of the system.

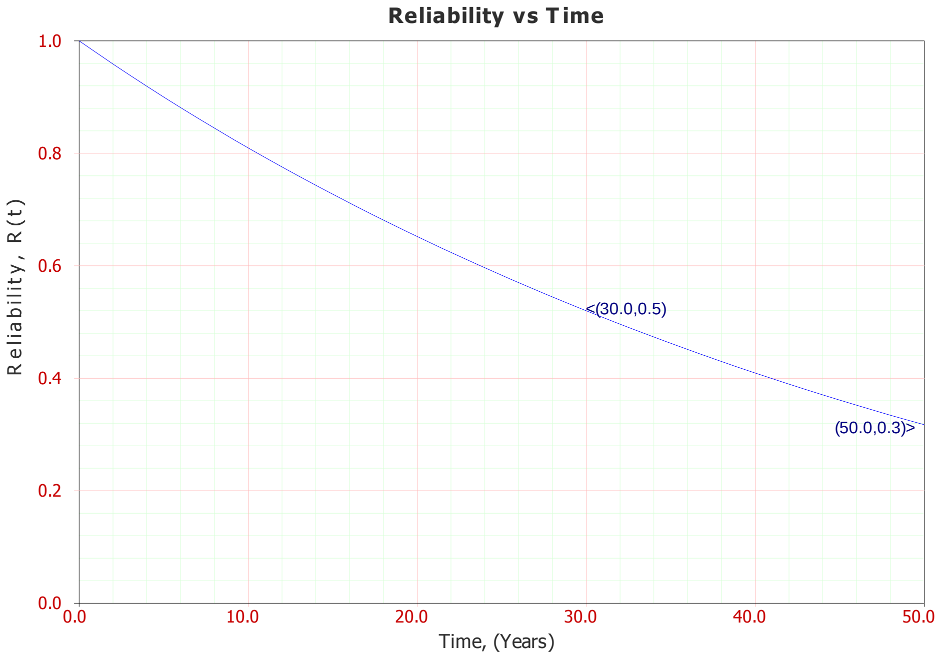


Figure 3-7 Reliability vs. Time plot for 2500 KVA SUB (without utility

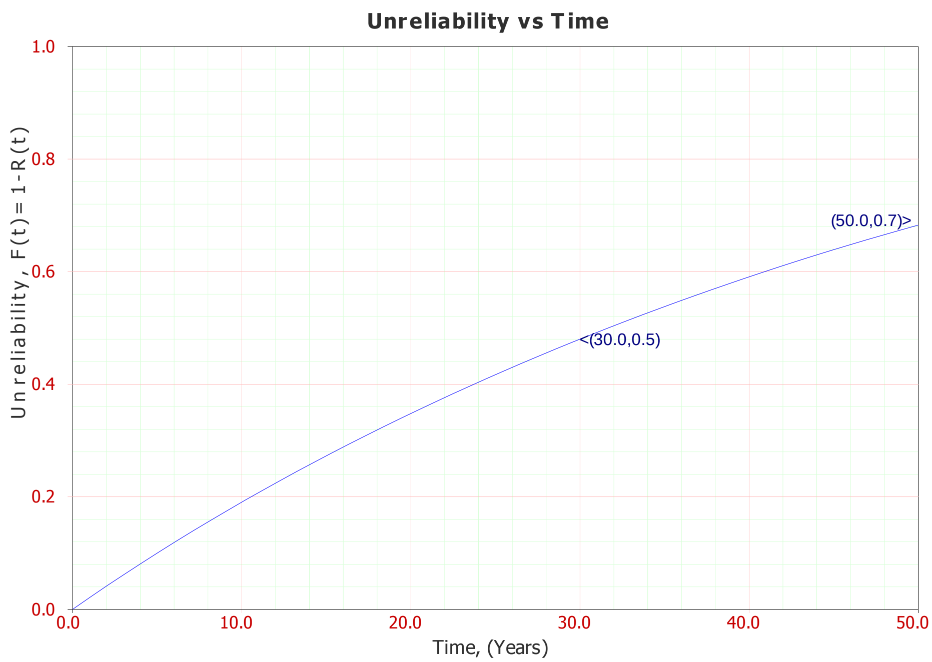


Figure 3-8 Unreliability vs. Time plot for 2500 KVA SUB (without utility)

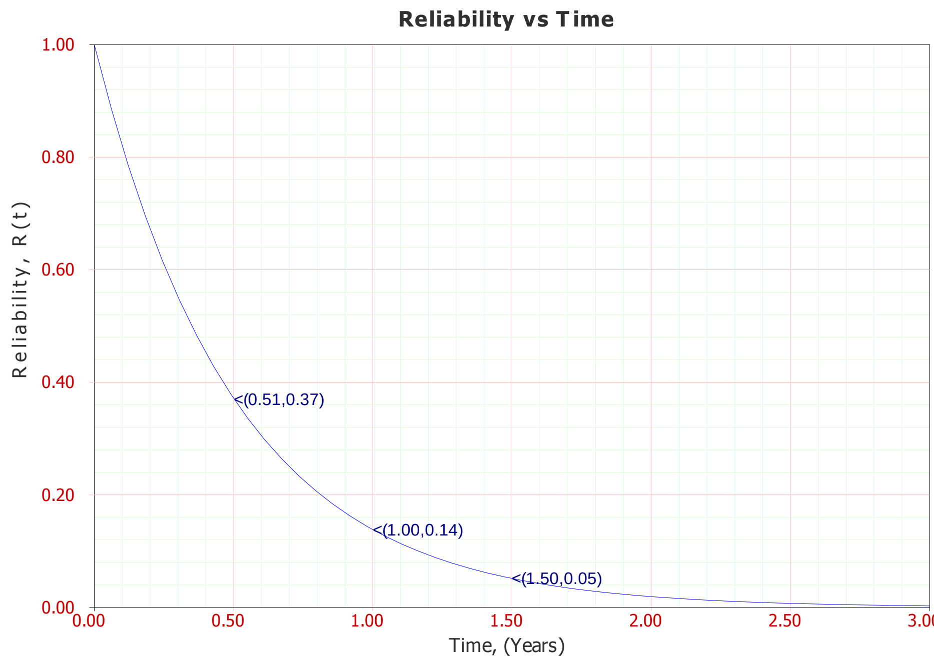


Figure 3-9 Reliability vs. Time plot for 2500 KVA SUB (including utility)

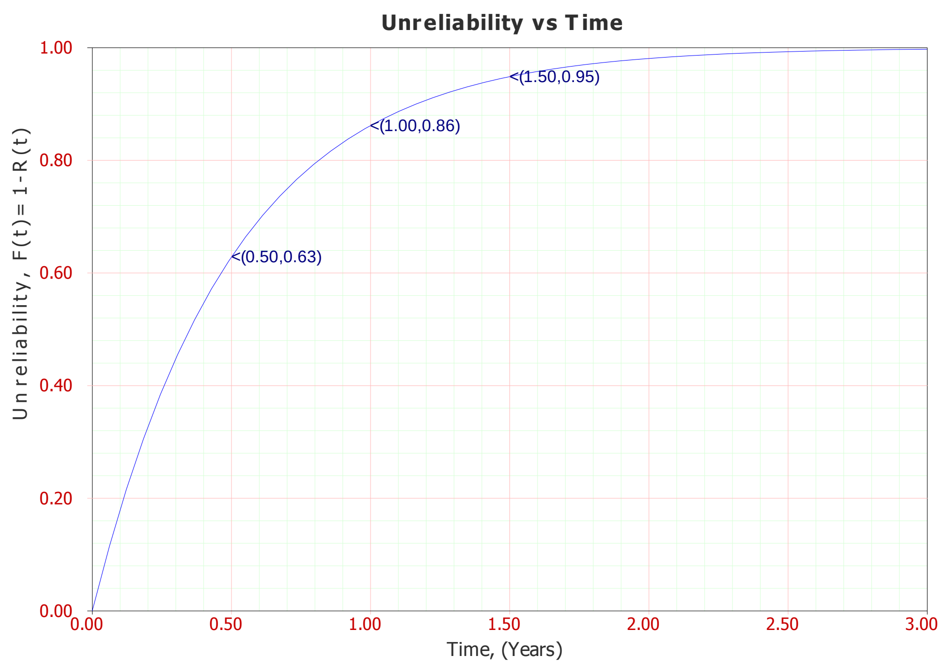


Figure 3-10 Unreliability vs. Time plot for 2500 KVA SUB (including utility)

Now that we have analyzed our first section of the system (2500KVA Substation) using BlockSim, we proceed to explain the plots for the second section of our system (4200KVA Substation). Just as it was done for the first section, the first set of plots that correspond to the analysis of the 4200 KVA Substation excluding the effect of the utility is going to be explained. Figure [3-11] show us the reliability curve for a case where the utility is considered 100% reliable, and then the reliability of the system for 30 years and 50 years are 47% and 22% respectively. In Figure [3-12] it’s possible to see how unreliable the system will be for the first 50 years, based on the assumption that the utility is 100% reliable on that period of time, then it can be seen that at 30 years the system is 53% unreliable and at 50 years the system will be 78% unreliable. As we already know the 4200 KVA Substation has the peculiarity of having a diesel generator that is redundant to the utility. When comparing the unreliability plots of both (figure [3-8] corresponding to 2500KVA substation and Figure [3-12] corresponding 4200KVA substation) you may think that the 2500 KVA Substation (section one) is more reliable than the 4200 KVA Substation (section two) when a 100% reliable utility is assumed. But it has to be considered that both are different systems with different configurations. For example, the 4200KVA substation has more components and also has a redundant diesel generator which adds more failure rates to the calculations. These calculations were made just to see how reliable was the power distribution design circuit without taking in to consideration the utility, which is the same as saying that the utility is 100% reliable at any time. But if you make the analysis when the utility is included as an item that can fail for both systems, it's possible to see that the 4200KVA Substation (shown in figure [3-14]) is more reliable than the 2500KVA Substation due to the redundant configuration. From these analyses it can be seen that at three years the 2500KVA Substation is totally unreliable while for the 4200KVA Substation it takes 8 years to become completely unreliable.

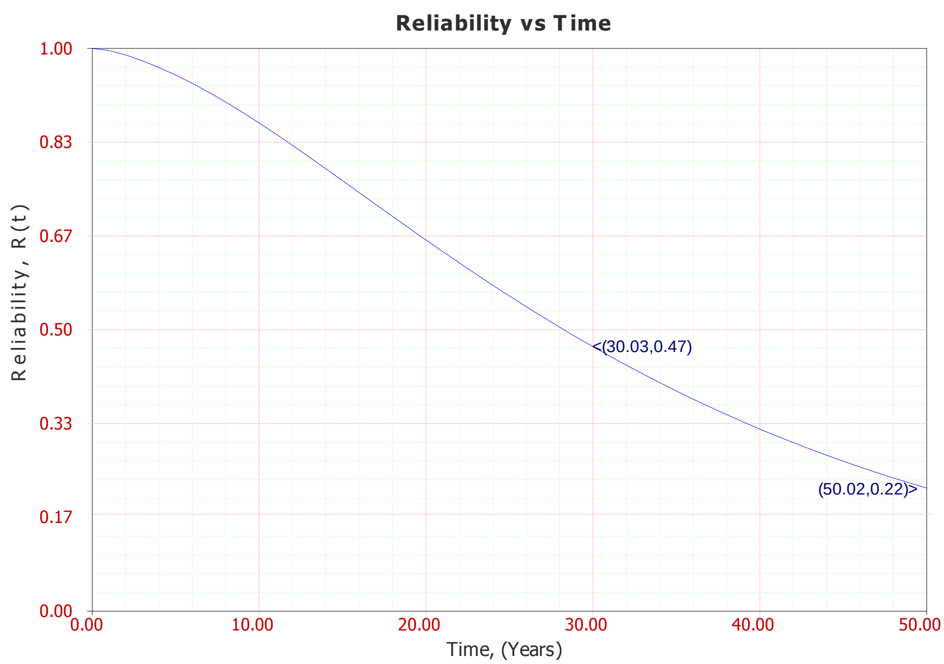


Figure 3-11 Reliability vs. Time Function plot for 4200 KVA SUB (without utility)

Figure 3-12 Unreliability vs. Time Function plot for 4200 KVA SUB (without utility)

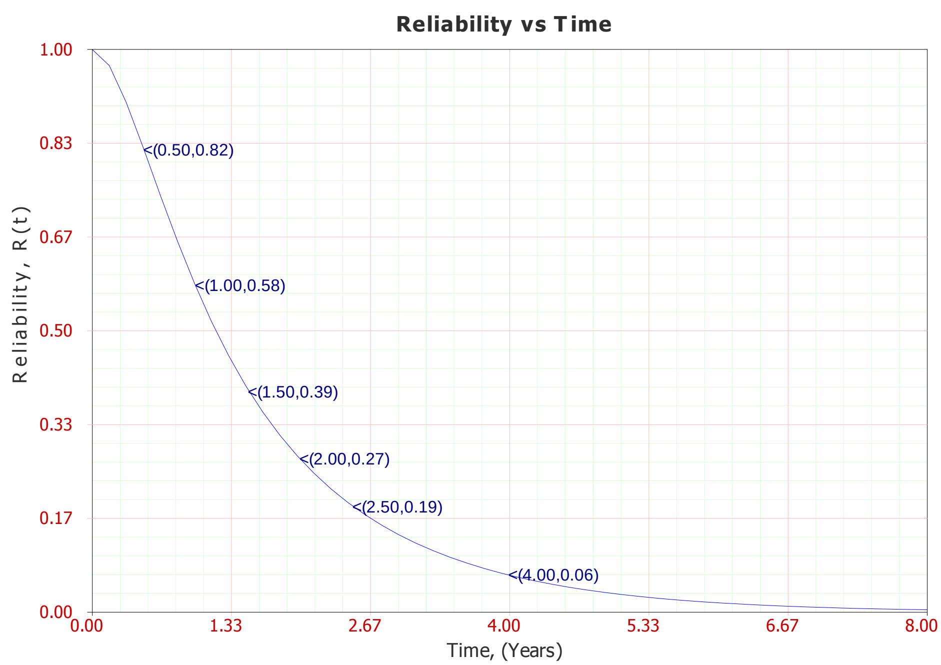


Figure 3-13 Reliability vs. Time Function plot for 4200 KVA SUB (including utility)

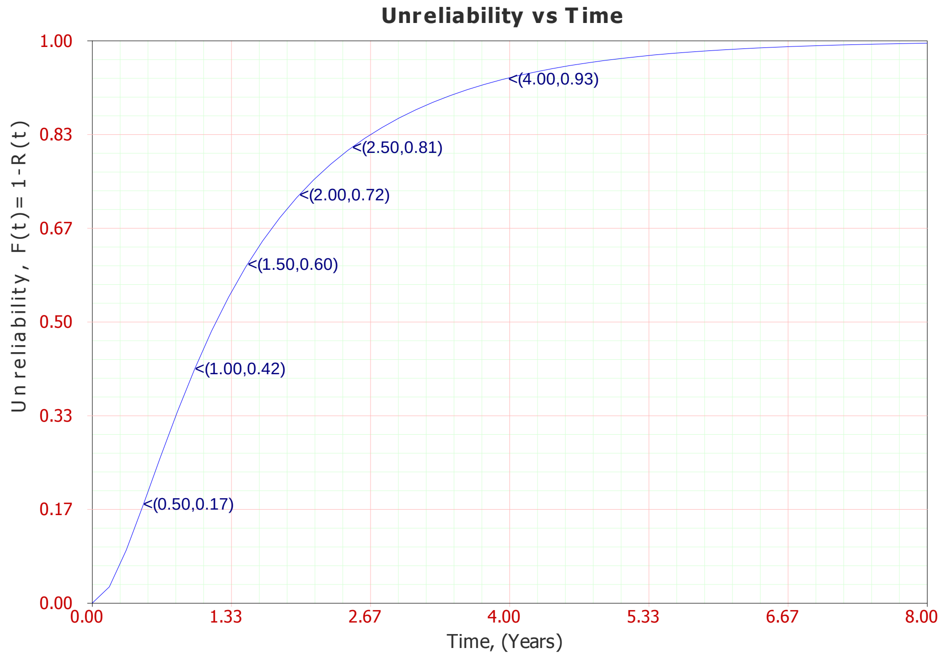


Figure 3-14 Unreliability vs. Time Function plot for 4200 KVA SUB (including utility)

3.3 CARMS Analysis

CARMS which stand for Computer Aided Rate Modeling and Simulation is an integrated tool that permits us to perform a reliability and availability evaluation. This tool is well suited to analyze India's Power distribution system reliability because this system is a fault tolerant design. CARMS is based on the discrete space, continuous time Markov Model and it compute the likelihood of events based on a probabilistic model that we, as a user, have defined.

3.3.1 Reliability Block Diagram for CARMS Analysis

To start the reliability analysis using this tool the first step will be to draw blocks and defined them with the reliability characteristics of each component. After this, the blocks are configured into a reliability block diagram (RBD) that represents the reliability wise configuration. This diagram shows major components as blocks interconnected together by lines that indicate how the components are related. To simplify the analysis and to make it more understandable we have divided the system in subsystems and have constructed the RBD for each portion. Figure [3-15] shows the Reliability Block Diagrams with its specifications for Section I (4200 KVA Substation). This RBD correspond to the one line diagram for section I shown in figure [3-16].

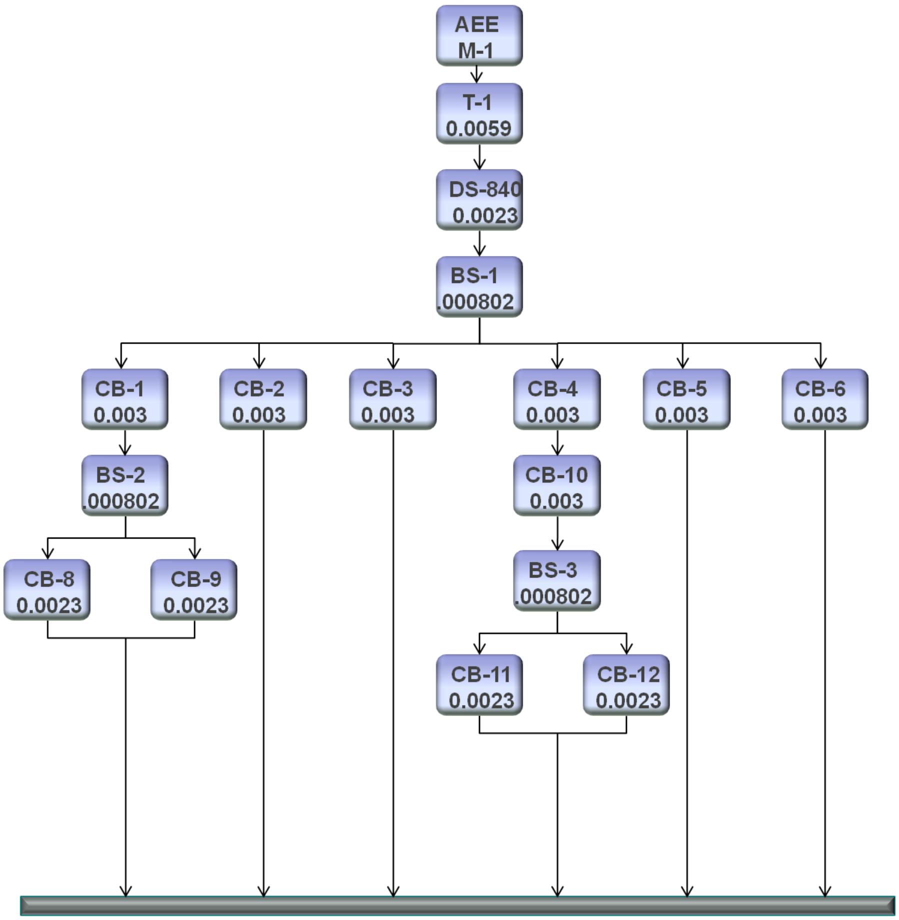


Figure 3-15 RBD for 2500 KVA Substation

From this block diagram it can be appreciated the series and parallel relationship between components. It is also seen that if transformer #1 (T-1), switchgear main circuit breaker (DS-840) or the main bus bar (BS-1) fails, the system lose power to every load. The original power distribution design for this 2500 KVA section (shown in figure [3-7]) does not provide redundancies to mitigate the critical effect that the system will experience if those components mentioned above fails. This fact affects the reliability of the overall system.

The other thing that we can observe from this RBD is that either of the circuit breakers on the lower paths needs to fail in order to lose power to any particular load. A failure in any of these circuit breakers means that the system will operate in degraded mode, but it does not mean that we will lose power to all loads or that the entire system is down.

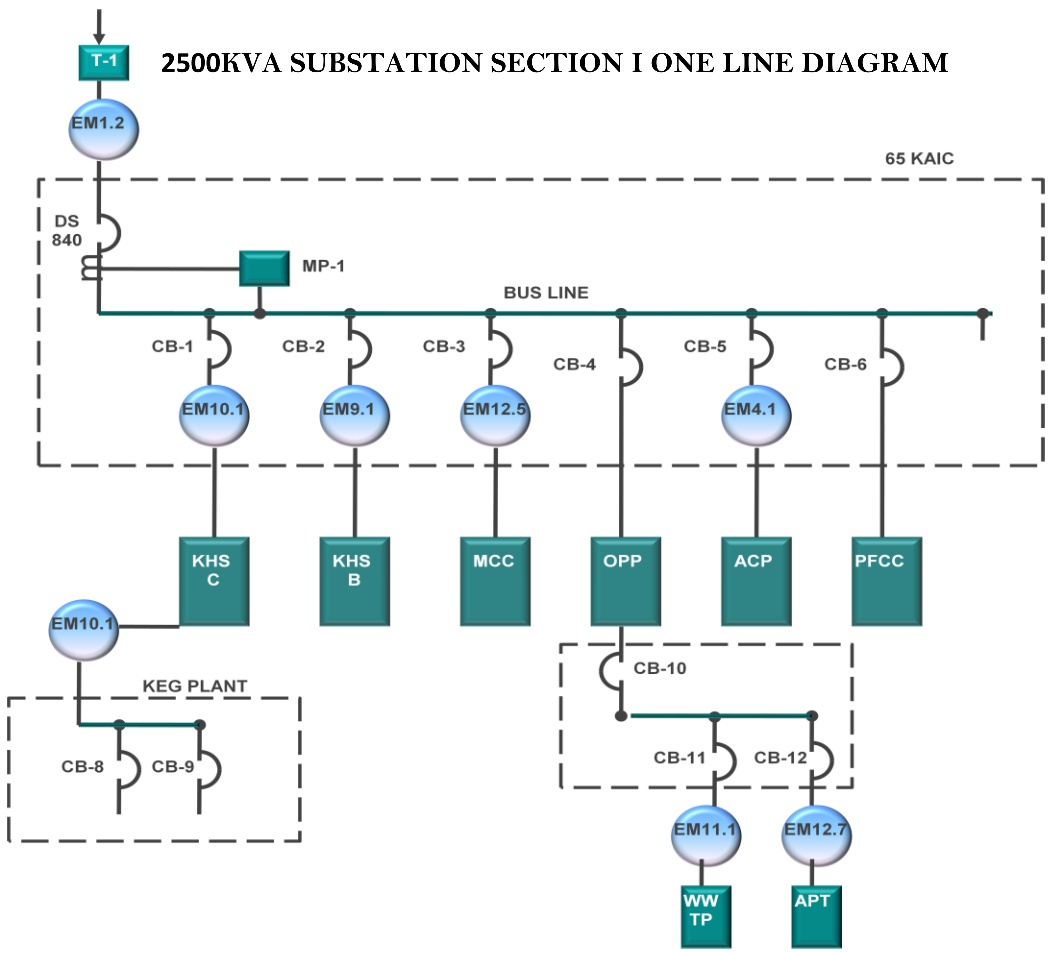


Figure 3-16 2500 KVA One Line Diagram. Taken from Appendix A

Because of the complexity of the system we have subdivided section II of the One Line Diagram in three circuits: A, B and C. This was done to facilitate the understanding of our analysis. Figure [3-17], shows the Reliability Block Diagrams with its specifications for Section II circuit A. This RBD correspond to the one line diagram for section II circuit A shown in figure [3-18].

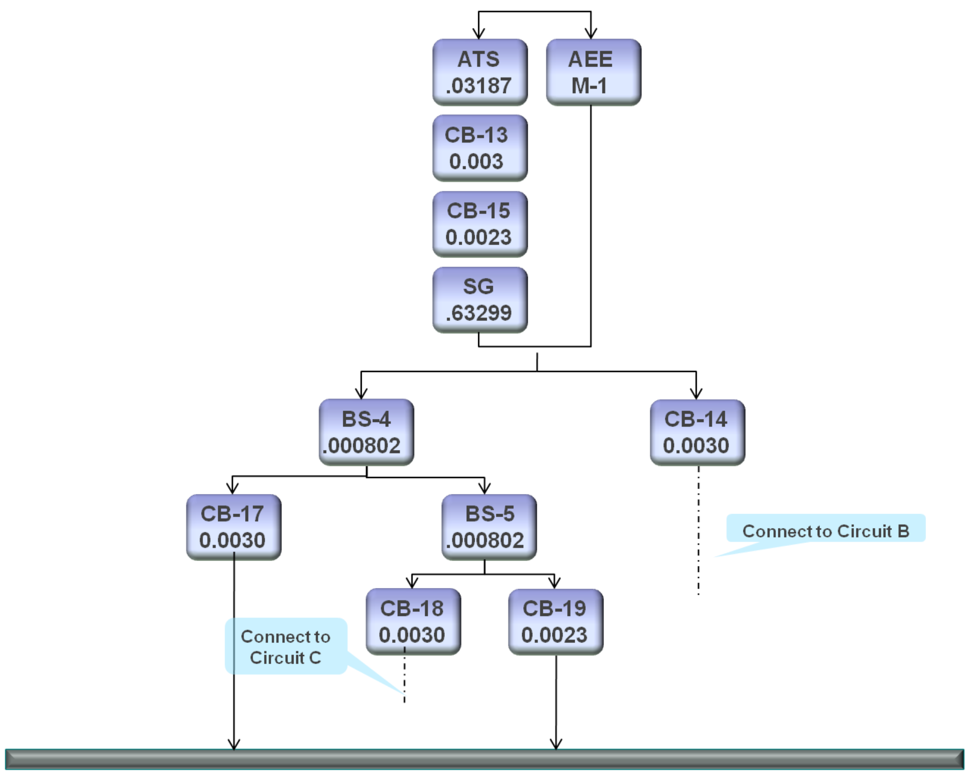


Figure 3-17 RBD for 4200 KVA Substation for Circuit A

From this RBD it can be seen that the design provides a standby generator (SG) as a redundant mean in case main power from the authority fails. Power from the Authority and the standby generator are in a parallel configuration because both will need to fail in order to have the whole system down. Also if we lose the Bus Bar (BS-4) power supply is interrupted to the majority of the loads. The same way, if CB-14 fails power is interrupted to the 65 KAIC Brew house switchboards and no redundancy is provided to mitigate this problem.

4200KVA SUBSTATION SECTION II CIRCUIT A ONE LINE DIAGRAM

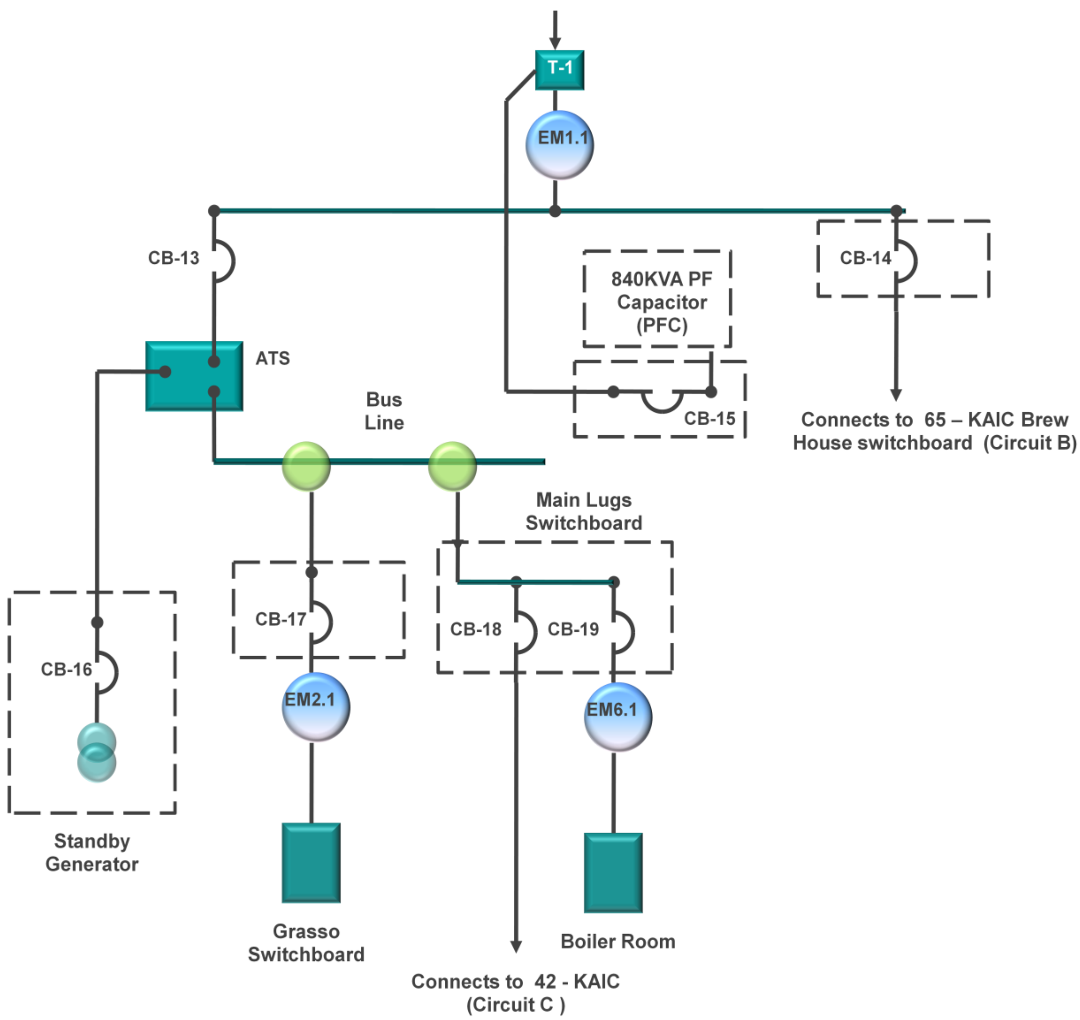


Figure 3-18 4200 KVA One Line Diagram for Section II Circuit A. Taken from Appendix A

Figure [3-19], shows the Reliability Block Diagrams with its specifications for Section II circuit B. This RBD correspond to the one line diagrams for section II circuit B shown in figure [3-20].

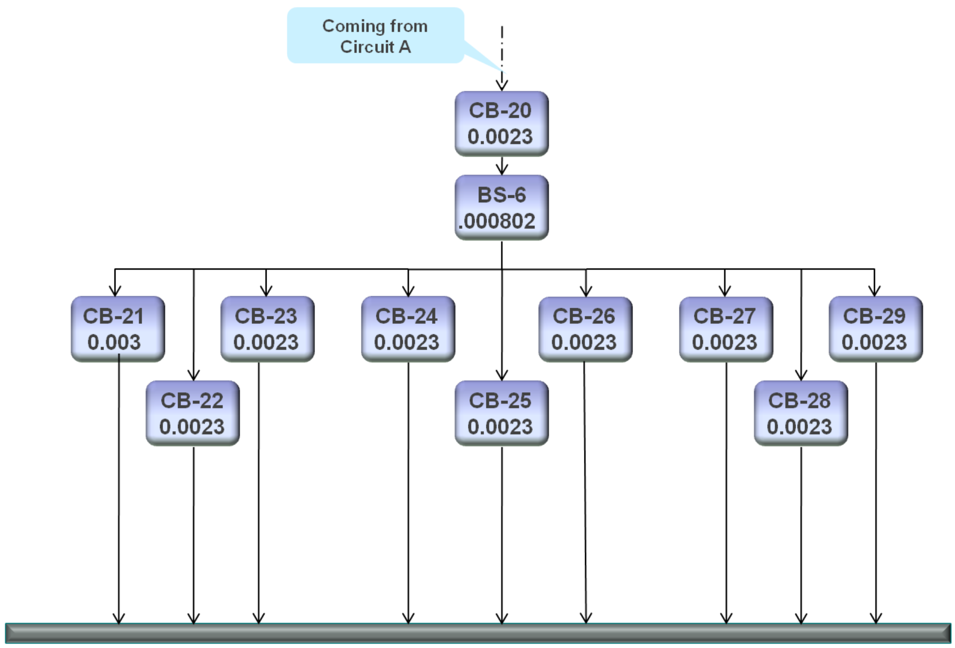


Figure 3-19 RBD for 4200 KVA Substation for Circuit B

From this RBD we can see that each circuit breaker on the lower paths (CB-21 to CB-29) are redundant to the main circuit breaker (CB-20). That means for example, if main circuit breaker fails to open when needed, all of the circuit breakers on the lower paths will open in order to protect their respective loads. Also, if any of the circuit breaker on the lower paths fails to open when needed then the main circuit breaker will open, interrupting power supply, in order to protect the system.

4200KVA SUBSTATION SECTION II CIRCUIT B ONE LINE DIAGRAM

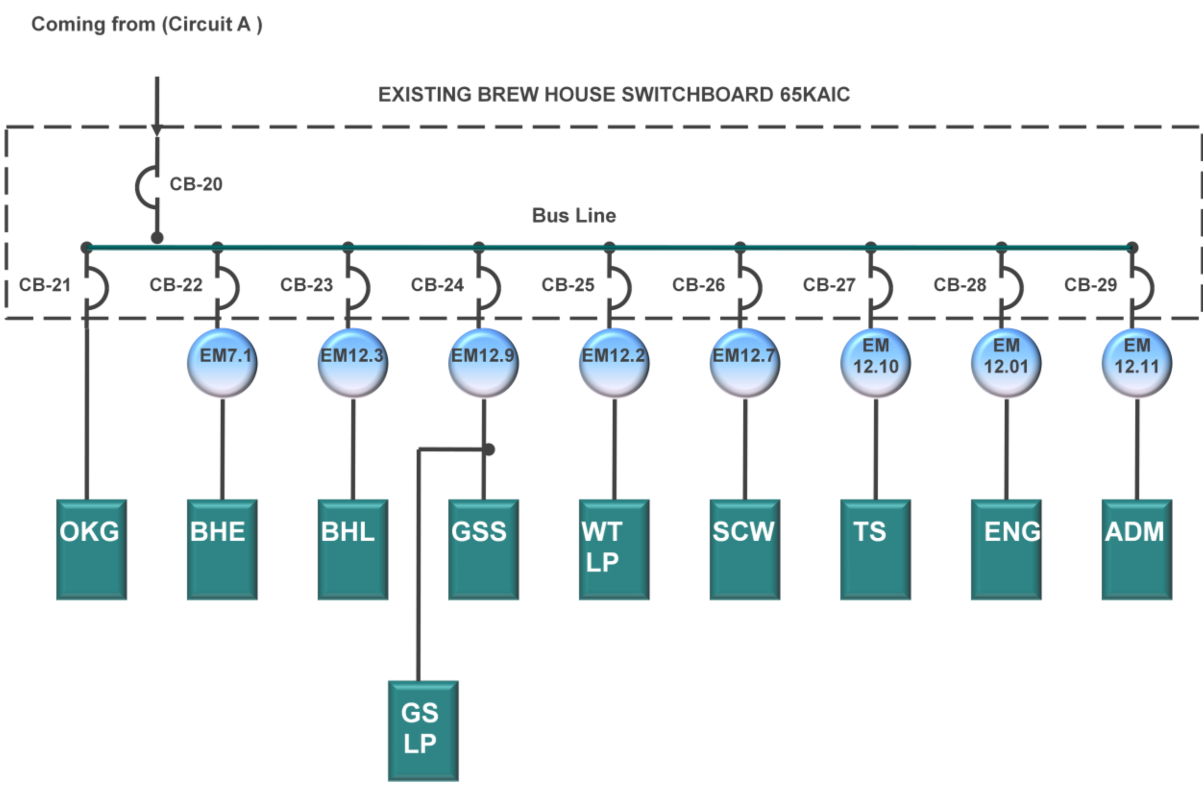


Figure 3-20 4200KVA One Line Diagram for Section II Circuit B. Taken from Appendix A

Figure [3-21] below, shows the Reliability Block Diagrams with its specifications for Section II part C. This RBD correspond to the one line diagrams for section II part C shown in figure [3-22].

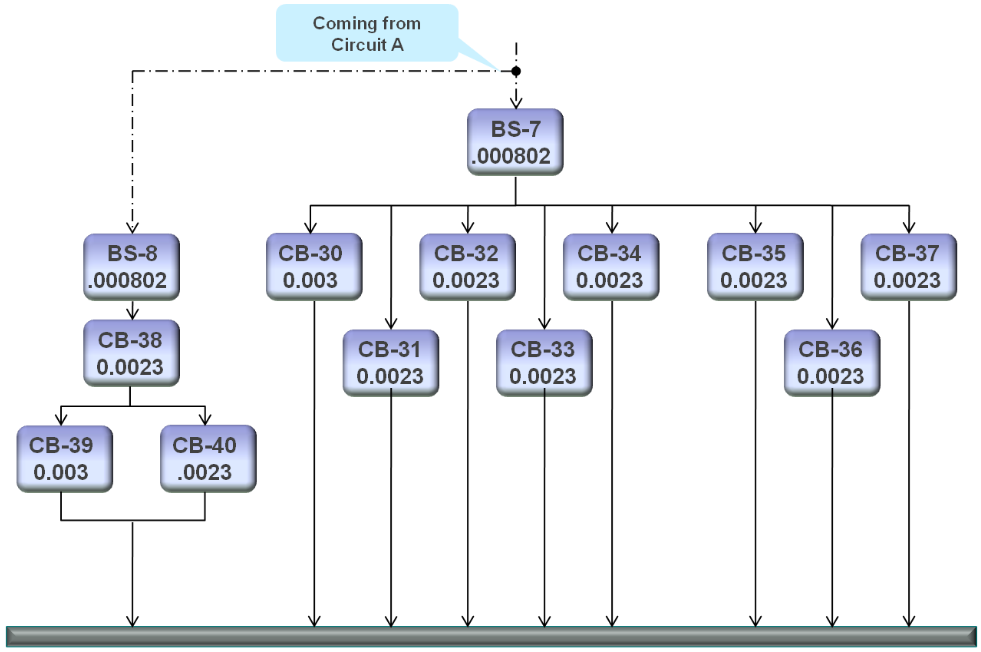


Figure 3-21 RBD for 4200 KVA Substation for Circuit C

In this RBD the first lower path which supply power to CRB and DRB loads has an extra bus bar (BS-8) that is been fed by another bus bar (BS-7). This means that if either bus bar 7 or bus bar 8 fails there will be a power interruption to those loads. Then bus bar 7 and bus bar 8 are in series configuration. If Circuit breaker 39 or Circuit breaker 40 fails such that power is loss to that specific path, then the system will operate in a degraded state.

4200KVA SUBSTATION SECTION II CIRCUIT C ONE LINE DIAGRAM

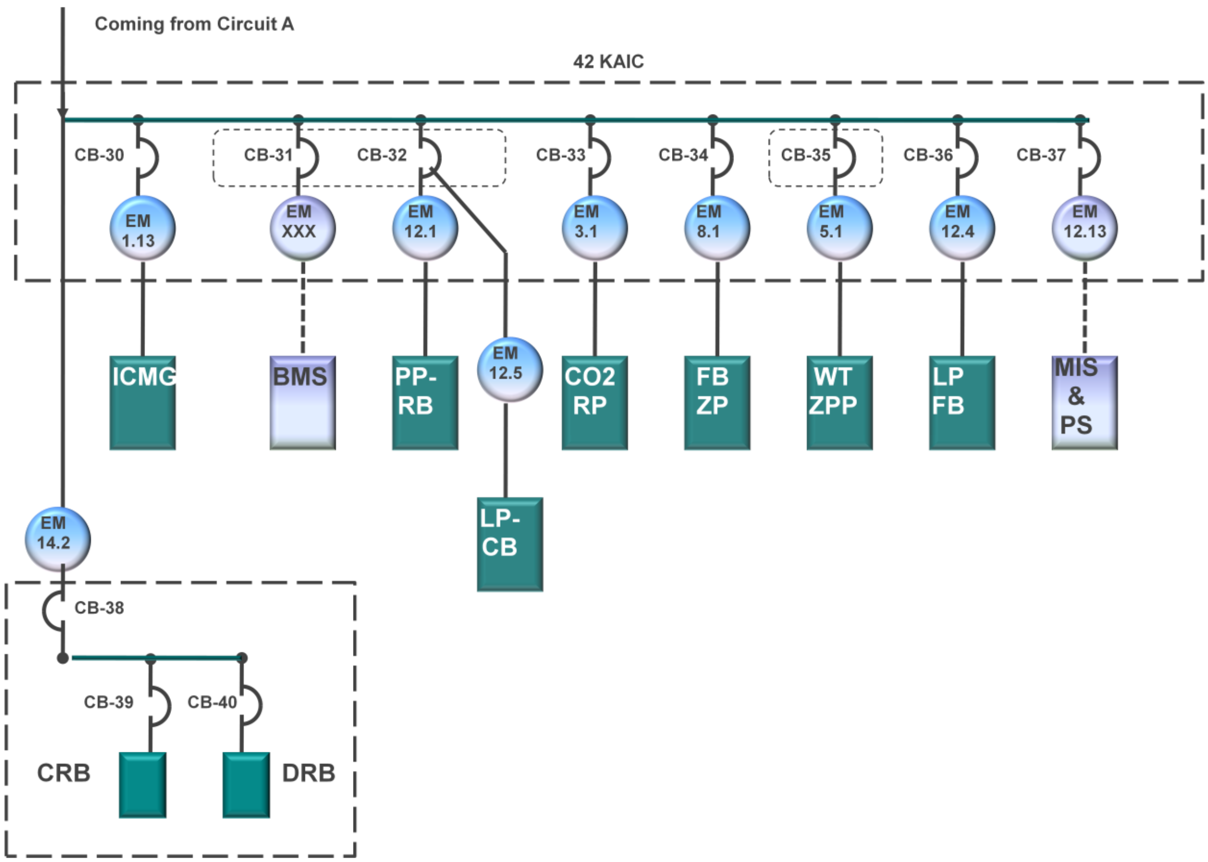


Figure 3-22 4200 KVA One Line Diagram for Section II Circuit C. Taken from Appendix A

3.3.2 State Diagram for CARMS Analysis

Once the one line diagrams are analyzed and an RBD is constructed for each section, we proceed to develop the state diagrams for each section of the power distribution system. After specifying which equipments should be working satisfactorily the state of the system is described in terms of the operation or failure of the equipment. We have made two approaches to analyze and create the state diagrams for this industrial power distribution system. First, we have analyzed the system up to the critical components. When talking about the 2500 KVA substation the critical component goes from the utility to the main 65 KAIC Switchgear circuit breakers. For the 4200 KVA substation the critical components goes from the utility to the bus bar 4 and bus bar 6. When those critical components fail, the power is interrupted to all loads. The second approach consists of analyzing the system up to the farthest load. This will represent the worst case scenario since the farthest load path contains the greatest number of components from utility to load. Each of these components will contribute to the overall reliability of the system.

Now, let's start the analysis with the 2500 KVA substation (section I) which block diagram is presented in figure [3-15]. Using this reliability block diagram as a guide we have constructed a state diagram up to the critical components. This state diagram (shown in figure [3-23]) is based on the reliability behavior of the circuit. The transition rate of each equipment is shown in table 3.4. It's important to mention that a system has finite probability of being in one of two distinct states; one that is operational and one that is failed. The way that these states are interconnected is dependent on the failure mode and transition rates. From 2500 KVA Substation state diagram (shown below) it is seen that only two states are possible with no other states in between. State S1 (the green sphere) correspond to a state where all equipments are operational and state S2 (the red sphere) correspond to a state where any of the equipments has failed and there is no power supplied to any load powered by that 2500 KVA Substation. The lambdas (which are explained in table 3.4) represent the transitional probabilities. In other words, the probability of losing a specific equipment and move to a state where no power could be supplied to the loads.

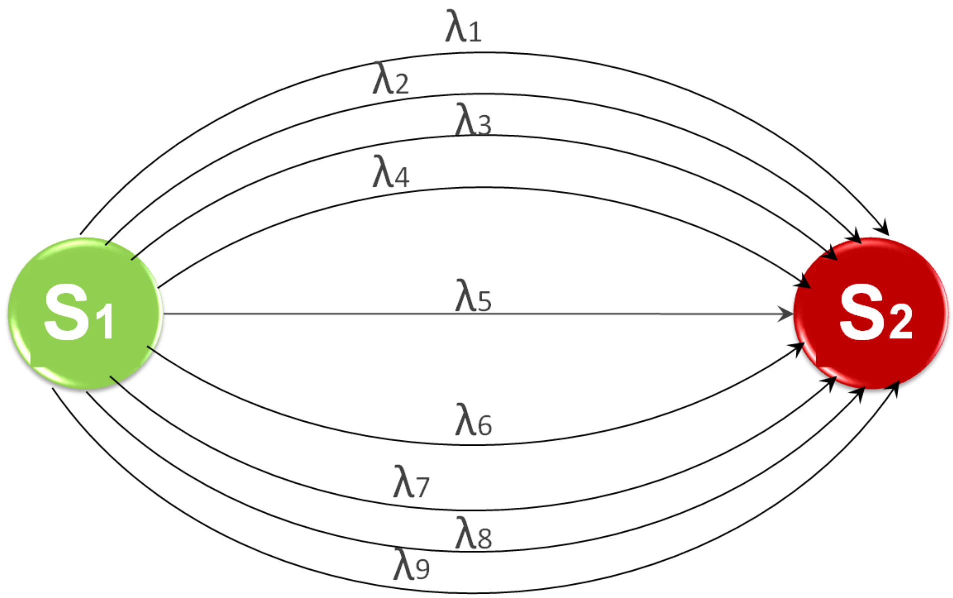


Figure 3-23 2500 KVA State Diagram Up to Switchgear Circuit

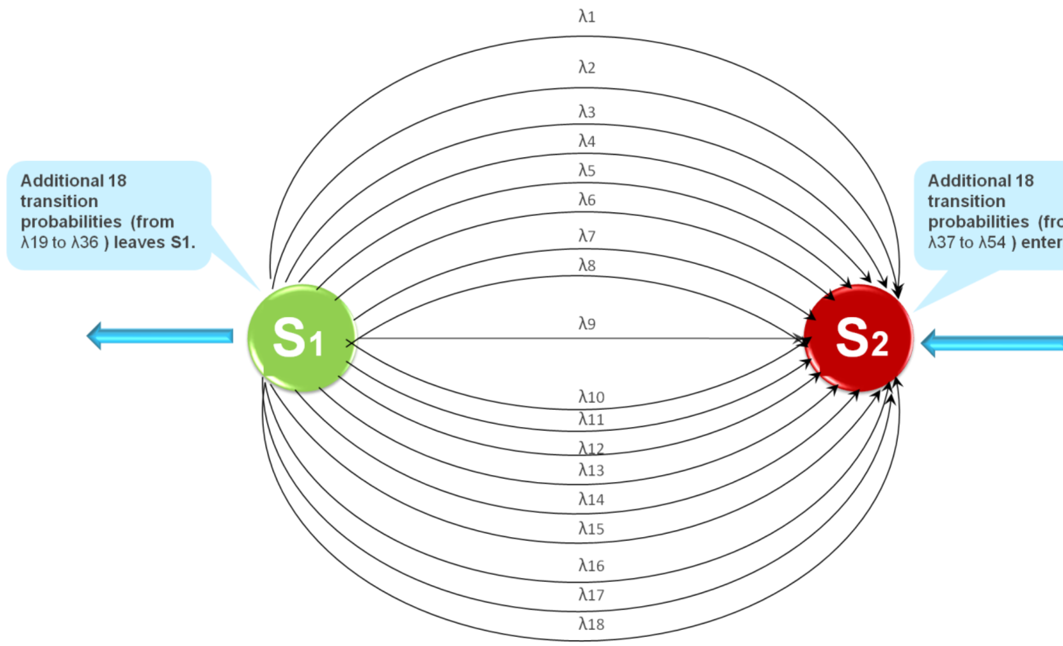
It is important to mention that the transition probability $\lambda 9$ represents the event where all circuits breakers from 1 through 6 fails at the same time. As it can be seen from the transition rate this event is extremely unlikely. Then the effect of this failure is almost negligible. Transition probabilities from λ_1 to λ_9 represents the events where a component or equipment fails such that power to all loads is interrupted. For example, λ_1 transitional probability which is equal to the utility failure rate λ_{M-1} represents the event where the utility stop supplying power to the circuit; then there will be no power to any of the loads. Again, λ_2 is a transitional probability equal to the line termination (TR-1) failure rate (λ_{TR-1}) and it represents the events where the line termination fails such that power is interrupted to all loads. This state diagram and transition table is uploaded into CARMS to create reliability plots.

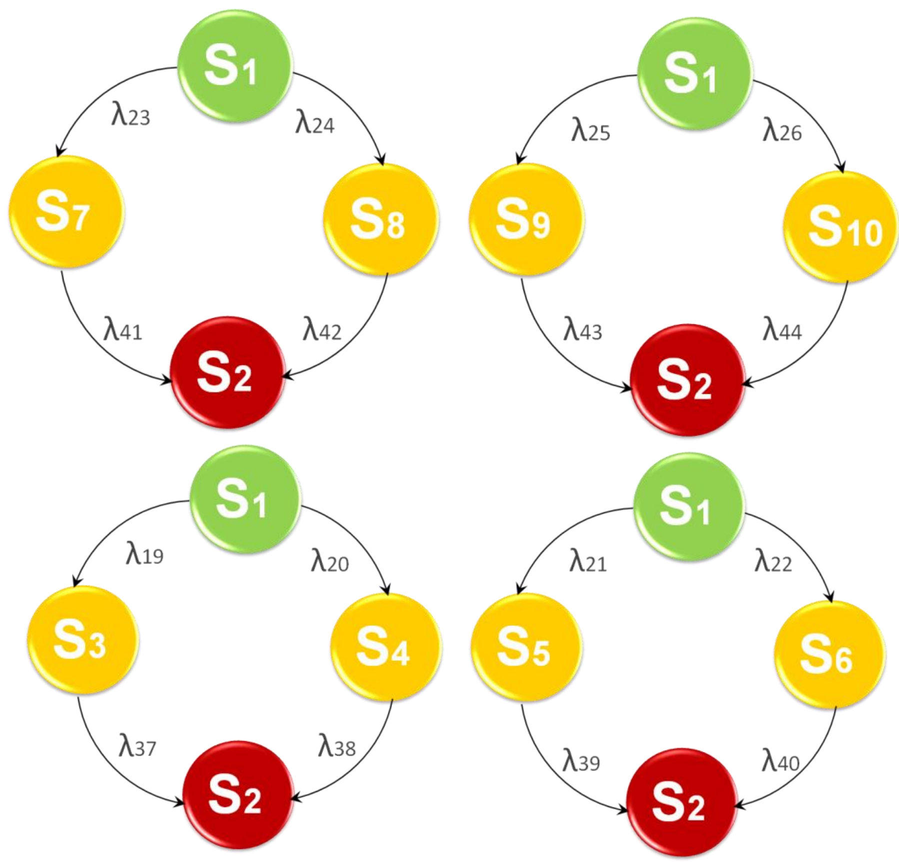
Table 3.4 2500 KVA Substation State Diagram Description Up to Circuit Breakers in Switchgear

STATE TRANSITION	TRANSITION PROBABILITY	TRAN RATE	α	EVENT DESCRIPTION
S1 → S2	$\lambda 1 = \lambda M\text{-}1$	1.956	1	Utility is down
S1 → S2	$\lambda 2 = \lambda TR\text{-}1$	0.00127	1	Line Termination TR-1 down
S1 → S2	$\lambda 3 = \lambda T\text{-}1$	0.0059	1	Transformer T-1 down
S1 → S2	$\lambda 4 = \lambda TR\text{-}2$	0.00127	1	TR-2 down
S1 → S2	$\lambda 5 = \lambda L\text{-}1$	0.00923	1	L-1 down
S1 → S2	$\lambda 6 = \lambda TR\text{-}3$	0.00127	1	Line Termination TR-3 down
S1 → S2	$\lambda 7 = \alpha\lambda DS\text{-}840$	0.00246	0.82	Circuit Breaker DS-840 down
S1 → S2	$\lambda 8 = \lambda BS\text{-}1$	0.000802	1	Bus Bar BS-1 down
S1 → S2	$\lambda 9 = \alpha \lambda CB\text{-}1 * \alpha \lambda CB\text{-}2 * \alpha \lambda CB\text{-}3 * \alpha \lambda CB\text{-}4 * \lambda CB\text{-}5 * \alpha \lambda CB\text{-}6$	2.37964E-13	0.82	All Circuit Breaker 1 through 6 are down

* S1: Represent the states where all components are working; S2: Represent the state where all components have failed and there is loss of power to all loads

Figure [3-24] and table 3.5 show the state diagram and transition table for the 2500 KVA substation up to the farthest load. In this case the farthest load path goes from utility to ATP load.


Additional 18 transition probabilities (from λ19 to λ36) leaves S1.
Additional 18 transition probabilities (from λ37 to λ54) enters S2.
S1
S2
λ1
λ2
λ3
λ4
λ5
λ6
λ7
λ8
λ9
λ10
λ11
λ12
λ13
λ14
λ15
λ16
λ17
λ18


S1
S7
S8
S2
λ23
λ24
λ41
λ42
S1
S9
S10
S2
λ25
λ26
λ43
λ44
S1
S3
S4
S2
λ19
λ20
λ37
λ38
S1
S5
S6
S2
λ21
λ22
λ39
λ40

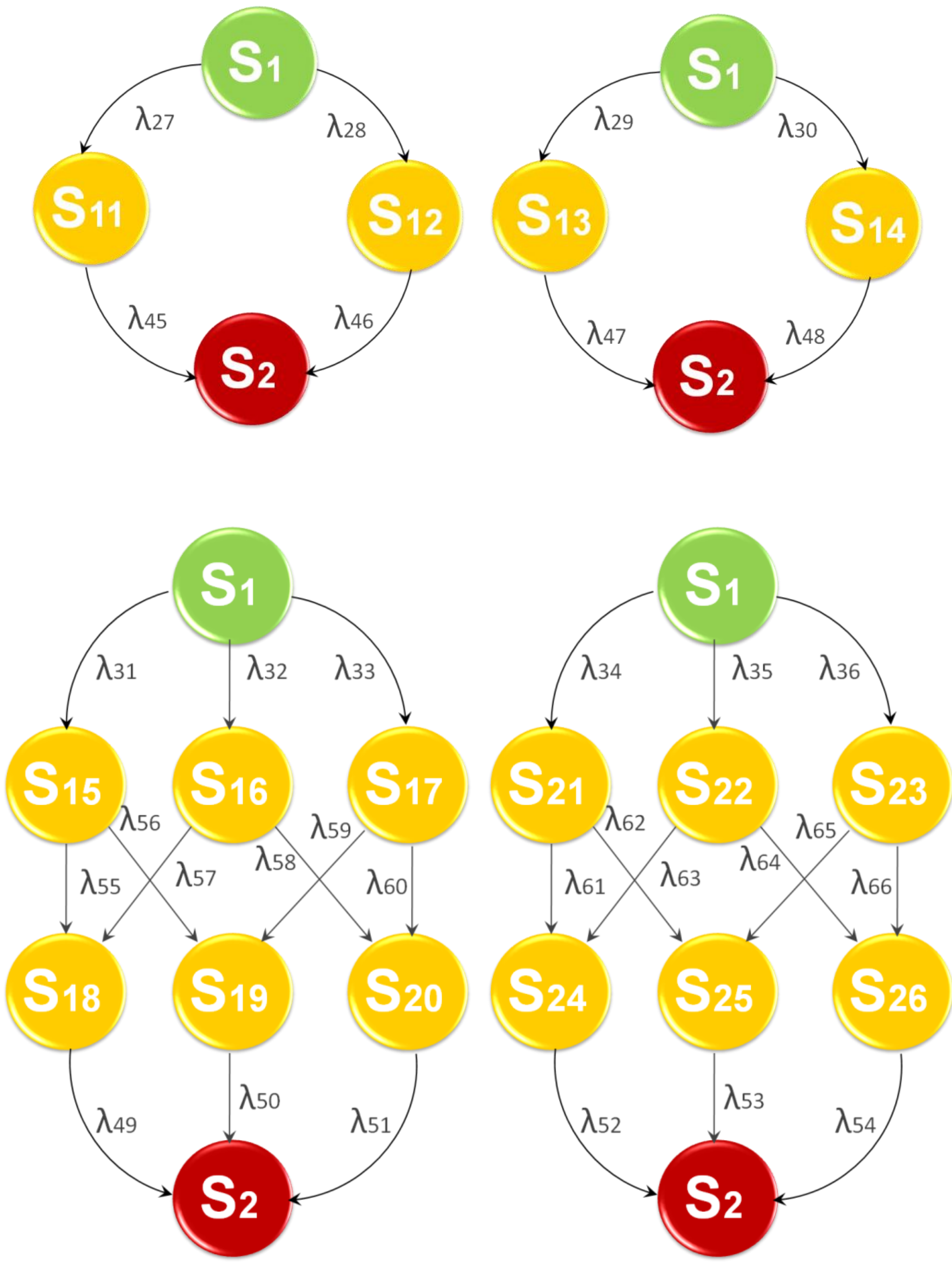


Figure 3-24 2500 KVA State Diagram up to farthest load (worst case scenario)

Table 3.5 2500 KVA Substation State Diagram Description Up to farthest load

STATE TRANSITION	TRANSITION PROBABILITY	TRAN RATE	α	EVENT DESCRIPTION
S1 → S2	$\lambda 1 = \lambda$M-1	1.956	1	Utility is down
S1 → S2	$\lambda 2 = \lambda$TR-1	0.00127	1	Line Termination TR-1 down
S1 → S2	$\lambda 3 = \lambda$T-1	0.0059	1	Transformer T-1 down
S1 → S2	$\lambda 4 = \lambda$TR-2	0.00127	1	TR-2 down
S1 → S2	$\lambda 5 = \lambda$L-1	0.00923	1	L-1 down
S1 → S2	$\lambda 6 = \lambda$TR-3	0.00127	1	Line Termination TR-3 down
S1 → S2	$\lambda 7 = \alpha\lambda$DS-840	0.00246	0.82	Circuit Breaker DS-840 down
S1 → S2	$\lambda 8 = \lambda$BS-1	0.000802	1	Bus Bar BS-1 down
S1 → S2	$\lambda 9 = \alpha\lambda$CB-4	0.00246	0.82	Circuit Breaker CB-4 down
S1 → S2	$\lambda 10 = \lambda$TR-7	0.00127	1	Line Termination TR-7 down
S1 → S2	$\lambda 11 = \lambda$L-5	0.00923	1	L-5 down
S1 → S2	$\lambda 12 = \lambda$TR-13	0.00127	1	Line Termination TR-13 down
S1 → S2	$\lambda 13 = \alpha\lambda$CB-10	0.00246	0.82	Circuit Breaker CB-10 down
S1 → S2	$\lambda 14 = \lambda$BS-3	0.000802	1	Bus Bar BS-3 down
S1 → S2	$\lambda 15 = \alpha\lambda$CB-12	0.001886	0.82	Circuit Breaker CB-12 down
S1 → S2	$\lambda 16 = \lambda$TR-19	0.00127	1	Line Termination TR-19 down
S1 → S2	$\lambda 17 = \lambda$L-12	0.00923	1	L-12 down
S1 → S2	$\lambda 18 = \lambda$TR-23	0.00127	1	Line Termination TR-23 down
S1 → S3	$\lambda 19 = \alpha\lambda$CB-6	0.00054	0.18	Circuit Breaker CB-6 down

S1 → S4	$\lambda20 = \alpha\,\lambda TR\text{-}9 + \alpha\,\lambda L\text{-}7 + \alpha\,\lambda TR\text{-}15$	0.0050214	.16,.5,.16	The event where Line Termination TR-9 or Line L-7 or Line Termination TR-5 fails
S1 → S5	$\lambda21 = \alpha\lambda CB\text{-}5$	0.00054	0.18	Circuit Breaker CB-5 down
S1 → S6	$\lambda22 = \alpha\,\lambda TR\text{-}8 + \alpha\,\lambda L\text{-}6 + \alpha\,\lambda TR\text{-}14$	0.0050214	.16,.5,.16	The event where Line Termination TR-8 or Line L-6 or Line Termination TR-14 fails
S1 → S7	$\lambda23 = \alpha\lambda CB\text{-}3$	0.00054	0.18	Circuit Breaker CB-3 down
S1 → S8	$\lambda24 = \alpha\,\lambda TR\text{-}6 + \alpha\,\lambda L\text{-}4 + \alpha\,\lambda TR\text{-}12$	0.0050214	.16,.5,.16	The event where Line Termination TR-6 or Line L-4 or Line Termination TR-12 fails
S1 → S9	$\lambda25 = \alpha\lambda CB\text{-}2$	0.00054	0.18	Circuit Breaker CB-2 down
S1 → S10	$\lambda26 = \alpha\,\lambda TR\text{-}5 + \alpha\,\lambda L\text{-}3 + \alpha\,\lambda TR\text{-}11$	0.0050214	.16,.5,.16	The event where Line Termination TR-5 or Line L-3 or Line Termination TR-11 fails
S1 → S11	$\lambda27 = \alpha\lambda CB\text{-}11$	0.000414	0.18	Circuit Breaker CB-11 down
S1 → S12	$\lambda28 = \alpha\,\lambda TR\text{-}18 + \alpha\,\lambda L\text{-}11 + \alpha\,\lambda TR\text{-}22$	0.0050214	.16,.5,.16	The event where Line Termination TR-18 or Line L-11 or Line Termination TR-22 fails
S1 → S13	$\lambda29 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down
S1 → S14	$\lambda30 = \alpha\,\lambda TR\text{-}4 + \alpha\,\lambda L\text{-}2 + \alpha\,\lambda TR\text{-}10 + \alpha\,\lambda L\text{-}8 + \alpha\,\lambda BS\text{-}2$	0.0100374	.16,.5,.16,.5,.5	The event where Line Termination TR-4 or Line L-2 or Line Termination TR-10 or Line L-8 or Bus Bar BS-2 fails
S1 → S15	$\lambda31 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down
S1 → S16	$\lambda32 = \alpha\lambda CB\text{-}8$	0.000414	0.18	Circuit Breaker CB-8 down
S1 → S17	$\lambda33 = \alpha\,\lambda TR\text{-}16 + \alpha\,\lambda L\text{-}9 + \alpha\,\lambda TR\text{-}20$	0.0050214	.16,.5,.16	The event where Line Termination TR-16 or Line L-9 or Line Termination TR-20 fails
S1 → S21	$\lambda34 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down

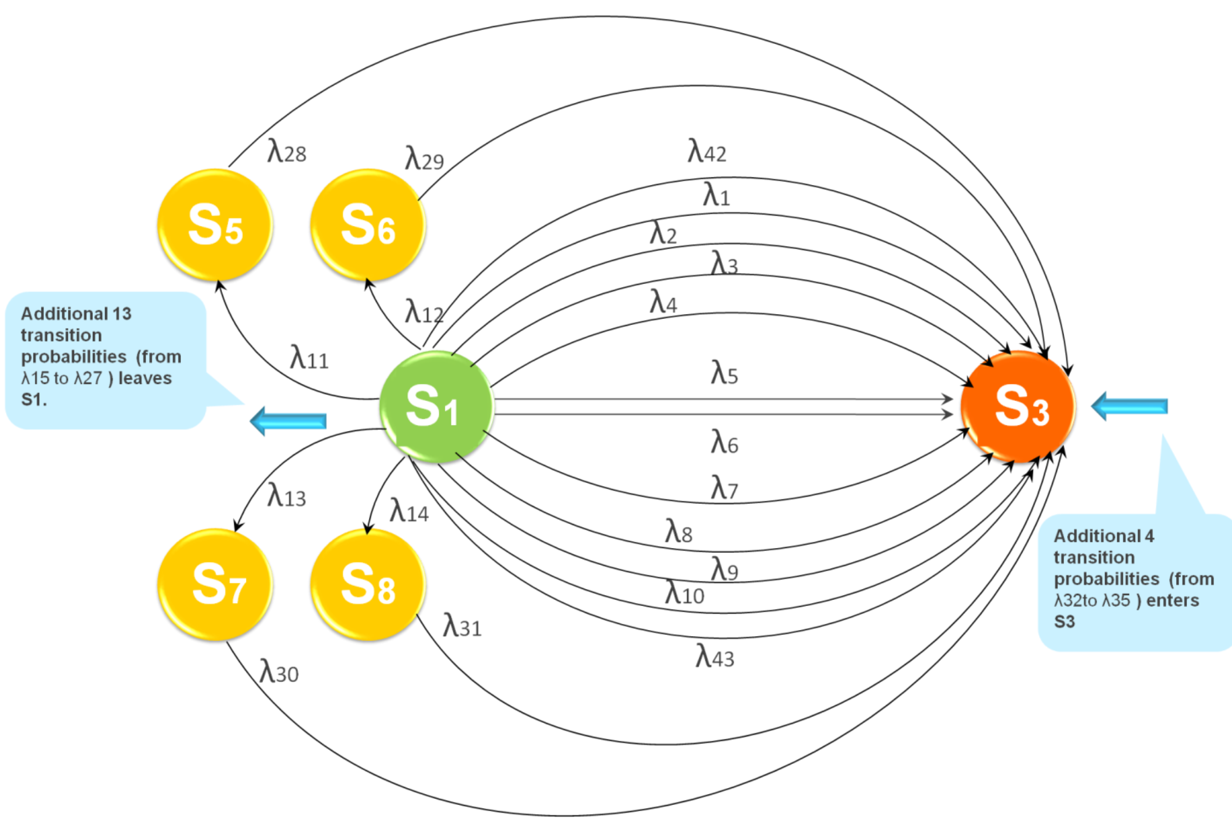
S1 → S22	$\lambda 35 = \alpha\lambda CB\text{-}9$	0.000414	0.18	Circuit Breaker CB-9 down
S1 → S23	$\lambda 36 = \alpha\, \lambda TR\text{-}17 + \alpha\, \lambda L\text{-}10 + \alpha\, \lambda TR\text{-}21$	0.0050214	.16,.5,.16	The event where Line Termination TR-17 or Line L-10 or Line Termination TR-21 fails
S3 → S2	$\lambda 37 = \alpha\, \lambda TR\text{-}9 + \alpha\, \lambda L\text{-}7 + \alpha\, \lambda TR\text{-}15$	0.0050214	.16,.5,.16	The event where Line Termination TR-9 or Line L-7 or Line Termination TR-15 fails
S4 → S2	$\lambda 38 = \alpha\lambda CB\text{-}6$	0.00054	0.18	Circuit Breaker CB-6 down
S5 → S2	$\lambda 39 = \alpha\, \lambda TR\text{-}8 + \alpha\, \lambda L\text{-}6 + \alpha\, \lambda TR\text{-}14$	0.0050214	.16,.5,.16	The event where Line Termination TR-8 or Line L-6 or Line Termination TR-14 fails
S6 → S2	$\lambda 40 = \alpha\lambda CB\text{-}5$	0.00054	0.18	Circuit Breaker CB-5 down
S7 → S2	$\lambda 41 = \alpha\, \lambda TR\text{-}6 + \alpha\, \lambda L\text{-}4 + \alpha\, \lambda TR\text{-}12$	0.0050214	.16,.5,.16	The event where Line Termination TR-6 or Line L-4 or Line Termination TR-12 fails
S8 → S2	$\lambda 42 = \alpha\lambda CB\text{-}3$	0.00054	0.18	Circuit Breaker CB-3 down
S9 → S2	$\lambda 43 = \alpha\, \lambda TR\text{-}5 + \alpha\, \lambda L\text{-}3 + \alpha\, \lambda TR\text{-}11$	0.0050214	.16,.5,.16	The event where Line Termination TR-5 or Line L-3 or Line Termination TR-11 fails
S10 → S2	$\lambda 44 = \alpha\lambda CB\text{-}2$	0.00054	0.18	Circuit Breaker CB-2 down
S11 → S2	$\lambda 45 = \alpha\, \lambda TR\text{-}18 + \alpha\, \lambda L\text{-}11 + \alpha\, \lambda TR\text{-}22$	0.0050214	.16,.5,.16	The event where Line Termination TR-18 or Line L-11 or Line Termination TR-22 fails
S12 → S2	$\lambda 46 = \alpha\lambda CB\text{-}11$	0.000414	0.18	Circuit Breaker CB-11 down
S13 → S2	$\lambda 47 = \alpha\, \lambda TR\text{-}4 + \alpha\, \lambda L\text{-}2 + \alpha\, \lambda TR\text{-}10 + \alpha\, \lambda L\text{-}8 + \alpha\, \lambda BS\text{-}2$	0.0100374	.16,.5,.16,.5,.5	The event where Line Termination TR-4 or Line L-2 or Line Termination TR-10 or Line L-8 or Bus Bar BS-2 fails
S14 → S2	$\lambda 48 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down

S18 → S2	$\lambda 49 = \alpha\, \lambda TR\text{-}16 + \alpha\, \lambda L\text{-}9 + \alpha\, \lambda TR\text{-}20$	0.0050214	.16,.5,.16	The event where Line Termination TR-16 or Line L-9 or Line Termination TR-20 fails
S19 → S2	$\lambda 50 = \alpha\lambda CB\text{-}8$	0.000414	0.18	Circuit Breaker CB-8 down
S20 → S2	$\lambda 51 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down
S24 → S2	$\lambda 52 = \alpha\, \lambda TR\text{-}17 + \alpha\, \lambda L\text{-}10 + \alpha\, \lambda TR\text{-}21$	0.0050214	.16,.5,.16	The event where Line Termination TR-17 or Line L-10 or Line Termination TR-21 fails
S25 → S2	$\lambda 53 = \alpha\lambda CB\text{-}9$	0.000414	0.18	Circuit Breaker CB-9 down
S26 → S2	$\lambda 54 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down
S15 → S18	$\lambda 55 = \alpha\lambda CB\text{-}8$	0.000414	0.18	Circuit Breaker CB-8 down
S15 → S19	$\lambda 56 = \alpha\, \lambda TR\text{-}16 + \alpha\, \lambda L\text{-}9 + \alpha\, \lambda TR\text{-}20$	0.0050214	.16,.5,.16	The event where Line Termination TR-16 or Line L-9 or Line Termination TR-20 fails
S16 → S18	$\lambda 57 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down
S16 → S20	$\lambda 58 = \alpha\, \lambda TR\text{-}16 + \alpha\, \lambda L\text{-}9 + \alpha\, \lambda TR\text{-}20$	0.0050214	.16,.5,.16	The event where Line Termination TR-16 or Line L-9 or Line Termination TR-20 fails
S17 → S19	$\lambda 59 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down
S17 → S20	$\lambda 60 = \alpha\lambda CB\text{-}8$	0.000414	0.18	Circuit Breaker CB-8 down
S21 → S24	$\lambda 61 = \alpha\lambda CB\text{-}9$	0.000414	0.18	Circuit Breaker CB-9 down
S21 → S25	$\lambda 62 = \alpha\, \lambda TR\text{-}17 + \alpha\, \lambda L\text{-}10 + \alpha\, \lambda TR\text{-}21$	0.0050214	.16,.5,.16	The event where Line Termination TR-17 or Line L-10 or Line Termination TR-21 fails
S22 → S24	$\lambda 63 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down
S22 → S26	$\lambda 64 = \alpha\, \lambda TR\text{-}17 + \alpha\, \lambda L\text{-}10 + \alpha\, \lambda TR\text{-}21$	0.0050214	.16,.5,.16	The event where Line Termination TR-17 or Line L-10 or Line Termination TR-21 fails
S23 → S25	$\lambda 65 = \alpha\lambda CB\text{-}1$	0.00054	0.18	Circuit Breaker CB-1 down

S23 → S26	$\lambda_{66} = \alpha\lambda_{CB-9}$	0.000414	0.18	Circuit Breaker CB-9 down

* S1: Represent the states where all components are working; S2: Represent the state where all components have failed and there is loss of power to the load. For a complete description of each state (from S1 to S26) please refer to Appendix E

Now we proceed to create the state diagram and transition tables for the 4200 KVA Substation analysis. Figure [3-25] represents the state diagram for the substation up to the critical components. As we have already mentioned, this means that we will do our analysis from the utility to the bus bar 4 (BS-4) and bus bar 6 (BS-6). We want to do that because if we lose BS-4 or BS-6, basically the majority of the system is down.



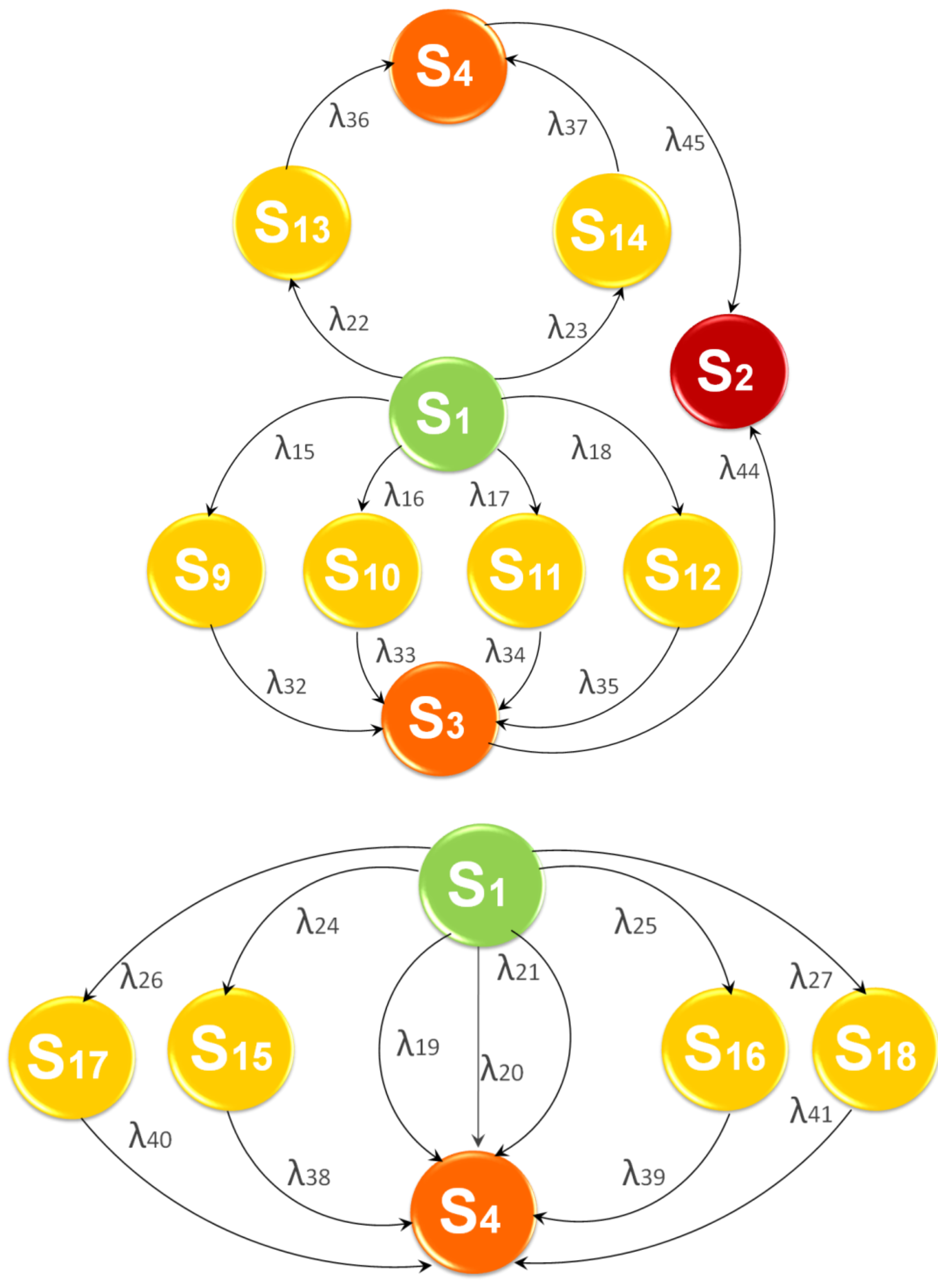


Figure 3-25 4200 KVA State Diagram up to the Bus Bar.

Table 3.6 4200 KVA Substation State Diagram Description Up to Bus Bars

STATE TRANSITION	TRANSITION PROBABILITY	TRAN RATE	α	EVENT DESCRIPTION
$S_1 \rightarrow S_3$	$\lambda_1 = \lambda_{L-14}$	0.00923	1	L-14 down
$S_1 \rightarrow S_3$	$\lambda_2 = \lambda_{TR-26}$	0.00127	1	TR-26 down
$S_1 \rightarrow S_3$	$\lambda_3 = \lambda_{CB-14}$	0.0015	.5	Circuit Breaker CB-14 down
$S_1 \rightarrow S_3$	$\lambda_4 = \lambda_{TR-27}$	0.00127	1	TR-27 down
$S_1 \rightarrow S_3$	$\lambda_5 = \lambda_{L-17}$	0.00923	1	L-17 down
$S_1 \rightarrow S_3$	$\lambda_6 = \lambda_{TR-28}$	0.00127	1	Line Termination TR-28 down
$S_1 \rightarrow S_3$	$\lambda_7 = \lambda_{CB-20}$	0.00115	.5	Circuit Breaker CB-20 down
$S_1 \rightarrow S_3$	$\lambda_8 = \lambda_{BS-6}$	0.000802	1	Bus Bar BS-6 down
$S_1 \rightarrow S_3$	$\lambda_9 = \alpha\ \lambda_{L-13}$	0.004615	0.5	L-13 down
$S_1 \rightarrow S_3$	$\lambda_{10} = \alpha\ \lambda_{TR-53}$	0.0002032	0.16	Line Termination TR-53 down
$S_1 \rightarrow S_5$	$\lambda_{11} = \alpha\ \lambda_{L-16} + \alpha\ \lambda_{TR-54}$	0.0048182	.16,.5	The event where Line L-16 or Line L-10 or Line Termination TR-54 fails
$S_1 \rightarrow S_6$	$\lambda_{12} = \alpha\ \lambda_{CB-13}$	0.00054	0.18	Circuit Breaker CB-13 down
$S_1 \rightarrow S_7$	$\lambda_{13} = \alpha\ \lambda_{SG} + \alpha\ \lambda_{TR-50} + \alpha\ \lambda_{CB-16} + \alpha\ \lambda_{TR-51} + \alpha\ \lambda_{L-30} + \alpha\ \lambda_{TR-52} + \alpha\ \lambda_{ATS} + \alpha\ \lambda_{TR-54} + \alpha\ \lambda_{L-16} + \alpha\ \lambda_{CB-13} + \alpha\ \lambda_{TR-53} + \alpha\ \lambda_{L-13}$	0.7049	1	The event where the standby generator SG fails or Line Termination TR-50 or Circuit Breaker CB-16 or Line Termination TR-51 or Line L-30 or Line Termination TR-52 or the Automatic Transfer Switch (ATS) or Line Termination TR-54 or Line L-16 or Circuit Breaker CB-16 or Line Termination TR-53 or

				or Line L-13 fails
$S_1 \rightarrow S_8$	$\lambda_{14} = \lambda_{M-1} + \lambda_{T-2} + \alpha \lambda_{TR-24}$	1.96317	1	The event where the Utility (M-1) or Transformer T-2 or Line Termination TR-24 fails
$S_1 \rightarrow S_9$	$\lambda_{15} = \alpha \lambda_{CB-15}$	0.000414	0.18	Circuit Breaker CB-15 down
$S_1 \rightarrow S_{10}$	$\lambda_{16} = \alpha\lambda_{PFC} + \alpha\lambda_{TR-30} + \alpha \lambda_{L-29} + \alpha \lambda_{TR-29}$	0.0904921	.49,.16,.5,.16	The event where Power Factor Capacitor (PFC) or Line Termination TR-30 or Line L-29 or Line Termination TR-29 fails
$S_1 \rightarrow S_{11}$	$\lambda_{17} = \alpha \lambda_{CB-13}$	0.00054	0.18	Circuit Breaker CB-13 down
$S_1 \rightarrow S_{12}$	$\lambda_{18} = \alpha\lambda_{TR-57} + \alpha\lambda_{L-32} + \alpha \lambda_{TR-56} + \alpha \lambda_{BS-5} + \alpha \lambda_{TR-61} + \alpha\lambda_{L-34} + \alpha\lambda_{TR-60} + \alpha \lambda_{BS-4} + \alpha \lambda_{TR-55} + \alpha \lambda_{L-31}$	0.015663	.16,.5,.16,.5,.16,.5,.16,.5,.16,.5	The event where Line Termination TR-57 or Line L-32 or Line Termination TR-56 or Bus Bar BS-5 or Line Termination TR-61 or Line L-34 or Line Termination TR-60 or Bus Bar BS-4 or Line Termination TR-55 or Line L-31 fails
$S_1 \rightarrow S_4$	$\lambda_{19} = \lambda_{L-31}$	0.00923	1	L-31 down
$S_1 \rightarrow S_4$	$\lambda_{20} = \lambda_{TR-55}$	0.00127	1	Line Termination TR-55 down
$S_1 \rightarrow S_4$	$\lambda_{21} = \lambda_{BS-4}$	0.000802	1	Bus Bar BS-4 down
$S_1 \rightarrow S_{13}$	$\lambda_{22} = \alpha\lambda_{SG} + \alpha\lambda_{TR-50} + \alpha \lambda_{CB-16} + \alpha \lambda_{TR-51} + \alpha \lambda_{TR-52} + \alpha\lambda_{L-30} + \alpha\lambda_{ATS}$	0.6794	1,1,.5,1,1,1,1	The event where the standby generator SG fails or Line Termination TR-50 or Circuit Breaker CB-16 or Line Termination TR-51 or Line L-30 or the Automatic Transfer Switch (ATS) fails
$S_1 \rightarrow S_{14}$	$\lambda_{23} = \alpha\lambda_{M-1} + \alpha\lambda_{T-2} + \alpha \lambda_{TR-24}$	1.96317	1	The event where the Utility (M-1) or Transformer T-2 or Line Termination TR-24 fails
$S_1 \rightarrow S_{15}$	$\lambda_{24} = \alpha \lambda_{CB-13}$	0.00054	0.18	Circuit Breaker CB-13 down

$S_1 \rightarrow S_{16}$	$\lambda_{25} = \alpha\lambda_{L\text{-}14} + \alpha\lambda_{TR\text{-}26} + \alpha\lambda_{L\text{-}15} + \alpha\lambda_{TR\text{-}25} + \alpha\lambda_{L\text{-}13} + \alpha\lambda_{TR\text{-}53}$	0.0144546	.5,.16,.5,.16,.5,.16	The event where Line L-14 or Line Termination TR-26 or Line L-15 or Line Termination TR-25 or Line L-13 or Line Termination TR-53 fails
$S_1 \rightarrow S_{17}$	$\lambda_{26} = \alpha\lambda_{CB\text{-}13}$	0.00054	0.18	Circuit Breaker CB-13 down
$S_1 \rightarrow S_{18}$	$\lambda_{27} = \alpha\lambda_{L\text{-}16} + \alpha\lambda_{TR\text{-}54}$	0.0048182	.5,.16	Line L-16 or Line Termination TR-54 fails
$S_5 \rightarrow S_3$	$\lambda_{28} = \alpha\lambda_{CB\text{-}13}$	0.00054	0.18	Circuit Breaker CB-13 down
$S_6 \rightarrow S_3$	$\lambda_{29} = \alpha\lambda_{L\text{-}16} + \alpha\lambda_{TR\text{-}54}$	0.0048182	.5,.16	The event where Line L-16 or Line Termination TR-54 fails
$S_7 \rightarrow S_3$	$\lambda_{30} = \lambda_{M\text{-}1} + \lambda_{T\text{-}2} + \alpha\lambda_{TR\text{-}24}$	1.96317	1	The event where the Utility (M-1) or Transformer T-2 or Line Termination TR-24 fails
$S_8 \rightarrow S_3$	$\lambda_{31} = \alpha\lambda_{SG} + \alpha\lambda_{TR\text{-}50} + \alpha\lambda_{CB\text{-}16} + \alpha\lambda_{TR\text{-}51} + \alpha\lambda_{L\text{-}30} + \alpha\lambda_{TR\text{-}52} + \alpha\lambda_{ATS} + \alpha\lambda_{TR\text{-}54} + \alpha\lambda_{L\text{-}16} + \alpha\lambda_{CB\text{-}13} + \alpha\lambda_{TR\text{-}53} + \alpha\lambda_{L\text{-}13}$	0.7049	1	The event where the standby generator SG fails or Line Termination TR-50 or Circuit Breaker CB-16 or Line Termination TR-51 or Line L-30 or Line Termination TR-52 or the Automatic Transfer Switch (ATS) or Line Termination TR-54 or Line L-16 or Circuit Breaker CB-16 or Line Termination TR-53 or or Line L-13 fails
$S_9 \rightarrow S_3$	$\lambda_{32} = \alpha\lambda_{PFC} + \alpha\lambda_{TR\text{-}30} + \alpha\lambda_{L\text{-}29} + \alpha\lambda_{TR\text{-}29}$	0.0904921	.49,.16,.5,.16	The event where Power Factor Capacitor (PFC) or Line Termination TR-30 or Line L-29 or Line Termination TR-29 fails
$S_{10} \rightarrow S_3$	$\lambda_{33} = \alpha\lambda_{CB\text{-}15}$	0.000414	0.18	Circuit Breaker CB-15 down

$S_{11} \rightarrow S_3$	$\lambda_{34} = \alpha\lambda_{TR-57} + \alpha\lambda_{L-32} + \alpha\lambda_{TR-56} + \alpha\lambda_{BS-5} + \alpha\lambda_{TR-61} + \alpha\lambda_{L-34} + \alpha\lambda_{TR-60} + \alpha\lambda_{BS-4} + \alpha\lambda_{TR-55} + \alpha\lambda_{L-31}$	0.015663	.16,.5,.16,.5,.16,.5,.16,.5,.16,.5	The event where Line Termination TR-57 or Line L-32 or Line Termination TR-56 or Bus Bar BS-5 or Line Termination TR-61 or Line L-34 or Line Termination TR-60 or Bus Bar BS-4 or Line Termination TR-55 or Line L-31 fails
$S_{12} \rightarrow S_3$	$\lambda_{35} = \alpha\lambda_{CB-13}$	0.00054	0.18	Circuit Breaker CB-13 down
$S_{13} \rightarrow S_4$	$\lambda_{36} = \alpha\lambda_{M-1} + \alpha\lambda_{T-2} + \alpha\lambda_{TR-24}$	1.96317	1	The event where the Utility (M-1) or Transformer T-2 or Line Termination TR-24 fails
$S_{14} \rightarrow S_4$	$\lambda_{37} = \alpha\lambda_{SG} + \alpha\lambda_{TR-50} + \alpha\lambda_{CB-16} + \alpha\lambda_{TR-51} + \alpha\lambda_{TR-52} + \alpha\lambda_{L-30} + \alpha\lambda_{ATS}$	0.6794	1,1,.5,1,1,1,1	The event where the standby generator SG fails or Line Termination TR-50 or Circuit Breaker CB-16 or Line Termination TR-51 or Line L-30 or the Automatic Transfer Switch (ATS) fails
$S_{15} \rightarrow S_4$	$\lambda_{38} = \alpha\lambda_{L-14} + \alpha\lambda_{TR-26} + \alpha\lambda_{L-15} + \alpha\lambda_{TR-25} + \alpha\lambda_{L-13} + \alpha\lambda_{TR-53}$	0.0144546	.5,.16,.5,.16,.5,.16	The event where Line L-14 or Line Termination TR-26 or Line L-15 or Line Termination TR-25 or Line L-13 or Line Termination TR-53 fails
$S_{16} \rightarrow S_4$	$\lambda_{39} = \alpha\lambda_{CB-13}$	0.00054	0.18	Circuit Breaker CB-13 down
$S_{17} \rightarrow S_4$	$\lambda_{40} = \alpha\lambda_{L-16} + \alpha\lambda_{TR-54}$	0.0048182	.5,.16	Line L-16 or Line Termination TR-54 fails
$S_{18} \rightarrow S_4$	$\lambda_{41} = \alpha\lambda_{CB-13}$	0.00054	0.18	Circuit Breaker CB-13 down
$S_1 \rightarrow S_3$	$\lambda_{42} = \alpha\lambda_{L-15}$	0.004615	0.5	Line L-15 down
$S_1 \rightarrow S_3$	$\lambda_{43} = \alpha\lambda_{TR-25}$	0.0002032	0.16	Line Termination TR-25 down

$S_4 \rightarrow S_2$	$\lambda_{44} = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_8 + \lambda_9 + \lambda_{10} + \lambda_{42} + \lambda_{43} + (\lambda_{12} * \lambda_{29}) + (\lambda_{11} * \lambda_{28}) + (\lambda_{13} * \lambda_{30}) + (\lambda_{14} * \lambda_{31}) + (\lambda_{15} * \lambda_{32}) + (\lambda_{16} * \lambda_{33}) + (\lambda_{17} * \lambda_{34}) + (\lambda_{18} * \lambda_{35})$	1.4839396207	n/a	The event where Bus Bar 4 is not able to provide power to any load and Bus Bar 6 is also not able to provide power to any loads
$S_3 \rightarrow S_2$	$\lambda_{45} = \lambda_{19} + \lambda_{20} + \lambda_{21} + (\lambda_{23} * \lambda_{37}) + (\lambda_{22} * \lambda_{36}) + (\lambda_{26} * \lambda_{40}) + (\lambda_{24} * \lambda_{38}) + (\lambda_{25} * \lambda_{39}) + (\lambda_{27} * \lambda_{41})$	1.3453817842	n/a	The event where Bus Bar 6 is not able to provide power to any load and Bus Bar 4 is also not able to provide power to any loads

* S1: Represents the states where all components are working; S2: Represents the state where all components have failed and there is loss of power to every single load. S3: Represents the state where Bus Bar 6 is not able to supply power to any loads. S4: Represents the state where Bus Bar 4 is not able to provide power to any loads. For a complete description of each state (from S1 to S18) please refer to Appendix E

Figure [3-26] and table 3.7 show the state diagram and transition table for the 4200 KVA substation up to the farthest load.

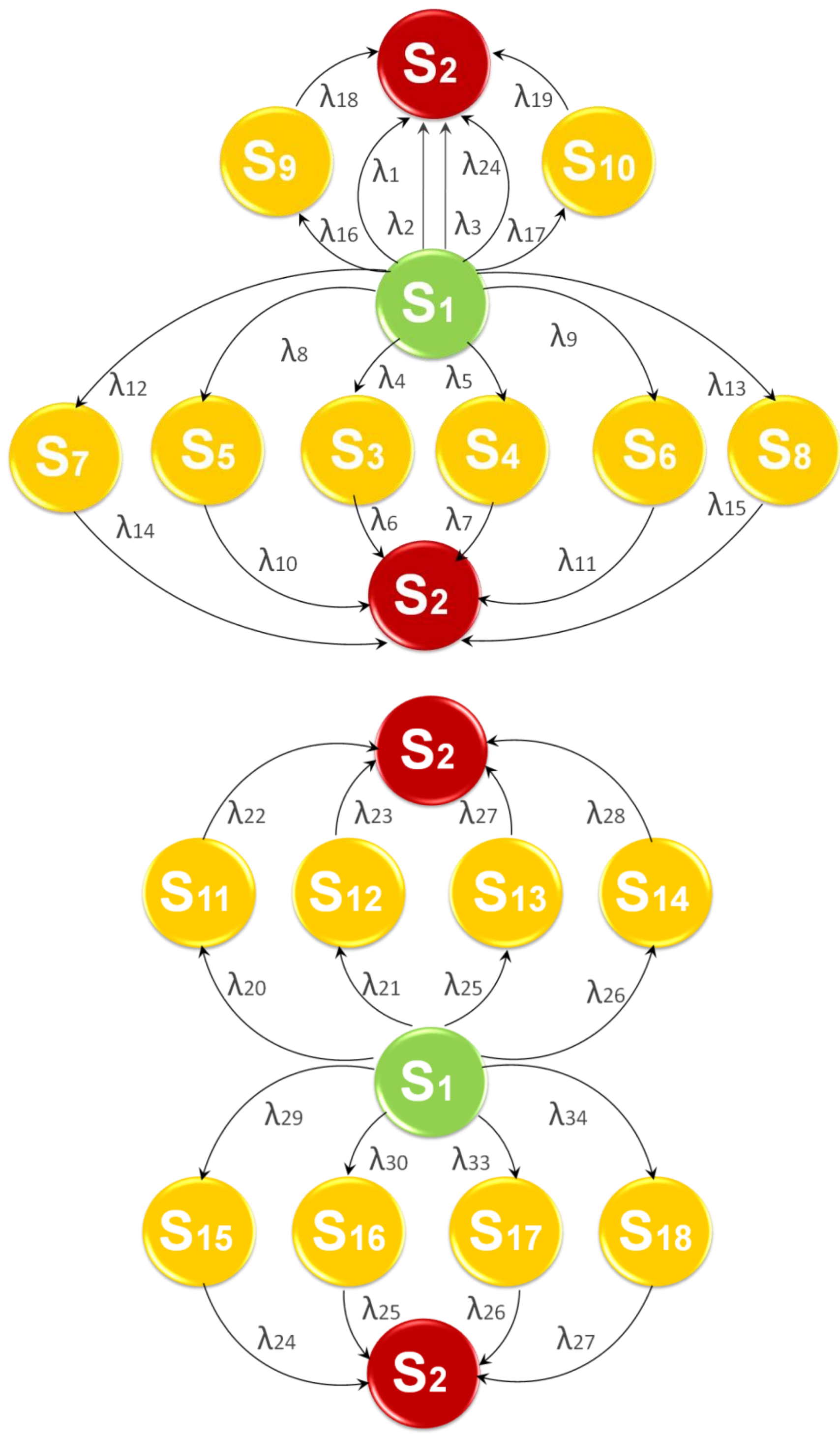


Figure 3-26 4200 KVA State Diagram up to farthest load (worst case scenario)

Table 3.7 4200 KVA Substation State Diagram Description Up to Farthest Load

STATE TRANSITION	TRANSITION PROBABILITY	TRAN RATE	α	EVENT DESCRIPTION
S1 → S2	λ1 = λL-31	0.00923	1	L-31 down
S1 → S2	λ2 = λTR-55	0.00127	1	Line Termination TR-55 down
S1 → S2	λ3 = λBS-4	0.000802	1	Bus Bar BS-4 down
S1 → S3	λ4 = λSG + λTR-50 + α λCB-16 + λTR-51 + λTR-52+ λL-30 + λATS	0.6794	0.5	The event where the standby generator SG fails or Line Termination TR-50 or Circuit Breaker CB-16 or Line Termination TR-51 or Line L-30 or the Automatic Transfer Switch (ATS) fails
S1 → S4	λ5 = αλM-1 + αλT-2 +α λTR-24	1.96317	1	The event where the Utility (M-1) or Transformer T-2 or Line Termination TR-24 fails
S3 → S2	λ6 = αλM-1 + αλT-2 +α λTR-24	1.96317	1	The event where the Utility (M-1) or Transformer T-2 or Line Termination TR-24 fails
S4 → S2	λ7= λSG + λTR-50 + α λCB-16 + λTR-51 + λTR-52+ λL-30 + λATS	0.6794	0.5	The event where the standby generator SG fails or Line Termination TR-50 or Circuit Breaker CB-16 or Line Termination TR-51 or Line L-30 or the Automatic Transfer Switch (ATS) fails
S1 → S5	λ8 = α λCB-13	0.00054	0.18	Circuit Breaker CB-13 down
S1 → S6	λ9 = αλL-14 + αλTR-26 + α λL-15 + α λTR-25 + αλL-13 + αλTR-53	0.014455	.5,.16, .5,.16, .5,.16	The event where Line L-14 or Line Termination TR-26 or Line L-15 or Line Termination TR-25 or Line L-13 or Line Termination TR-53 fails

S5 → S2	$\lambda 10 = \alpha\lambda L\text{-}14 + \alpha\lambda TR\text{-}26 + \alpha\ \lambda L\text{-}15 + \alpha\ \lambda TR\text{-}25 + \alpha\lambda L\text{-}13 + \alpha\lambda TR\text{-}53$	0.014455	.5,.16, .5,.16, .5,.16	The event where Line L-14 or Line Termination TR-26 or Line L-15 or Line Termination TR-25 or Line L-13 or Line Termination TR-53 fails
S6 → S2	$\lambda 11 = \alpha\ \lambda CB\text{-}13$	0.00054	0.18	Circuit Breaker CB-13 down
S1 → S7	$\lambda 12 = \alpha\ \lambda CB\text{-}13$	0.00054	0.18	Circuit Breaker CB-13 down
S1 → S8	$\lambda 13 = \alpha\ \lambda L\text{-}16 + \alpha\ \lambda TR\text{-}54$	.0048182	1	Line L-16 or Line terminationTR-54 fails
S7 → S2	$\lambda 14 = \alpha\ \lambda L\text{-}16 + \alpha\ \lambda TR\text{-}54$	.0048182	1	Line L-16 or Line terminationTR-54 fails
S8 → S2	$\lambda 15 = \alpha\ \lambda CB\text{-}13$	0.00054	0.18	Circuit Breaker CB-13 down
S1 → S9	$\lambda 16 = \alpha\ \lambda CB\text{-}32$	0.000414	0.18	Circuit Breaker CB-32 down
S1 → S10	$\lambda 17 = \alpha\ \lambda TR\text{-}74 + \alpha\ \lambda L\text{-}42 + \alpha\ \lambda L\text{-}43 + \alpha\ \lambda TR\text{-}82 + \alpha\ \lambda TR\text{-}83$	0.00984	.16,.5, .5,.16, .16	The event where Line Termination TR-74 or Line L-42 or Line L-43 or Line Termination TR-82 or Line Termination TR-83 fails
S9 → S2	$\lambda 18 = \alpha\ \lambda TR\text{-}74 + \alpha\ \lambda L\text{-}42 + \alpha\ \lambda L\text{-}43 + \alpha\ \lambda TR\text{-}82 + \alpha\ \lambda TR\text{-}83$	0.00984	.16,.5, .5,.16, .16	The event where Line Termination TR-74 or Line L-42 or Line L-43 or Line Termination TR-82 or Line Termination TR-83 fails
S10 → S2	$\lambda 19 = \alpha\ \lambda CB\text{-}32$	0.000414	0.18	Circuit Breaker CB-32 down
S1 → S11	$\lambda 20 = \alpha\ \lambda TR\text{-}58 + \alpha\ \lambda L\text{-}33 + \alpha\ \lambda TR\text{-}59$	0.005021	.16,.5, .16	The event where Line Termination TR-58 or Line L-33 or Line Termination TR-59 fails
S1 → S12	$\lambda 21 = \alpha\ \lambda CB\text{-}17$	0.00054	0.18	Circuit Breaker CB-17 down
S11→ S2	$\lambda 22 = \alpha\ \lambda CB\text{-}17$	0.00054	0.18	Circuit Breaker CB-17 down
S12→ S2	$\lambda 23 = \alpha\ \lambda TR\text{-}58 + \alpha\ \lambda L\text{-}33 + \alpha\ \lambda TR\text{-}59$	0.005021	.16,.5, .16	The event where Line Termination TR-58 or Line L-33 or Line Termination TR-59 fails

S1 → S2	λ24 = α λTR-56 + α λL-32 + α λTR-57 + λTR-60 + λL-34 + λTR-61 + λBS-5 + αλCB-18+ λTR-64 + λL-36 + λTR-65+ λBS-7 +λTR-66 + λL-37 + λTR-67 + αλCB-38 + λBS-8 + αλCB-40 + λTR-69 + λL-39+ λTR-71	0.0583074	.16,.5, .16,.5, .5,.5	The event where the Line Termination TR-56 or Line L-32 or Line Termination TR-57 or Line Termination TR-60 or Line L34 or Line Termination TR-61 or Bus Bar BS-5 or Circuit breaker CB-18 or Line Termination TR-64 or Line L-36 or Line Termination TR-65 Bar BS-7 or Line Termination TR-66 or Bus or Line L-37 or Line Termination TR-67 or Circuit Breaker CB-38 or Bus Bar BS-8 or Circuit Breaker CB-40 or Line Termination TR-69 or Line L-39 or Line Termination TR-71
S1 → S13	λ25 = α λTR-62 + α λL-35 + α λTR-63	0.005021	.16,.5, .16	The event where Line Termination TR-62 or Line L-35 or Line Termination TR-63 fails
S1 → S14	λ26 = α λCB-19	0.000414	0.18	Circuit Breaker CB-19 down
S13 → S2	λ27 = α λCB-19	0.000414	0.18	Circuit Breaker CB-19 down
S14 → S2	λ28 = α λTR-62 + α λL-35 + α λTR-63	0.005021	.16,.5, .16	The event where Line Termination TR-62 or Line L-35 or Line Termination TR-63 fails
S1 → S15	λ29 = α λTR-68 + α λL-38 + α λTR-70	0.005021	.16,.5, 16	The event where Line Termination TR-68 or Line L-38 or Line Termination TR-70 fails
S1 → S16	λ30 = α λCB-39	0.000414	0.18	Circuit Breaker CB-39 down
S15 → S2	λ31 = α λCB-39	0.000414	0.18	Circuit Breaker CB-39 down
S16 → S2	λ32 = α λTR-68 + α λL-38 + α λTR-70	0.005021	.16,.5, 16	The event where Line Termination TR-68 or Line L-38 or Line Termination TR-70 fails
S1 → S17	λ33 = α λCB-30	0.000414	0.18	Circuit Breaker CB-30 down

S1 → S18	$\lambda 34 = 7^*(\alpha\ \lambda TR\text{-}72 + \alpha\ \lambda L\text{-}40 + \alpha\ \lambda TR\text{-}80)$	0.002898	.16,.5, .16	The event where Line Termination TR-72 or Line L-40 or Line Termination TR-80 fails
S17 → S2	$\lambda 35 = 7^*(\alpha\ \lambda TR\text{-}72 + \alpha\ \lambda L\text{-}40 + \alpha\ \lambda TR\text{-}80)$	0.002898	.16,.5, .16	The event where Line Termination TR-72 or Line L-40 or Line Termination TR-80 fails
S18 → S2	$\lambda 36 = \alpha\ \lambda CB\text{-}30$	0.000414	0.18	Circuit Breaker CB-30 down

* S1: Represent the states where all components are working; S2: Represent the state where all components have failed and there is loss of power to the load. For a complete description of each state (from S1 to S26) please refer to Appendix E

Because Markov is a stochastic process the all state transitions probabilistic (determined by random choice). At each step the system may change its state from the current state or simply remain in the same state according to a probabilistic distribution. The changes of states are called transitions and the probability associated with various state changes are called transition probability. Tables 3.4, 3.5, 3.6 and 3.7 have shown us the transition probability from state to state in our system. Now that we have analyzed all possible states and probabilities in our system lets proceed to use this information as inputs to CARM software in order to generate several simulation plots that will help us assess the reliability of the India's power distribution system.

3.3.3 CARMS Simulations and Results

In this section we will assess the impact of analyzing our 2500KVA Substation and 4200KVA Substation utilizing different reliability configurations. We will see that some configurations are fault tolerant while others are not fault tolerant depending on which design component failure rates are been considered for the analysis. For example figure [3-27] shown below, shows us the system reliability curve up to the switchgear for the 2500KVA Substation (Section I) of the India's Brewery Power Distribution System analyzed up to the switchgear and taking into account the utility failure rate.

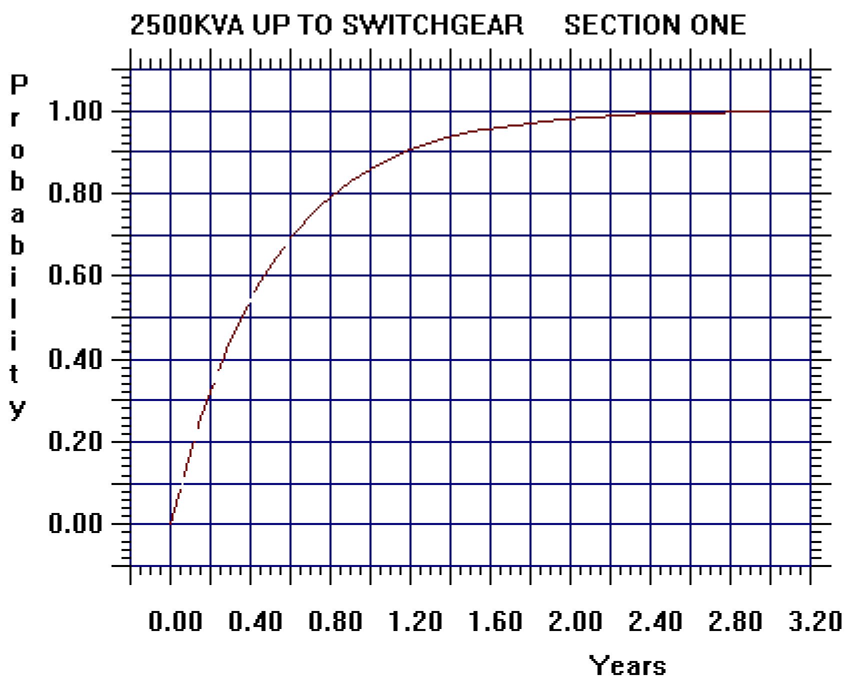


Figure 3-27 2500 KVA Substation Section 1 (Up to switchgear and including utility)

It is seen that the results obtained using CARMS method does not differ much from the results obtained using the Reliability Block Diagram Method (shown in Figure [3-9]). This is due to the fact that we took into consideration that this system is a radial system without redundancies and we have included the utility for both analyses (CARMS and Reliability Block Diagram). Let's recall that utility failure rate is approximately 1.956 per year, and then it has a big impact in the system analysis wherever it is included since failure rates for other system components such as lines, circuit breakers, transformers, terminations or capacitors are much smaller. Failure rates for other system components other than utility have values ranging between .0001-.9. When comparing the utility failure rate with the other system components failure rate it is seen that the utility failure is approximately 200% bigger. After noticing this huge difference between failure rates and after performing the required simulations we know that this system is not a fault tolerant system anymore. Knowing this, it is implied that a simple reliability estimation like the one we did for the reliability block diagram analysis, where we only considered the probability of a system working properly or not working at all, will be enough to arrive to any reliability results without the need of using failure modes (refer to Failure Mode Analysis in Appendix C).

Table 3.8 Markov and RBD Failure Probability Results for 2500 KVA Substation Section 1 (Up to switchgear, including utility)

Years	RBD	Markov Approach	% Error
0.5	0.63	0.62	1.612
1	0.86	0.85	1.176
1.5	0.95	0.94	1.063
2	0.985	0.977	0.818

Table 3.8 is a comparison between failure probabilities obtained using both methods, reliability block diagram (RBD) and Markov approach (CARMS). The failure probability with respect to time of both analyses is almost the same; and the error percentage between

both analyses is 1%. This error percentage could be slightly better; we need to take in to consideration that this analysis (Markov) was made up to the switchgear and not up to the load. For the analysis of a non fault tolerant system is better to use the RBD Method since it gives us a better approximation. Also the RBD method is simpler and faster.

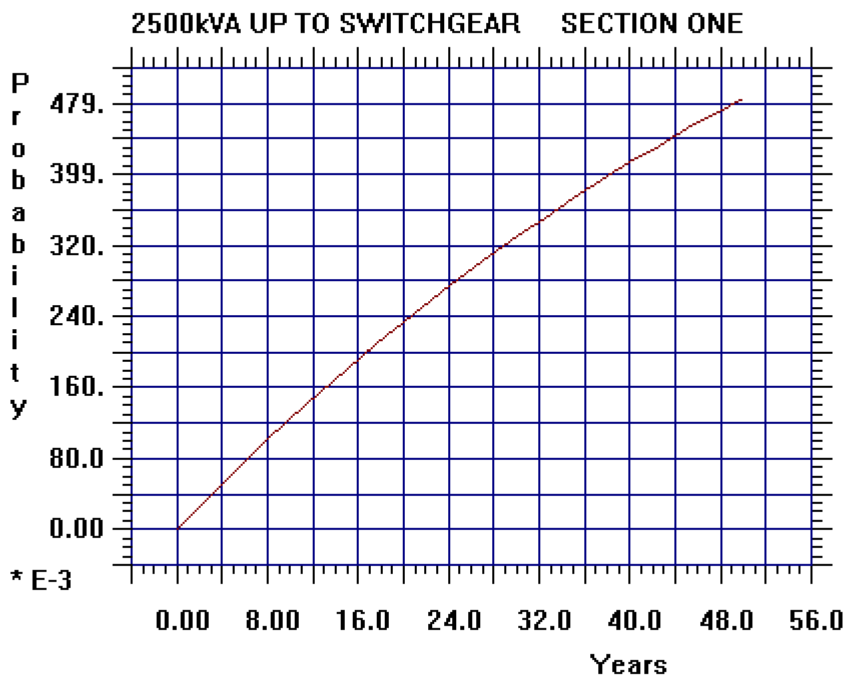


Figure 3-28 2500 KVA Substation Section 1 without utility and up to switchgear

Figure [3-28] shows the Reliability Curve for the 2500KVA Substation (Section I) up to the switchgear. In this Analysis the effect of the utility failure rate was not taken in to consideration. Since the utility failure rate is eliminated from this analysis then we can consider our system as a fault tolerant one and the simulation time varies from 30 to 50 years. This is because the system is expected to last longer (to be fault tolerant) than if the utility failure rate is consider for the analysis (not fault tolerant). The difference through time for both simulations can be seen in figure [3-28] (Markov Approach), figure [3.7] (Reliability Block Diagram) and table 3.9 shown below.

Table 3.9 : Markov and RBD Failure Probability Results for 2500 KVA Substation Section 1 without utility and up to switchgear

Years	RBD	Markov Approach	% Error
8	0.16	0.1	60
16	0.285	0.19	50
24	0.4	0.275	45.4
30	0.5	0.33	51.5
40	0.59	0.415	42
48	0.66	0.472	40
50	0.7	0.487	43.7

From this table is appreciated that the error percentage of both methods (Markov and RBD) have an average value of 47% which indicates us that Reliability Block Diagram method cannot manage fault tolerant system very well.

It is important to mention that not all probabilities that produce reliability success on our system are considered in the next simulations to be discussed in this section. For example, failure rate number 9 ($\lambda 9$) contained in table 3.4 represent the failure probability when all circuit breakers 1 through 6 are down. This probability is extremely low and has no effect on the simulation. Then, the next question arises; how many circuit breakers would have to fail in order to see an impact on the system simulation? The answer to this question is very simple: Only One Circuit Breaker would have to fail to see an impact on the system simulation. If a circuit breaker fails in combination with another electrical component such as a line, bus bar, or termination for example, the total failure rate will be in the order of 10^-6 which is a good failure rate for a fault tolerant system. The failure probability of one system component and two circuit breakers is around 10^-9, this number is so low that it does not have any effect on the simulation.

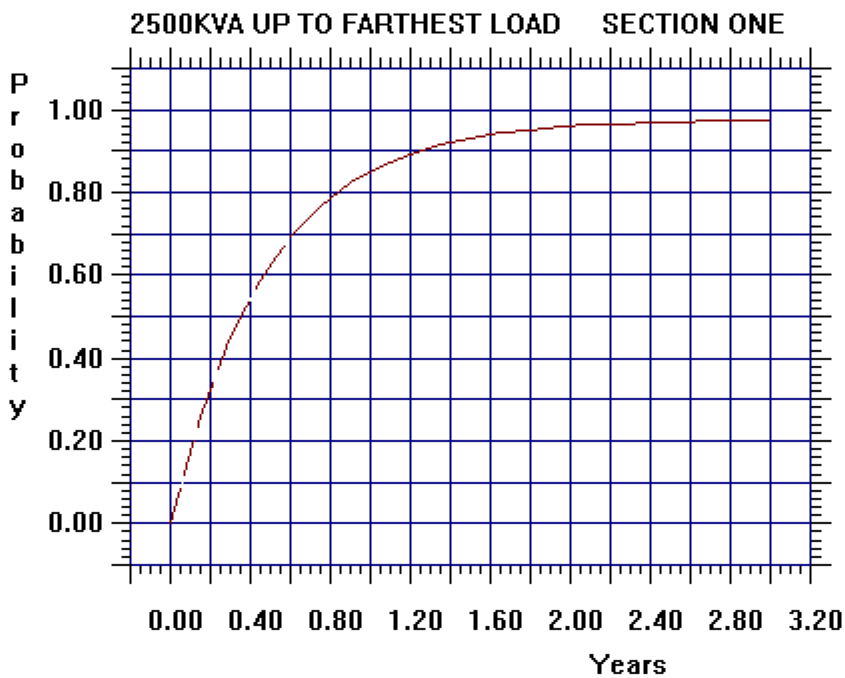


Figure 3-29 2500 KVA Substation Section 1 (with utility and up to farthest load)

Figure [3-29] shown above, shows us the reliability curve for the 2500KVA Substation up to the farthest load considering the effect of the utility failure rate. This curve presented in figure [3-29] is similar to the curve presented in figure [3-27] (simulation up to switchgear), knowing this we can ask ourselves the next question: Why there is no difference between curve generated from the analysis up to the switchgear and the curve generated from the analysis up to the farthest load? The answer to this question is that simulations made using Markov method utilize differential equations where each equation represents the failure probability ratio with respect to time. Same equations are used for both simulations with some extra equations for the farthest load simulation. The equation holding the utility failure rate is the equation that has the biggest overall failure rate and if we add to this equation other equations with smaller failures probabilities this will not have any effect on the system reliability. This is the reason why the reliability curve for the farthest load simulation is similar to the reliability curve up to the switchgear. Also, this is the reason why when you add the utility failure rate to the analysis the system is no longer a fault tolerance system.

Table 3.10 Markov and RBD Failure Probability Results for 2500 KVA Substation Section 1 with utility and up to farthest load

Years	**Markov up switchgear**	**Markov up to farthest load**
0.5	0.62	0.62
1	0.85	0.85
1.5	0.94	0.94
2	0.977	0.975

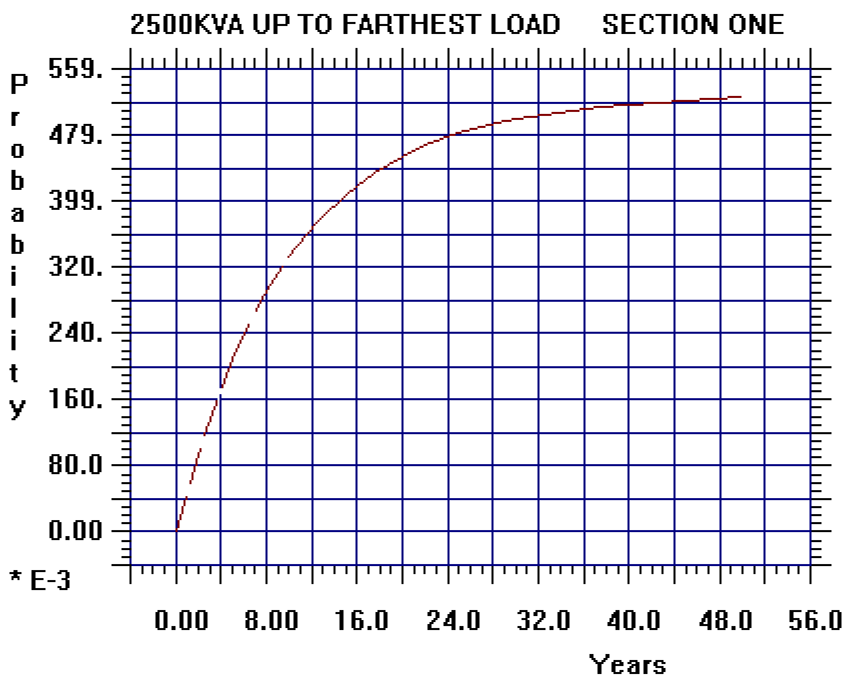


Figure 3-30 Figure 3-30 2500 KVA Substation Section 1 without utility and up to farthest load

Figure [3-30] above, shows us the reliability curve for the 2500 KVA Substation (section I) up to the farthest load. For this analysis we are not considering the effect of the utility failure rate. The system becomes less reliable depending on how many components exist between the utility and the load. Figure [3.24] shows us the diagram for this specific analysis configuration where we are performing a reliability analysis up to the farthest load. From this Figure [3.24] it can be seen that the configuration up to the farthest load takes more states than the configuration up to the switchgear shown on figure [3.23]. It is also important to mention that the failure rate per year for each line is a function of longitude, then if the only difference between both configurations is a line of great longitude that will be enough to cause an impact on the reliability curve of the system. From this, it can be concluded that the failure probability of a load that is far from the energy source is greater than the failure probability of load that is closer to the energy source.

Table 3.11 Markov and RBD Failure Probability Results for 2500 KVA Substation Section 1 without utility and up to farthest load

Years	Markov Approach up to switchgear	Markov up to farthest
8	0.1	0.29
16	0.19	0.42
24	0.275	0.479
30	0.33	0.5
40	0.415	0.519
48	0.472	0.523
50	0.487	0.526

Table 3.11 shows the tabulated results from the same analysis using Markov method and Reliability Block Diagram Method. For the first 30 years the failure probability slope is greater for the farthest load analysis than for the up to the switchgear analysis. Also from table 3.11, figure [3.28] and figure [3.30] it is noted a difference in failure probability through time where the farthest load analysis produce a less reliable number and the analysis up to the switchgear has better reliability number.

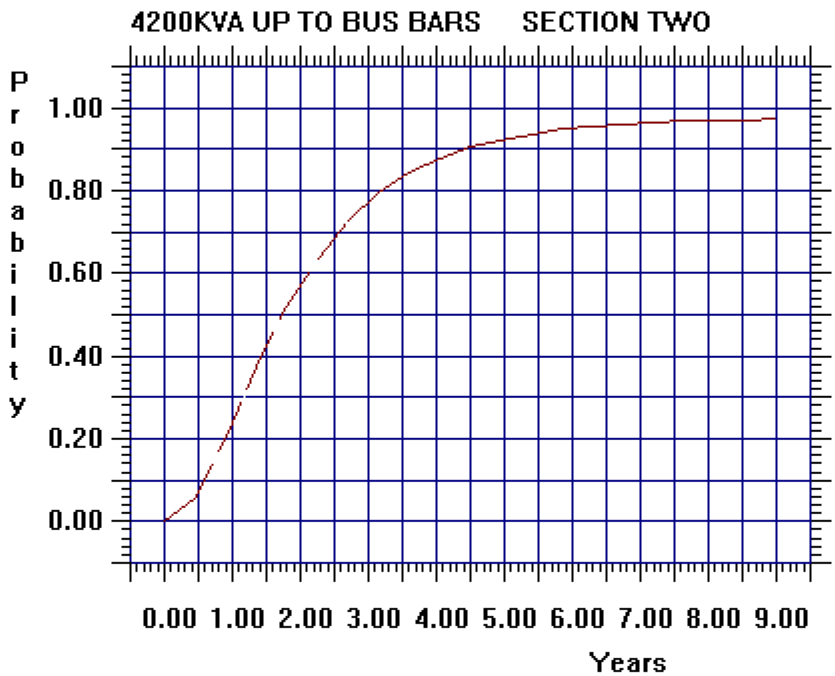


Figure 3-31 4200 KVA Substation Section 2 (with utility and up to bus bar)

Figure [3-31] shown above, shows us the probability curve where busbar-4 and busbar-5 fails simultaneously. This analysis is done for the 4200KVA Substation (Section II) of India's Brewery Company. In the event of both Bus bars (fourth and sixth) failing at the same time no power will be supplied to any load on the system. This 4200 KVA Substations electrical system is basically the same as the electrical system for the 2500 KVA Substation, noticing a difference that for Section II we have a diesel generator as a redundant power supply in case of an outage. It is important to mention that the operations logistics for this redundant system was assumed in order to complete the analysis. It was assumed that there is a relay that is monitoring the system at all times in case there is an abnormal situation in the transformer low voltage side. Once an abnormal situation occurs a signal is send to a transfer switch which supply power to the electrical system. This assumption was made due to the fact that we had no access to the control system squematic for this configuration.

Even when the 2500 KVA Substation and the 4200 KVA Substation are slightly different we can still compare both to see what advantages arise when having a redundant configuration. Sometimes is difficult to compare two electrical designs but in this case we can say that if section II would not have had the redundant configuration; it would have been less reliable than section I. This is because section II has more components which increase the failure probability. When comparing figure [3-31] and figure [3-14] it can be seen that there is a change in failure probability. The Failure probability with respect to time for section I, is greater than the failure probability of section II by approximately a factor of 3.

Table 3.12 Markov and RBD Failure Probability Results for 4200 KVA Substation Section 2 with utility and up to bus bar

Years	RBD	Markov Approach	% Error
1	0.42	0.22	90.1
2	0.72	0.57	26.31
3	0.87	0.85	2.35
4	0.93	0.92	1.0869
5	0.966	0.95	1.68
6	0.983	0.97	1.34
7	0.989	0.98	0.918
8	0.99	0.985	0.507
9	1	0.985	1.522

Table 3.12 presents the values obtained from figure [3-31] and figure [3-14] when the reliability block diagram and Markov method are used. From this table it can be seen that both curves differ at the beginning of the time (during the first two years mainly). During the first year there is a 90% error and during the second year there is a 26% error between both curves. After the third year both methods tend to converge to the same failure probability number.

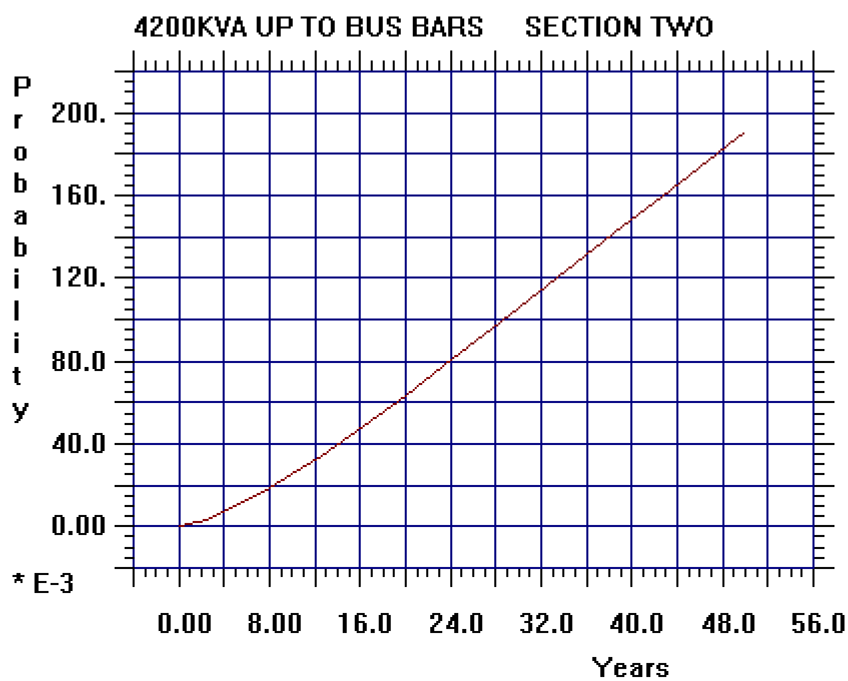


Figure 3-32 4200 KVA Substation Section 2 (without utility and up to bus bar)

Figure [3-32] shows us the reliability curve up to the bus bar 4 and bus bar 6 for the 4200KVA Substation (section II). For this specific analysis it is considered that the power provided by the utility is 100% reliable, in other words that the utility failure rate is not going to be considered for this analysis (as it was done in the second simulation for the 2500KVA Substation). This simulation was performed to see what would be the failure probability up to the bus bar 4 and bus bar 6 (including the diesel generator) if it were not to be considered the utility failure rate. Since this is a fault tolerant configuration the analysis must be done from 30 to 50 years in order to determine any changes in failure probabilities through time. If it's compared, figure [3-32] and figure [3-12] which are the probability curves for this same configuration obtained using reliability block diagram method and Markov method respectively, it is going to be seen that both simulations shows a different incremental behavior. The RBD method provides a greater failure probability through time, with a 383% of error (refer to table 3.13) when compared with the value obtained using Markov method. This difference arises because for RBD method it was analyzed the whole system while for Markov Method we analyze only up to the Bus Bars. Even when the utility failure rate is not considered in the analysis the failure probability of our system (even without redundancy) is about .20 which is a good number if considering that our system has been analyzed for 50 years. Table 3.13 below shows the error percentage for this analysis.

Table 3.13 Markov and RBD Failure Probability Results for 4200 KVA Substation Section 2 without utility and up to bus bar

Year	RBD	Markov Approach	% Error
8	0.102	0.02	410
16	0.27	0.05	440
24	0.425	0.08	431
30	0.53	0.105	404
32	0.578	0.115	402
40	0.68	0.15	353
48	0.782	0.185	322
50	0.788	0.195	304

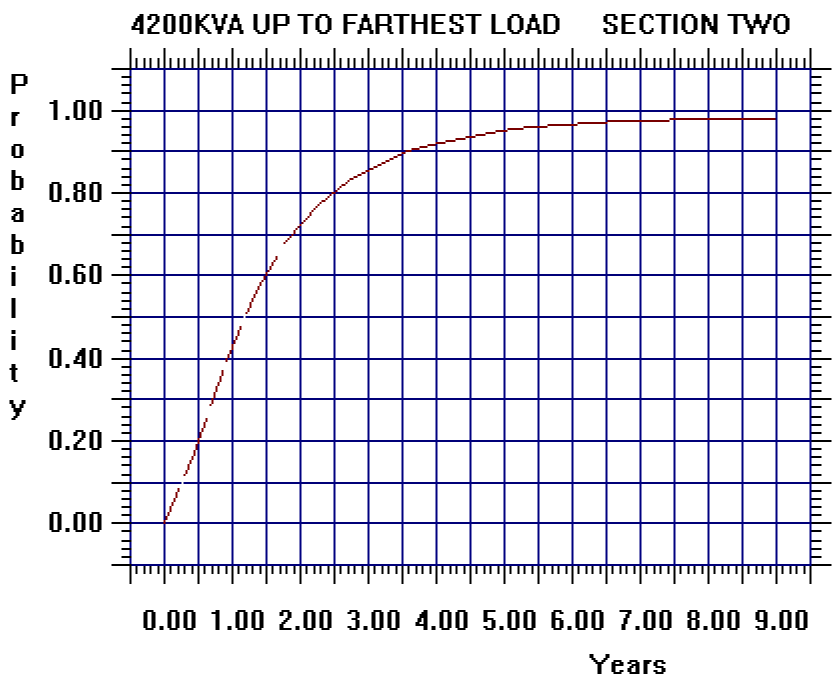


Figure 3-33 4200 KVA Substation Section 2 (with utility and up to farthest load)

Figure [3-33] shows the reliability curves for the 4200 KVA substation up to the farthest load including the utility failure rate. As it was said before the analysis up to the farthest load is the worst case scenario. Its failure probability is higher because of all its electrical components included directly and indirectly into the design. For example, if the one line diagram for the 4200KVA Substation is take it can be seen that the farthest load is located at terminal TR-71, then all circuits in this path (from utility to the load at TR-71) can potentially fail (these are known as direct failures). Also there is the case were other electrical components that are not located in the direct path between the utility and TR-71 can potentially cause a failure in the system (These are known as indirect failures). For example, going back to the one line diagram it can be seen from it that if any of the circuit breakers from CB-30 to CB-37 fails open, this failure will be reflected upstream on another circuit breaker (located on the direct path from the utility to TR-71) which will open in order to protect the system. Because of this, the farthest load will experiment a power interruption.

Taking a close look to this figure [3-33] it can be seen that at nine years the failure probability is .98, which tells us that if the system has not failed during nine years the probability that it will fail as the prediction says is high. If figure [3-33] is compared with figure [3-31] (up to bus bar) it can be thought that there is not much difference between both because at nine years the probability is .96, but the truth is that both plots converge towards the same value. If we analyze the slope of figure [3-33] it is seen that the $\lim_{t\to 0}\left(\frac{\Delta P}{\Delta t}\right)$ that characterize the failure probability function is greater.

Table 3.14 Markov up to farthest load and up to bus bar failure probabilities through time for 4200 KVA Substation Section 2 with utility and up to farthest load

Years	**Markov up to Farthest Load**	**Markov up to Bus Bar**
1	0.43	0.22
2	0.72	0.57
3	0.85	0.76
4	0.92	0.87
5	0.95	0.93
6	0.97	0.955
7	0.98	0.97
8	0.985	0.975
9	0.985	0.98

From table 3.14 we can see that the greatest difference happen from 0 to 4 years. During this time period the failure probability is greater for the farthest load analysis than for the analysis it is taken into consideration the electrical components up to the bus bar.

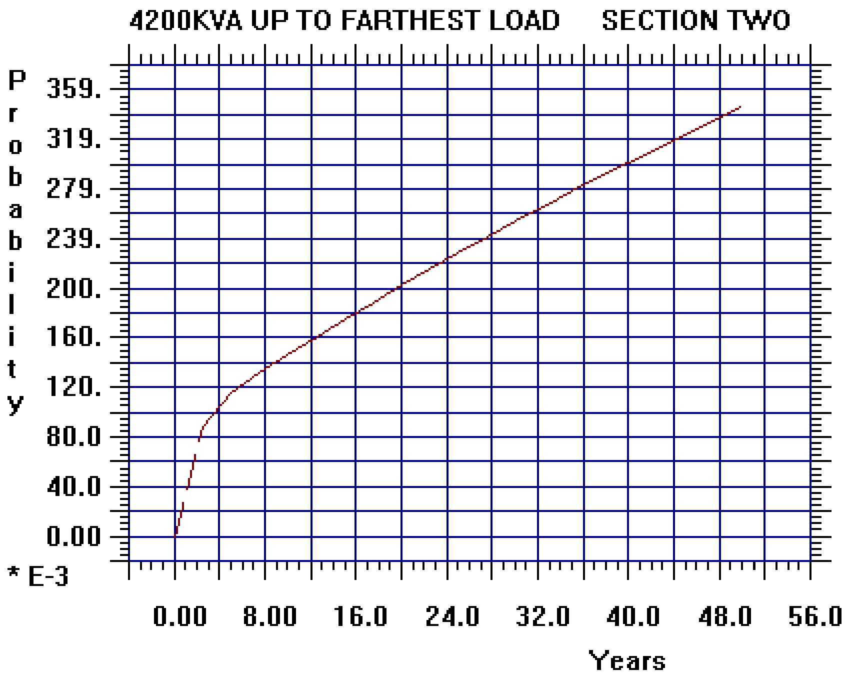


Figure 3-34 4200 KVA Substation Section 2 (without utility and up to farthest load)

Figure [3-34] shows the probability curve for the 4200KVA Substation (Section II) up to the farthest load disregarding the effect of the utility failure rate. As it was learned from previous cases this represents the worst case scenario because of all the electrical components the system have between the transformer and the farthest load. All of these components affect the failure probability of the system directly or indirectly. Since the effect of the utility failure rate has been neglected then it can be considered this as a fault tolerant system. This means that its simulation time will be around 50 years. There is a need to show the worst case scenario because if we were to improve a design we need to know its weaknesses. Now, if we take a close look to table 3.15, figure [3-34] and figure [3-31], it is noticed a big reliability difference through time. Here it is seen that the failure probability up to the farthest load is three times greater than the failure probability up to the bus bars.

Table 3.15 Markov up to farthest load and up to bus bar failure probabilities through time for 4200 KVA Substation Section 2 without utility and up to farthest load

Years	Markov up to Farthest Load	Markov up to Bus Bar
8	0.135	0.02
16	0.18	0.05
24	0.224	0.08
30	0.249	0.105
32	0.259	0.115
40	0.299	0.15
48	0.339	0.185
50	0.346	0.195

4 CONCLUSIONS AND FUTURE WORK

In this engineering project it was performed a Reliability Analysis on India's Power Distribution System design in order to assess any reliability problems. A Failure Mode Effect Analysis (FMEA) was performed in order to be able to address any potential critical or catastrophic failures in this design. This FMEA analysis should be done on the early stages of the design. Since we were not designing but assessing any potential reliability problem on the design, this tool was used to identify those systems weak spots. It is important to say that no catastrophic failures were found on the power system during this analysis. However, some design improvements or compensating provisions were provided in order to address the critical failures that were found. For examples it was found that if power transformer on 2500 KVA Substation System fails open, short or with a parameter change, this will cause loss of power to all loads and subsequently to the whole substation (This event is considered a critical failure since a major function of the system is lost). Although this kind of failure is unlikely, it was seen from the original design that no compensating provision is being provided to mitigate it. For this reason it was suggested that a system redundancy such as a second transformer connected in parallel or an alternate 480V AC generation system should be provided in order to mitigate this failure.

The next step was to quantify the reliability of our system, for this, different methods were used. The first method used in this work was the Reliability Block Diagrams (RBD's) method. This method is one of the most used because of its simplicity and ease of use. We have modeled our power distribution system using RBD as an aid to understand the different reliability configurations in our system. This analysis helped us understand which components were connected in series or in parallel as well as to understand the impact of each configuration in the overall system reliability. To perform this analysis it has been used the exponential distribution. The exponential distribution is one of the most important distributions in reliability calculations. Specifically, it is used heavily for reliability prediction of electronic equipment. This is due to the general lack of a wearout mechanism on electrical components. Electrical components present a constant failure rate through time. An exponential distribution is good for modeling items whose failure rate changes negligibly with age (as the components been used on this projects) and equipments whose infant mortalities have been eliminated. Then, using the exponential distribution as a mathematical model it was seen that the reliability of our system decreased exponentially through time. This behavior is due to the increase in failure probability for each component through time. The third method used in this work and the most important was the reliability analysis using Markov approach where state diagrams were used to provide reliability numbers more closely to reality. Two tools were used as an aid to implement these methods, the first tool was BlockSim were the reliability block diagrams created were used as an input to produce the results and CARMS tools were the state space model created were also used as an input to produce reliability results.

Using both tools different simulations were performed on the 2500 KVA substation and the 4200 KVA Substation. These were:

- Simulation up to switchgear considering the effect of utility failure rate (All loads failed).
- Simulation up to switchgear not considering the effect of the utility failure rate (All loads failed).
- Simulation up to the farthest load considering the effect of the utility failure rate (Worst Case Scenario).
- Simulation up to the farthest load not considering the utility failure rate (Worst Case Scenario).

For both Substations analysis it was seen that the reliability numbers does not varied much when analyzing up to the switchgear versus analyzing up to the farthest load which is the worst case scenario (as it was seen on figures 3-27, 3-29 and 3-31, 3-33.). Both analyses were made considering the effect of the utility failure rate. The reason that there is basically no difference between the two simulations is due to the fact that these simulations are based on a series of differential equations which contains the utility failure rates in it. For this very same reason when we compared simulations made not considering the utility failure rate it was seen a noticeable difference on failure probabilities vs. time. Also, if RBD and Markov methods simulations (not considering utility failure rate) are compared, it is seen that there is no bigger difference between both curves. This makes the RBD method a good approximation. On the other hand it was seen that wherever the utility failure rate was neglected the change in reliability numbers when analyzing up to the farthest load vs. when analyzing up to the switchgear was well appreciated. From this, we have concluded that the more complexity on the systems the more components we will have that will increase the failure probability of the system, thus decreasing the overall reliability. From all these analyses we have assess the importance of redundant configurations such as redundant diesel generators to increase the overall system reliability. Redundant configurations mitigate the failure probability of a system.

Using these tools to analyze the system we have also concluded that if we consider our system a fault tolerant one, this system will be able to last approximately 30 years while if we analyzed the system as a not fault tolerant system it will last approximately from 3 to 10 years only.

The existent India's Brewery Power Distribution System does meet a good reliability performance. Considering the system a fault tolerant one we have that this power system is able to last up to 30 years. However, slight improvements could be done on the design as to make it even more reliable.

Two possible approaches to improving the reliability of a system will be:

- To make the system Fault Tolerant
- The system to have Fault Avoidance

Fault avoidance is achieved by using high-quality and high-reliability components and is usually less expensive than fault tolerance. Fault tolerance, on the other hand, is achieved by redundancy. Redundancy can result in increased design complexity and increased costs through additional weight, space, etc. These methods are suggested to improve reliability in basically any design and any of them can be used as an approach to improve our system reliability, but that really depends on the company and how much money they will like to invest in improving system reliability. Before deciding whether to improve the reliability of a system by fault tolerance or fault avoidance, a reliability assessment for each component in the system should be made. This was done throughout the work of this engineering project. The reliability of each system component was assessed and their behavior when working together as a system. Once the reliability values for the components were quantified, an analysis was performed in order to determine if the system's reliability goal was met. Since the India Power distribution system (located at Mayaguez, Puerto Rico) was used as a mean to perform our reliability study, we really did not have any system reliability requirement to meet. What it was really needed was to assess the reliability of the existent system and see how the system behaved and how reliable it was. The methods to perform reliability assessments presented throughout this work can not only be used to measure the reliability of the India's brewery distribution power system, but it can also be applied to all other power distributions systems designs of all other industries in Puerto Rico. This way we are able to explore new design configurations that will have the ability to provide better system reliabilities. This study also opens the door to explore new technologies that could possibly replace actual designs in order to make them more efficient, reliable and cost effective.

Having completed this industrial reliability power distribution assessment the next step will be to perform a complete *Life Cycle Cost Analysis* [1] on the different design configurations. This study should also be extended to the rest of the design in order to address new changes. We also suggest performing the reliability study presented throughout this work taking into account all systems loads; this, with the purpose of observing and analyzing the impact on the reliability curves. A maintainability and testability analysis can also be performed on this power distribution design to see the effect on the reliability and availability of the system once it is maintained regularly. Correct testing and maintenance of the systems will mitigate the failure probability with respect to time.

The reliability study using different reliability methods presented in this work it's also the step Stone to perform reliability studies on future renewable energy systems in order to determine their benefits and to assess the differences with the traditional power systems designs.

[1] The sum of initial and future costs associated with the construction and operation of electrical system over a period of time is called the life cycle cost of a power system.

REFERENCES

[1] IEEE Std. 493-1997 **"Reliability Analysis and Cost Evaluations"**, Standards Coordinating Committee, IEEE 1998, pp.101-133.

[2] Kobi Yahav; Gideon Oron; Warren Young; **"Reliability Assessment and Performance Based Incentives Of Power Distribution Systems"**, IEEE Transactions on Power Systems, 2008, pp222-226.

[3] Antonio, Pievatolo; Enrico, Tironi; Ivan, Valade; **"Semi-Markov Processes for Power System Reliability Assessment With Application to Uninterruptible Power Supply"**, IEEE Transactions on Power Systems, Vol. 19, No. 3, August 2004, pp1326-1333.

[4] Jasper F. L.; Van Casterener; Math H. J. Bollen; Martin E. Schmieg; **"Reliability Assessment in Electrical Power Systems: The Weibull-Markov Stochastic Model"**, IEEE Press, 2000, pp911-915.

[5] Wandai Wang; James M. Loman; Arno, Pantelis Vassiliou; Edward R. Furlong; Doug Odgen; **"Reliability Block Diagram Simulation Techniques Applied to the IEEE Std. 493 Standard Network"**, IEEE Press, 2004, pp.887-895.

[6] Fang Yang; A. P. Sakis Meliopoulos; George J. Cokkinides, Q. Binh Dam; **"Effects of Protection System Hidden Failures on Bulk Power System Reliabilitgy"**, IEEE Press, 2000, pp517-523.

[7] Dan, Zhu; **"Power System Reliability Analysis with Distributed Generators"**, IEEE Press, Blacksburg, VA, May 2003, pp.1-80.

[8] Department of Defense United States of America; **"Reliability Prediction of Electronic Equipment**" MIL-HDBK-217F 1 December 1991. Pages 1-205.

[9] IEEE Std. 493-1997 **"Gold Book, IEEE recommended practice for the design of reliable industrial and commercial power systems"**, Standards Coordinating Committee, August 1998.

[10] Pukite, Jan; Pukite, Paul **"Modeling for Reliability Analysis, Markov Modeling for Reliability, Maintainability, Safety, and Supportability Analyses of Complex Computer Systems"**, IEEE Press Series, 1998.

[11] David Irwin, J.; **"Basic Engineering Circuit Analysis"**, 3rd ed., Macmillan Publishing Company: NY, USA, 1990, pp.890-899.

[12] Douglas C., Montgomery; George C., Runger; **"Applied Statistics and Probability for Engineeris"**, 3rd ed., John Wiley & Sons, Inc: 2003.

[13] John A, Camara; **"Electrical Engineering Reference Manual for the Electrical and Computer PE Exam"**, 6th ed., Professional Publications, Inc: Belmont, CA, 2002, pp49.1-51.10.

[14] Thomas L., Floyd **"Digital Fundamentals"**, 8th ed., Prentice Hall: Columbus, OH, 2003.

[15] ReliaSoft **"BlockSim 7 Training Guide"**, ReliaSoft Corporation, USA, 2008, pp1-101.

[16] Department of Defense United States of America; **"Electronic Reliability Design Handbook"**, MIL-HDBK-338B, 1 October 1998.

[17] F. Shi, A, Sullivan; H. Sahagian; **"Integrated Power Systems with Fault Tolerant Attributes"**, IEEE, 1997, pp443-447.

[18] M.E Jackowski; Mark W., Bailey; **"The Development of A High Reliability Auxiliary Power System for a Coal Fired Cycling Generating Station"**, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 6, June 1983, pp1482-1485.

[19] J. Endrenyi; **"Reliability Modeling in Electric Power Systems"**, John Wiley, 1978, pp.1-91

[20] R. Billinton; R. Allan; **"Reliability Evaluation of Power Systems"**, 2nd ed., Plenum Press, 1996, pp. 222-298.

[21] Gabriel J., Paoletti; Martin, Baier; **"Failure Contributors of MV Electrical Equipment and Condition Assessment Program Development "**, IEEE Press, 2002, pp.1668-1675

[22] DigSilent; **"Reliability Analysis and Reliability Assessment"**, DigSilent Software, August 1998, pp.1-12.

[23] R. Billinton; R. Allan; L. Salvaderi; **"Applied Reliability Assessment in Electrical Power Systems"**, IEEE Press, 1991.

[24] J. Endrenyi; **"Reliability Modeling in Electric Power Systems"**, John Wiley, 1978, pp.1-91

[25] S. B. Choi; K.Y. Nam; D. K. Kim; S. H. Jeong; H. S. Ryoo; J.D. Lee; **"Evaluation of Reliability of Distribution Power System in Industrial Complex in Korea"**, IEEE, PSCE, 2006, pp718-724.

[26] James D., McCalley; **"Reliability Assessment of Electric Power Systems"**. [Online] Available: http://www.ee.iastate.edu/~jdm/ee455/admin.doc.

[27] Item Software; **"Reliability and Risk Analysis, Fault Tree Analysis"**. [Online] Available: http://www.reliabilityeducation.com

[28] Walpole, Myers; Ye, Myers; **"Probability & Statistics For Engineers and Scientists", 7th ed.**, Pearson Education, Inc , 2002.

[29] William Grant, Ireson; Clyde F, Coombs; Richard Y. Moss ; **"Handbook of Reliability Engineering and Managements", 2nd ed.**, McGraw-Hill Professionals Publishing , 2000, pp.1-816.

[30] Richard E., Brown; **"Electric Power Distribution Reliability",** CRC Press, 2002, pp.1-365

[31] Alessandro, Birolini; **"Reliability Engineering", 5th ed.**, Springer, Inc , 2007, pp.1-593.

[32] Erkki, Lakervi; E. J. Holmes; **"Electricity and Distribution Network Design", 2nd ed.**, IET , 1996, pp.70-100.

[33] H. Wayne Beaty; **"Electric Power Distribution System",** PennWell Books , 1998, pp.47-66.

[34] MIL-HDBK-217F; **"Military Handbook, Reliability Prediction of Electronic Equipment",** Department of Defense, Washington DC, December 1991, pp.1-205.

[35] Sannino, A.; Postiglione, G.; Bollen, M.H.J.; **"Feasibility of a DC network for commercial facilities"** Industry Application, IEEE Transactions on, 2003. Pages 1-8.

[36] MIL-HDBK-338B; **"Military Handbook, Electronic Reliability Design Handbook",** Department of Defense, Washington DC, October 1998, pp.1-1046.

[37] J. Ciezki, R. Ashton, **"Selection and Stability Issues Associated with Navy Shipboard DC Zonal Electric Distribution System,"** IEEE Transactions on Power Delivery, vol.15, no.2 Apr 2000, pages 665-669

[38] Sannino, A.; Nilsson, D.; **"Efficiency analysis of low-and medium-voltage DC distribution systems"** Power Engineering Society General Meeting, 2004.IEEE Pages 2315-2321.

[39] Engelen, Kristof; Shun, Erik Leung; Vermeyen, Pieter; Pardon, lef; D'hulst, Reinhilde; Driesen, Johan; Belmans, Ronnie; **"The Feasibility of Small-Scale Residential DC Distribution Systems"** IEEE Industrial Electronics, IECON 2006-32nd Annual Conference on, Pages 2618-2623

[40] Starke, Michael; Tolbert, Leon; Ozpineci, Burak; **"AC vs. DC Distribution: A Loss Comparison"** Power Engineering Society, 2008.IEEE Press, Pages 1-7.

[41] MIL-HDBK-1629; **"Military Handbook, Procedure for Performing a Failure Mode, Effect and Criticality Analysis",** Department of Defense, Washington DC, October 1998, pp.1-80.

APPENDIX A. ONE LINE DIAGRAM

2500KVA SUBSTATION SECTION I ONE LINE DIAGRAM

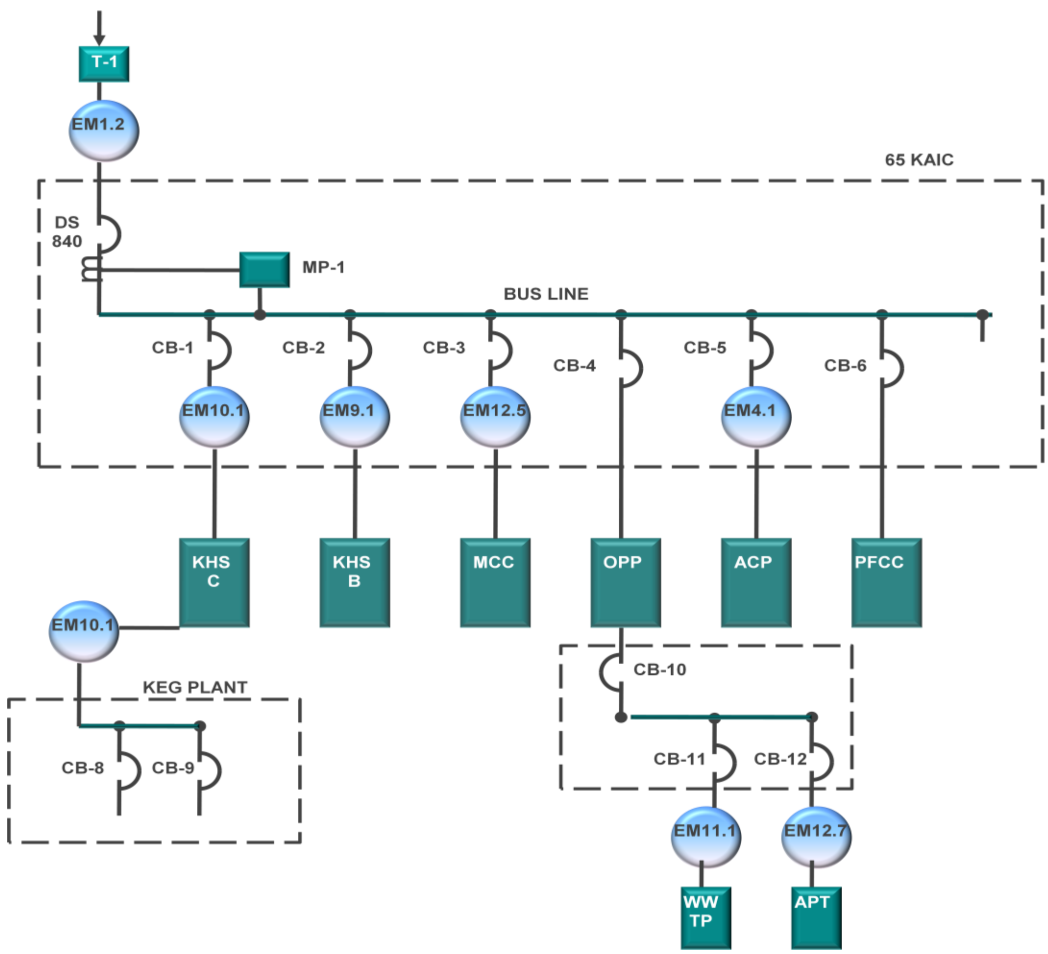


Figure A-1: 2500 KVA Substation One Line Diagram. Refer to Appendix B for more details on components ratings and descriptions.

4200KVA SUBSTATION SECTION II CIRCUIT A ONE LINE DIAGRAM

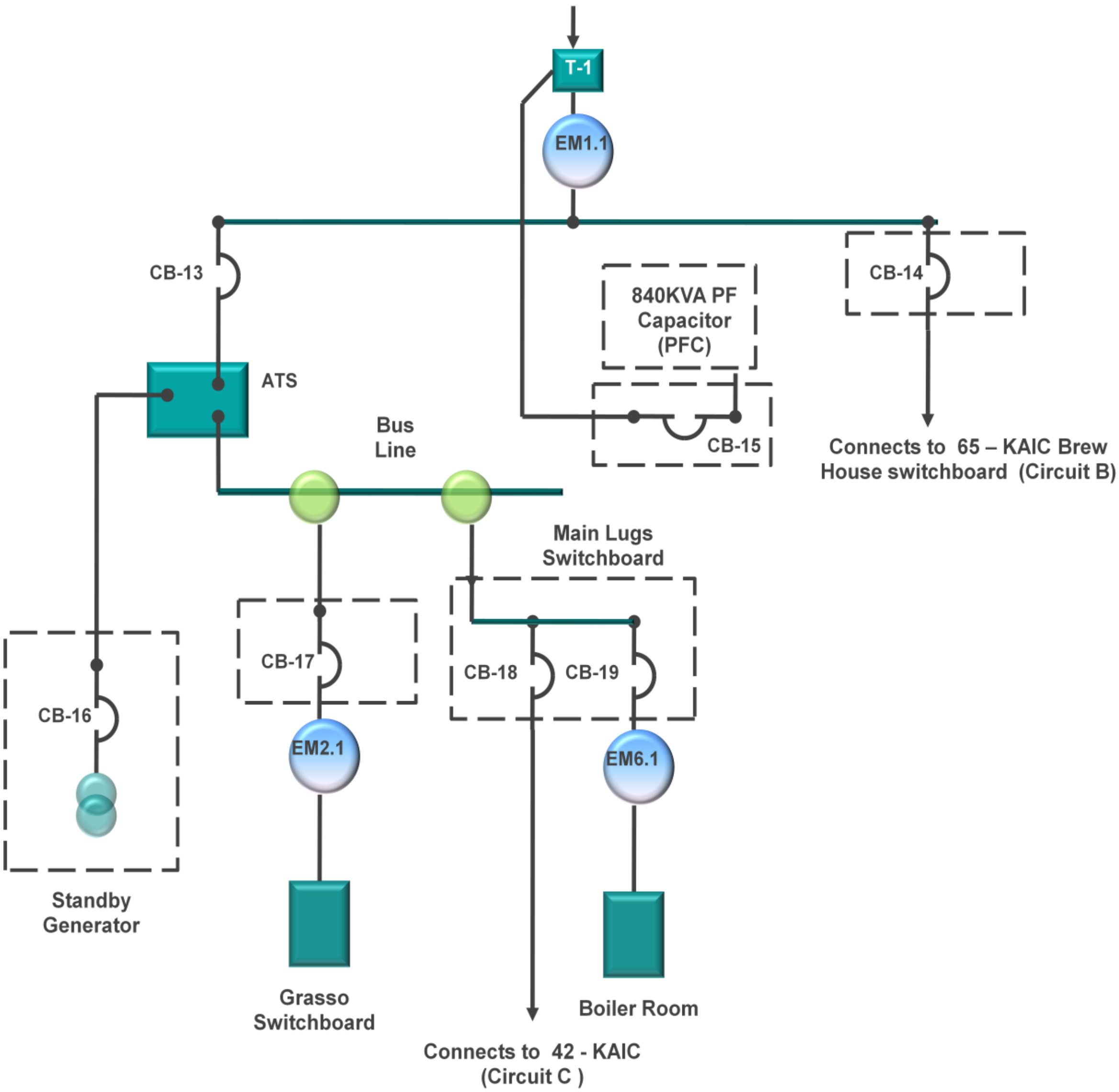


Figure A-2: 4200 KVA Substation One Line Diagram for Section II Circuit A. Refer to Appendix B for more details on components ratings and descriptions.

4200KVA SUBSTATION SECTION II CIRCUIT B ONE LINE DIAGRAM

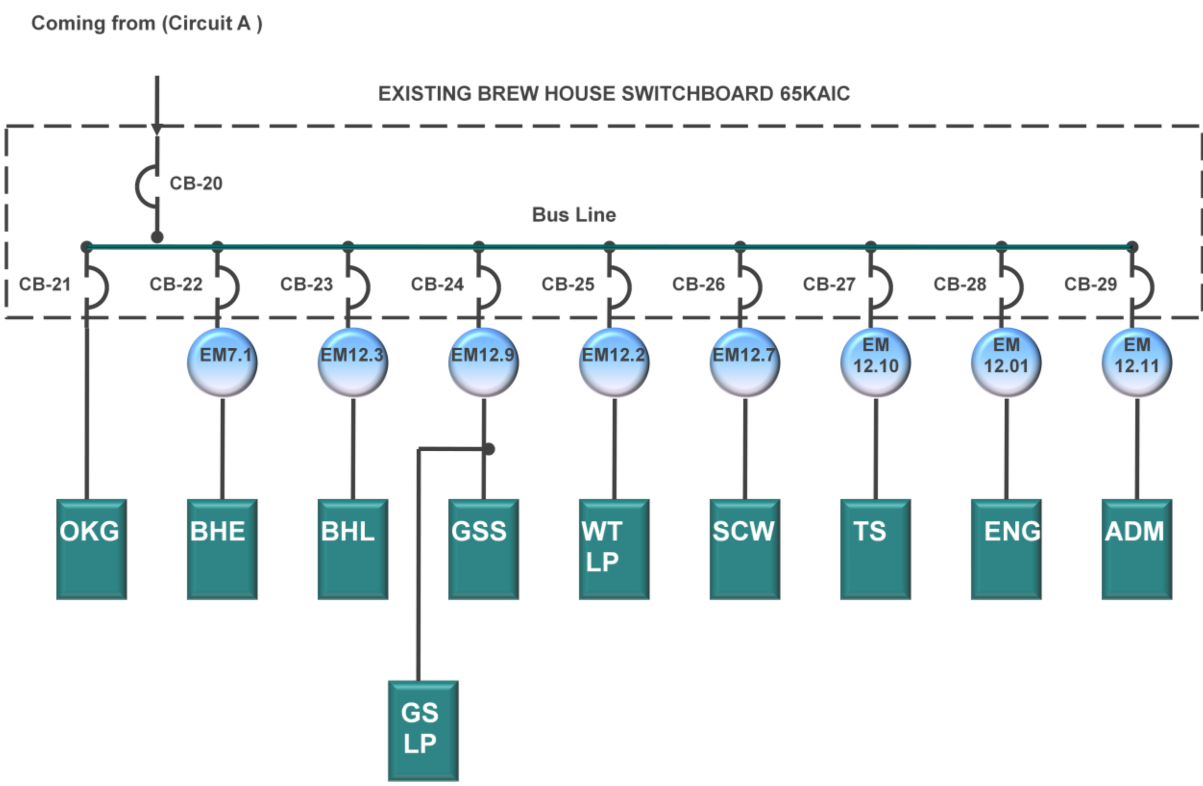


Figure A-3: 4200 KVA Substation One Line Diagram for Section II Circuit B (Brew House). Refer to Appendix B for more details on components ratings and descriptions.

4200KVA SUBSTATION SECTION II CIRCUIT C ONE LINE DIAGRAM

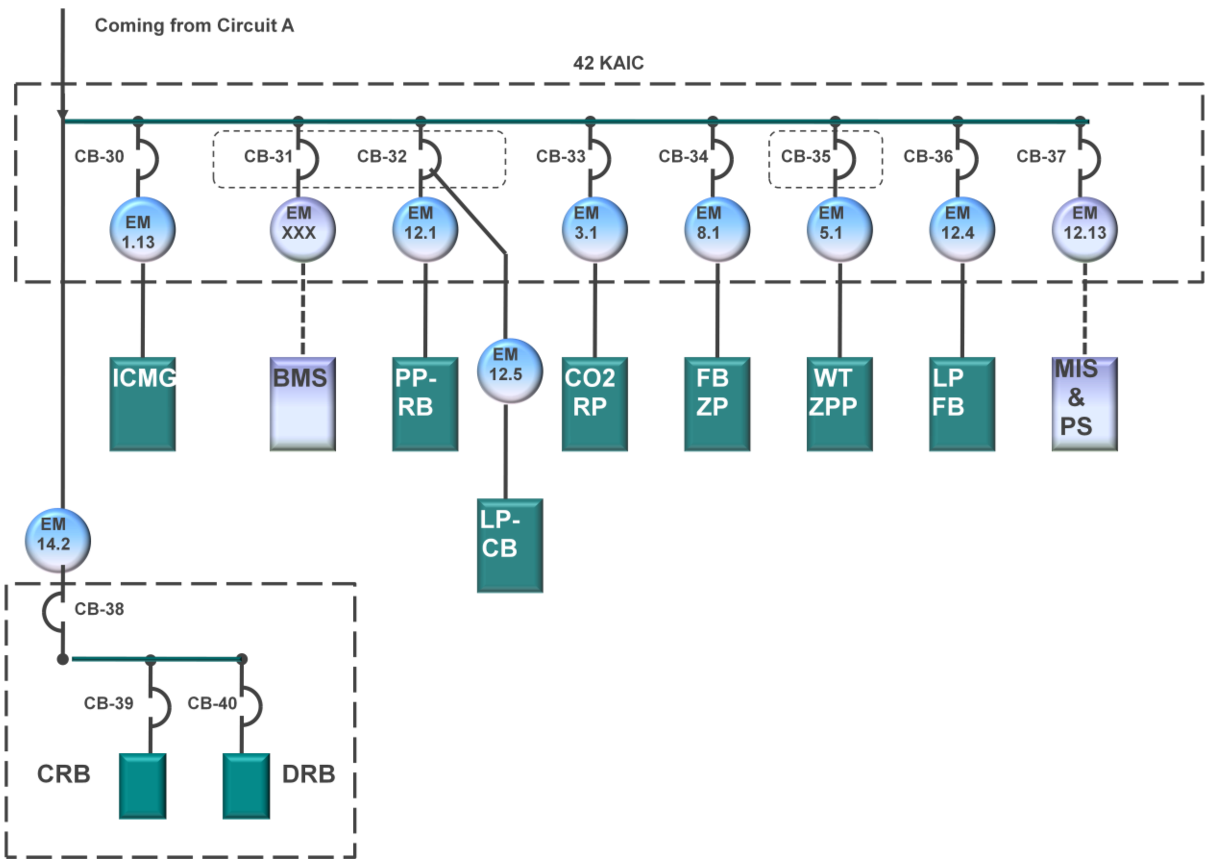


Figure A-4: 4200 KVA Substation One Line Diagram for Section II Circuit C. Refer to Appendix B for more details on components ratings and descriptions.

APPENDIX B. PART LISTS

INDIA'S BREWERY COMPONENT LIST FOR SECTION I

SYSTEM: 2500KVA SUBSTATION NONE LINE | DATE: 07/20/2009

IDENTURE LEVEL: 1 & 2

REFERENCE DRAWING: E1-01-REV 71409

IND LEVEL	IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION	RATINGS	ITEM DESCRIPTION
1	T-1	Transformer	38KVΔ , 2500KVA , 480VΔ	Δ-Δ Main Power Transformer supply power to distribution system.
1	EM1.2	Transformer Meter	2500KVA	2500KVA Transformer Meter.
1	DS-1	Outdoor Switch Board (65 KAIC)	480V, 3Φ, 3W, 4000 Amp Main Bus	Non Walk-in Outdoor switchboard-sloped roof. 480V, 3Φ, 3W, 4000 Amp Main Bus, Ground Bus Cutler Hammer Power Line I. Switchboard 100% rated low voltage power. Circuit Breakers individually mounted distribution devices. Stainless steel enclosure.
2	DS 840	Circuit Breaker	4000AF / 4000 AT (LSI)	Protects 65 KAIC from high current
2	MP-1	Metering Package	-	Connected to a Current Transformer. Measure current and voltage from the 65 KAIC switchgear.
2	CB-1	Circuit Breaker	1600AF / 1200AT	Protects KHS Can line Switchboard from high current
2	CB-2	Circuit Breaker	1600AF / 1200AT	Protect KHS Bottle Line from high current
2	CB-3	Circuit Breaker	800AF / 400AT	(MCC) Bottling Building and New Tunnel
2	CB-4	Circuit Breaker	1600AF / 1200AT	Protect Outdoor Power Panel WWTP, APT 2000 Amps from high current
2	CB-5	Circuit Breaker	800AF / 600AT	Protect Air compressors panel at refrigeration building
2	CB-6	Circuit Breaker	800AF / SPACE	Protect New PF Correction Capacitor from high current
2	SPR	Spare slot in Switchboard	800AF / SPACE	SPARE Space in switchboard / For future connections
2	EM10.1	Line Meter	-	Can Line Meter
2	EM9.1	Line Meter	-	New Glass Line Meter
2	EM12.5	Power Meter	-	CB Lightning and Power meter
2	EM4.1	Transformer Meter	2500KVA	Air compressor (#2 & #3) at 2500KVA transformer meter
2	BS-1	Bus Line	4000 Amo Main bus	Provides power to loads connected to it

INDIA'S BREWERY COMPONENT LIST FOR SECTION I - (CONT)

SYSTEM: 2500KVA SUBSTATION NONE LINE DATE: 07/20/2009
IDENTURE LEVEL: 1 & 2
REFERENCE DRAWING: E1-01-REV 71409

IND LEVEL	IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION	RATINGS	ITEM DESCRIPTION
1	KHS C	Switch Board	-	Can line Switch Board
1	KHS B	Switch Board	-	Bottle Line Switch Board. Feed conveyors and palletizers
1	MCC	Motor Center Controller	-	Bottling Building Motor Control. Monitors motor electrical properties
1	OPP	Power Panel	2000 Amps	Outdoor Power Panel WWTP, APT 2000 Amps
1	ACP	Air Compressor Panel	-	Feeds Air Compressors
1	PFCC	Capacitor	-	Power Factor Correction Capacitor
1	EM10.2	Line Meter	-	Measures power from the New Keg plant Swicthgear
1	KP	Switchgear	-	Keg Plant Switchgear
2	CB-8	Circuit Breaker	50A / 3	Protects AVQ1-Q10 KZE KEG Liner from high current
2	CB-9	Circuit Breaker	40A / 3	Protect AVQ1-Q14 KEG Line from high current
1	WWTP,ATP	Switchgear	-	Switchgear for WWTP and ATP from high
2	CB-10	Circuit Breaker	1200A / 3	Protect swicthgear line bus
2	CB-11	Circuit Breaker	600A / 3	Protect WWTP
2	CB-12	Circuit Breaker	250A / 3	Protect ATP
1	EM11.1	Meter	-	WWTP Machinery and Lightning Equipment Meter
1	EM12.7	Meter	-	Supply Chain Lightning And Power Meter

INDIA'S BREWERY COMPONENT LIST FOR SECTION II

SYSTEM: 4200KVA SUBSTATION NONE LINE DATE: 07/20/2009
IDENTURE LEVEL: 1 & 2
REFERENCE DRAWING: E1-01-REV 71409

IND LEVEL	IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION	RATINGS	ITEM DESCRIPTION
1	T-2	Transformer	38KVΔ , 3000 / 4200KVA , 480Y / 277V , Z=6.5%	Δ-Y Main Power Transformer supply power to distribution system.
1	EM1.1	Transformer Meter	4200 KVA	4200 KVA Transformer Meter
1	CB-13	Circuit Breaker	3000A / 3P	Protects 3000Amps ATS from high current
1	CB-14	Circuit Breaker	1000A / 3P	Protects existing Brew House Swicthboard (65 KAIC)
1	ATS	Swicth	3000A	Switch between standby generator and CU bus Bars
1	CB-16	Circuit Breaker	-	Protects 2000 KVA Standby Generator
1	SG	Standby Generator	2000 KVA	Standby Generator
1	CB-15	Circuit Breaker	400A / 3P	Protects power transformer
1	PFC	Power Factor Capacitor	840 KVAR	Provides Power Factor Correction
1	CB-17	Circuit Breaker	2000A / 3P	Protects Grasso Switchboard
1	MLS	Swicthboard	1600A	1600A Main Lugs switchboard non walk-in outdoor. Satinless steel enclosure.
2	CB-18	Circuit Breaker	1200A / 3P	Protects Compresor 1 and Atlas 1 in the refrigeration building
2	CB-19	Circuit Breaker	400A / 3	Protects Boiler Room
1	EM2.1	Meter	-	Grasso Refrigeration Utility Meter
1	EM6.1	Meter	-	Steam Generation Utility Meter
1	GS	Swicthboard	-	Grasso Switchboard
1	BHS	Switchboard	65 KAIC	Existing Brew House Switchboard (65 KAIC)
2	CB-20	Circuit Breaker	-	Protect entire Brew House switchboard
2	CB-21	Circuit Breaker	800A / 3	Protects Old Keg Plant. Shall be eliminated once the NBB Starts
2	CB-22	Circuit Breaker	100A / 3	Protect Brew House equipment. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-23	Circuit Breaker	300A / 3	Protect Brew House Lightning. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-24	Circuit Breaker	150 / 3	Protect Grain Storage Silos. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-25	Circuit Breaker	-	Protect WT Lightning panel. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-26	Circuit Breaker	-	Protects supply chain warehouse. Will remain until the decomission of line #1 and #2 and the Keg Plant.

INDIA'S BREWERY COMPONENT LIST FOR SECTION II - (CONT)

SYSTEM: 4200KVA SUBSTATION NONE LINE DATE: 07/20/2009
IDENTURE LEVEL: 1 & 2
REFERENCE DRAWING: E1-01-REV 71409

IND LEVEL	IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION	RATINGS	ITEM DESCRIPTION
2	CB-27	Circuit Breaker	-	Protect Technical Services. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-28	Circuit Breaker	-	Protect Engineering Offices. Will remain until the decomission of line #1 and #2 and the Keg Plant.
2	CB-29	Circuit Breaker	-	Protect Administration Offices. Will remain until the decomission of line #1 and #2 and the Keg Plant.
1	EM7.1	Meter	-	Brew House Equipment and Machinery Meter
1	EM12.3	Power Meter	-	Brew House Lightning and Power Meter
1	EM12.9	Power Meter	-	Grain Storage Silos and Lightning and Power Meter
1	EM12.2	Power Meter	-	WT Lightning and Power Meter
1	EM12.7	Power Meter	-	Supply Chain Lightning and Power Meter
1	EM12.10	Power Meter	-	Engineering Lightning and Power Meter
1	EM12.10	Power Meter	-	Engineering Lightning and Power Meter
1	EM12.1	Power Meter	-	RB Lightning and Power Meter
1	42-SG	Swicthgear	42 KAIC	42 KAIC Switchgear
2	CB-30	Circuit Breaker	150 / 3	Protects Infirmary Cooperative Main Gate
2	CB-31	Circuit Breaker	-	Protects LP-TF-02 BMS Future
2	CB-32	Circuit Breaker	150 / 3	Protects PP-RB and LP-CB
2	CB-33	Circuit Breaker	400 / 3	Protects Haffmans CO2 Recovery Plant Refrigeration Building
2	CB-34	Circuit Breaker	500 / 3	Protects Filtration Building Ziemann Power Panel
2	CB-35	Circuit Breaker	400 / 3	Protects Water Treatment Ziemman Power Panel
2	CB-36	Circuit Breaker	150 / 3	Protects LP-FB
2	CB-37	Circuit Breaker	50 / 3	Protects MIS & Phone Switchboard Future
2	EM1.13	Meter	-	Main gate Meter
2	EMXXX	Meter	-	BMS Futute Meter
2	EM3.1	Meter	-	CO2 Recovery and Distribution Utility Meter
2	EM8.1	Meter	-	Filtration Equipment Meter
2	EM5.1	Meter	-	New Water Treatment Plant Meter
2	EM12.4	Power Meter	-	FB Lightning and Power Meter
2	EM12.13	Meter	-	MIS and Phone Swicthboard Meter
1	EM12.1	Meter	-	RB Lightning and Power Meter
1	EM12.5	Meter	-	CB Lightning and Power Meter
1	EM14.2	Transformer Meter	-	Air Compressor Transformer Meter
1	REF-S	Swicthboard	-	ATLAS COPCO in Refrigeration Building
2	CB-38	Circuit Breaker	400 / 3	Protects Refrigeration Building Switchboard
2	CB-39	Circuit Breaker	250 / 3	Protects Compresor #1
2	CB-40	Circuit Breaker	50 / 3	Protects Dryer #1

APPENDIX C. FMECA

FAILURE MODE AND EFFECT ANALYSIS

SYSTEM: ____________________ DATE: ____________________

DENTURE LEVEL: ____________________ SHEET: ____________________

REFERENCE DRAWING: ____________________ COMPILED BY: ____________________

MISSION: ____________________ APPROVED BY: ____________________

DENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION	FUNCTION	FAILURE MODES AND CAUSES	MISSION PHASE/ OPERATIONAL MODE	FAILURE EFFECT			COMPENSATING PROVISIONS	SEVERITY CLASS	COMMENTS /REMARKS
					LOCAL EFFECTS	NEXT HIGHER EFFECT	END EFFECTS			

FAILURE MODE EFFECT AND CRITICALLITY ANALYSIS

SYSTEM: ____________________ DATE: ________________________

IDENTURE LEVEL: ______________ SHEET: ________________________

REFERENCE DRAWING: __________ COMPILED BY: ___________________

MISSION: ____________________ APPROVED BY: ___________________

IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION	FUNCTION	FAILURE RATE (λp)	FAILURE MODES AND CAUSES	FAILURE MODE RATION (α)	MISSION PHASE/ OPERATIONAL MODE	FAILURE EFFECT			COMPENSATING PROVISIONS	SEVERITY CLASS	COMMENTS /REMARKS
							LOCAL EFFECTS	NEXT HIGHER EFFECT	END EFFECTS			

FMECA ANALYSIS.xlsx

APPENDIX D. STATE DESCRIPTIONS

2500 KVA SUBSTATION STATE DESCRIPTION UP TO FARTHEST LOAD

STATE	STATE DESCRIPTION
S1	All components working properly
S2	No power to loads
S3	Standby state where only CB-6 has failed. Then either TR-9, L-7 or TR-15 would have to fail in order to move to S2 where the system provides no power
S4	Standby state where either TR-9, L-7 or TR-15 have failed. Then CB-6 would have to fail in order to move to S2 where the system provides no power
S5	Standby state where only CB-5 has failed. Then either TR-8, L-6 or TR-14 would have to fail in order to move to S2 where the system provides no power
S6	Standby state where either TR-8, L-6 or TR-14 have failed. Then CB-5 would have to fail in order to move to S2 where the system provides no power
S7	Standby state where only CB-3 has failed. Then either TR-6, L-4 or TR-12 would have to fail in order to move to S2 where the system provides no power
S8	Standby state where either TR-6, L-4 or TR-12 have failed. Then CB-3 would have to fail in order to move to S2 where the system provides no power
S9	Standby state where only CB-2 has failed. Then either TR-5, L-13 or TR-11 would have to fail in order to move to S2 where the system provides no power
S10	Standby state where either TR-5, L-13 or TR-11 have failed. Then CB-2 would have to fail in order to move to S2 where the system provides no power
S11	Standby state where only CB-11 has failed. Then either TR-18, L-11 or TR-22 would have to fail in order to move to S2 where the system provides no power
S12	Standby state where either TR-5, L-13 or TR-11 have failed. Then CB-11 would have to fail in order to move to S2 where the system provides no power
S13	Standby state where only CB-1 has failed. Then either TR-4, L-2, TR-10, L-8 or BS-2 would have to fail in order to move to S2 where the system provides no power
S14	Standby state where either TR-4, L-2, TR-10, L-8 or BS-2 have failed. Then CB-1 would have to fail in order to move to S2 where the system provides no power
S15	Standby state where only CB-1 has failed. CB-8 will have to fail to move to S18 standby state or either TR-16, L-9 or TR-20 would have to fail in order to move to S19 standby state.
S16	Standby state where only CB-8 has failed. CB-8 will have to fail to move to S18 standby state or either TR-16, L-9 or TR-20 would have to fail in order to move to S19 standby state.
S17	Standby state where either TR-16, L-9 or TR-20 have failed. CB-1 will have to fail to move to S19 standby state or CB-8 will have to fail to move to S20 standby state
S18	Standby state where either TR-16, L-9 or TR-20 will have to fail in order to move to the down state S2 where no power is provided

S19	Standby state where CB-1 will have to fail in order to move to the down state S2 where no power is provided
S20	Standby state where either CB-8 will have to fail in order to move to the down state S2 where no power is provided
S21	Standby state where only CB-1 has failed. CB-9 will have to fail to move to S24 standby state or either TR-17, L-10 or TR-21 would have to fail in order to move to S25 standby state.
S22	Standby state where only CB-9 has failed. CB-1 will have to fail to move to S24 standby state or either TR-17, L-10 or TR-21 would have to fail in order to move to S26 standby state.
S23	Standby state where either TR-17, L-10 or TR-21 have failed. CB-1 will have to fail to move to S25 standby state or CB-9 will have to fail to move to S26 standby state
S24	Standby state where either TR-17, L-10 or TR-21 will have to fail in order to move to the down state S2 where no power is provided
S25	Standby state where CB-9 will have to fail in order to move to the down state S2 where no power is provided
S26	Standby state where either CB-1 will have to fail in order to move to the down state S2 where no power is provided

4200 KVA SUBSTATION STATE DESCRIPTION UP TO BUS BAR

STATE	STATE DESCRIPTION
S1	All components working properly
S2	No power to loads
S3	State where Bus Bar 6 (BS-6) is not able to provide power to loads
S4	State where Bus Bar 4 (BS-4) is not able to provide power to loads
S5	Standby state where L-6 or TR-54 has failed. Then CB-13 would have to fail in order to move to S3 where the system provides no power loads connected to BS-6
S6	Standby state where only CB-13 has failed. Then either L-6 or TR-54 would have to fail in order to move to S3 where the system provides no power loads connected to BS-6
S7	Standby state where either SG, TR-50, CB-16, TR-51, L-30, TR-52, ATS, L-16, TR-54, CB-13, TR-53, or L-16 has failed. Then either the utility, T-2 or TR-24 would have to fail in order to move to S3 where the system provides no power loads connected to BS-6
S8	Standby state where either the utility, T-2 or TR-24 has failed. Then either SG, TR-50, CB-16, TR-51, L-30, TR-52, ATS, L-16, TR-54, CB-13, TR-53, or L-16 would have to fail in order to move to S3 where the system provides no power loads connected to BS-6
S9	Standby state where only CB-15 has failed. Then either PFC, TR-30, L-29 or TR-29 would have to fail in order to move to S3 where the system provides no power loads connected to BS-6
S10	Standby state where either PFC, TR-30, L-29 or TR-29 has failed. Then CB-15 would have to fail in order to move to S3 where the system provides no power loads connected to BS-6
S11	Standby state where only CB-13 has failed. Then either TR-57, L-32, TR-56, BS-5, TR-61, L-34, TR-60, BS-4, TR-55, or L-31 would have to fail in order to move to S3 where the system provides no power loads connected to BS-6

S12	Standby state where either TR-57, L-32, TR-56, BS-5, TR-61, L-34, TR-60, BS-4, TR-55, or L-31 has failed. Then CB-13 would have to fail in order to move to S3 where the system provides no power loads connected to BS-6
S13	Standby state where either SG, TR-50, CB-16, TR-51, L-30, TR-52, or ATS has failed. Then either the utility, T-2 or TR-24 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S14	Standby state where either utility, T-2 or TR-24 has failed. Then either either SG, TR-50, CB-16, TR-51, L-30, TR-52, or ATS would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S15	Standby state where CB-13 has failed. Then either either L-14, TR-26, L-15, TR-25, L-13, or TR-53 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S16	Standby state where either L-14, TR-26, L-15, TR-25, L-13, or TR-53 has failed. Then CB-13 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S17	Standby state where CB-13 has failed. Then either either TR-54 or L-16 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S18	Standby state where TR-54 or L-16 has failed. Then CB-13 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4

4200 KVA SUBSTATION STATE DESCRIPTION UP TO FARTHEST LOAD

STATE	STATE DESCRIPTION
S1	All components working properly
S2	No power to loads
S3	Standby state where either SG, TR-50, CB-16, TR-51, L-30, TR-52, or ATS has failed. Then either the utility, T-2 or TR-24 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S4	Standby state where either utility, T-2 or TR-24 has failed. Then either either SG, TR-50, CB-16, TR-51, L-30, TR-52, or ATS would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S5	Standby state where CB-13 has failed. Then either L-14, TR-26, L-15, TR-25, L-13, or TR-53 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S6	Standby state where either L-14, TR-26, L-15, TR-25, L-13, or TR-53 has failed. Then CB-13 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S7	Standby state where CB-13 has failed. Then either TR-54 or L-16 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S8	Standby state where TR-54 or L-16 has failed. Then CB-13 would have to fail in order to move to S4 where the system provides no power loads connected to BS-4
S9	Standby state where CB-32 has failed. Then either TR-74, L-16, L-43, TR-82, or TR-83 would have to fail in order to move to S2 where the system is down
S10	Standby state where either TR-74, L-16, L-43, TR-82, or TR-83 has failed. Then CB-32 would have to fail in order to move to S2 where the system is down

S11	Standby state where either TR-58, L-33, or TR-59 has failed. Then CB-17 would have to fail in order to move to S2 where the system is down
S12	Standby state where CB-17 has failed. Then either TR-58, L-33, or TR-59 would have to fail in order to move to S2 where the system is down
S13	Standby state where either TR-62, L-35, or TR-63 has failed. Then CB-19 would have to fail in order to move to S2 where the system is down
S14	Standby state where CB-19 has failed. Then either TR-62, L-35, or TR-63 would have to fail in order to move to S2 where the system is down
S15	Standby state where either TR-68, L-38, or TR-7 has failed. Then CB-39 would have to fail in order to move to S2 where the system is down
S16	Standby state where CB-39 has failed. Then either TR-68, L-38, or TR-70 would have to fail in order to move to S2 where the system is down
S17	Standby state where CB-30 has failed. Then either TR-52, L-40, or TR-80 would have to fail in order to move to S2 where the system is down
S18	Standby state where either TR-52, L-40, or TR-80 has failed. Then CB-30 would have to fail in order to move to S2 where the system is down