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Operational Reliability Evaluation of Hydroelectric power Stations Case Study:- Beles Hydroelectric power station

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BAHIR DAR UNIVERSITY
BAHIR DAR INSTITUTE OF TECHNOLOGY
SCHOOL OF RESEARCH AND POSTGRADUATE STUDIES
FACULTY ELECTRICAL&COMPUTER ENGINEERING

Operational Reliability Evaluation of Hydroelectric power Stations

Case Study:- Beles Hydroelectric power station

By

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Bahirdar, Ethiopia

July 30,2020

Operational Reliability Evaluation of Hydroelectric Power Stations

Case Study: Beles Hydroelectric Power Station

Woldemariam Worku

A thesis submitted to the school of Research and Graduate Studies of Bahir Dar Institute of Technology, BDU in partial fulfillment of the requirements for the degree of MSc in Power System Engineering faculty of Electrical & Computer Engineering.

Advisor Name: Tassew Tadiwos(Ph. D)

Bahirdar, Ethiopia
July 30,2020

DECLARATION

I, the undersigned, declare that the thesis comprises my own work. In compliance with internationally accepted practices, I have acknowledged and refereed all materials used in this work. I understand that non-adherence to the principles of academic honesty and integrity, misrepresentation/ fabrication of any idea/data/fact/source will constitute sufficient ground for disciplinary action by the University and can also evoke penal action from the sources which have not been properly cited or acknowledged.

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Date of submission: July 30,2020

Place: Bahir Dar

This thesis has been submitted for examination with my approval as a university advisor.

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ABSTRACT

By virtue of the vital nature of electric power, both to the economic and personal wellbeing, a power system is expected to supply electrical energy as economical as possible and with a high degree of quality and reliability. But electric supply in Ethiopia has been erratic and unreliable due to faults inherent in the long operation of the station and aging of their associated auxiliary equipment often lead to forced outage of the generating unit. This thesis presents reliability evaluation based on probabilistic and analytical method used to assess and evaluate the reliability, availability and performance index parameters. The research aimed at evaluating the reliability performance of Beles hydroelectric power station of Ethiopia. A set of reliability parameters which quantify generating unit reliability were computed for each generating unit using the annual outage duration of Beles hydro power stations for period of study 2014 - 2017.The most important reliability indices like, failure rate (λ), repair rate (μ), mean time to repair (MTTR), mean time between failures (MTBF), mean time to failures (MTTF) have been determined through data collection and analysis. The data of each year for each unit is time scheduled. The results showed the average reliability of the four units of the plant as 0.872, 0.860, 0.899 and 0.886 for units 1, 2, 3 and 4 respectively while the overall reliability was 0.879 and the plants average availability were 0.8476 for the period of study .The generation loss analysis indicated that inadequate water in the reservoir, lack of spare part, grid constraints and plant unavailability prevented the plant from running at maximum continuous rating.

Keywords: Hydropower, Reliability, Availability, Failure rate, Repair rate, Service hour.

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LIST OF ABBREVATIONS

COPT	Capacity outage probability table
EENS	Expected energy not supplied
FACTS	Flexible alternative current transmission system
FER	Failure event record
FOH	Forced Outage Hours
FOR	Forced Outage Rate
HEPP	Hydroelectric power plant
HL-I	Hierarchical level I
IEEE	International electronics and electrical engineering
LDC	Load dispatch center
LOEE	Loss Of Energy Expectation
LOENS	Loss Of Energy Not Served
LOEP	Loos Of Energy Probability
LOLD	Loss Of load Duration
LOLE	Loss of load expectation
LOLF	Loss Of Load Frequency
LOLP	Loos Of Load probability
MTBF	Mean time between failures
MTR	Main transformer
MTTF	Mean time to failures
MTTR	Mean time to repair
O&M	Operation and maintenance
PMF	Probability mass function
RTS	Reliability test system
SH	Service hours
SOR	Schedule outage

LIST OF SYMBOLS

A_s	Average system availability
$\grave{A}_s$	Average system unavailability
$f\ (t)$	Probability of failure
t	Operating period
p_i(t)	Probability that a system is in state i at time t
p_j(t)	Probability that a system is in state j at time t
T_i	Mean duration of the state
T_r	Repair time
T_{ci}	Mean cycle time
f_i	State frequency
$Fc_{(XK)}$	Frequency of probability due to k Failed unit
(XK)	Level of outage probability due to K failed unit
$P_{(XK)}$	Exact probability of K failed unit
$Pc_{(XK)}$	Commutative probability due to k failed state
λ	Failure rate of a system
μ	Repair rate of a system

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CHAPTER 1: INTRODUCTION

1.1. Background

The primary function of a power system is to provide electrical energy to its customers with an acceptable degree of quality. Reliability of power supply is one of the features of power quality. The two constraints of economics and reliability are competitive because increased reliability of supply generally requires increased capital investment. These two constraints are balanced in many different ways in different countries and by different utilities, although generally they are all based on various sets of criteria [1].

The generation; transmission and retailing of electricity have existed hundred years in providing the much needed electricity. Due to the nature of electricity systems, the variable demand at every moment needs to be met by consistent electricity supply in making sure the continuous availability of the resources. Not meeting the demand in any case will lead to a huge loss of income to the generators as well as to the consumers. The reliability of the generation, transmission and distribution of electricity in this sense is crucial for the continuous supply of electricity to meet the demand [2].

Reliability of the generated power system is afflicted with the load curve characteristics, peak duration and variety between levels of the peak at each hour, day and month of each season of a year. Various kinds of customers might have different load curve charts. The most frequent categorization for electrical loads is residential, commercial and industrial which usually each load curves contains a characteristic chart. Such a process's quality is just a strong task of the dispatcher's understanding of the system topology, utilization of automation, and typical trouble call techniques. Probability based models have already been advanced for precisely reflect the stochastic nature of generators behavior and determine its reliability interpretation. Today the power quality and reliability are one of the most crucial features combined with the cost in the power generation [3].

Reliability analysis techniques have been gradually accepted as standard tools for the planning, design, operation and maintenance of electric power system. The function of an electric power system is to provide electricity to its customers efficiently and with a reasonable assurance of continuity and quality [4]. The task of achieving economic efficiency is assigned to system operators or competitive markets, depending on the type of industry structure adopted. On the other hand, the quality of the service is evaluated by the extent to which the supply of electricity is available to customers at a usable voltage and frequency [5]. The reliability of power supply is, therefore, related to the probability of providing customers with continuous service and with a voltage and frequency within prescribed ranges around the nominal values. A modern power system is complex, highly integrated and very large. Fortunately, the system can be divided into appropriately subsystems or functional areas that can be analyzed separately. These functional areas are generation, transmission and distribution. Reliability studies are carried out individually and in combinations of the three areas [6]. This work is limited to the evaluation of the generation reliability. Generating stations form an important and integral part of the overall power system and their reliability is reflected in the reliability of the overall national supply [4]. Reliability of a generating station is a function of the reliability of the constituent generating units. Accurate estimates of generating unit reliability are needed for generating capacity planning and to aid improved criteria for future designs and operations. Reliability assessment of a generating system is fundamentally concerned with predicting if the system can meet its load demand adequately for the period of time intended [7]. To achieve a standard degree of reliability at the customer level, each of these systems must provide an even higher degree of reliability. However as systems grew larger and more complex, the need for rigorous analysis in the form of formal concepts and methods of reliability theory have been applied to almost every aspect of power system reliability evaluations.

1.2. Problem Statement

The high rate of electricity demand requires stable and continuous supply of electrical power to consumers. Hence improvement of the operational performance of a nation's electric supply is vital for its economic and social developments. Because electricity is used for the twenty four (24) hours of the day, it has come to play an important role in all aspects of our life. It has been observed that the energy generated by the major hydro-electric power stations in Ethiopia does not supply the expected load to customer due to reliability issues in the power system network of the national grid.

Consumers of electricity both domestic and industries have been experiencing incessant power cut or failures that have cost implication in terms of appliance damage and loss of production. Furthermore faults inherent in the long operation of the station and aging of their associated auxiliary equipment often lead to forced outage of the generating units which have contributed to the apparent unreliability of the station.

Beles hydroelectric Power stations suffered an average of 1425.53hr per year of forced outage and 371.95 hr. per year scheduled outage .These two types of outage costs loss of million units of power generation during 2013/14 to 2016/17 due to subsequent avoidable forced outages on account of above reasons.

Reliability of a generating station is a function of the reliability of the constituent generating units. Accurate estimates of generating unit reliability are needed for generating capacity planning and to aid improved criteria for future designs and operations. In this study an assessment of the reliability of power generation plant was carried out to provide opportunity to check frequent fault occurrence and prolonged outages. Hence this thesis work can provide significant contribution for generation expansion planning and evaluating of the operational reliability performance of hydropower station of Ethiopia.

1.3. Objective of the study

1.3.1. General objective

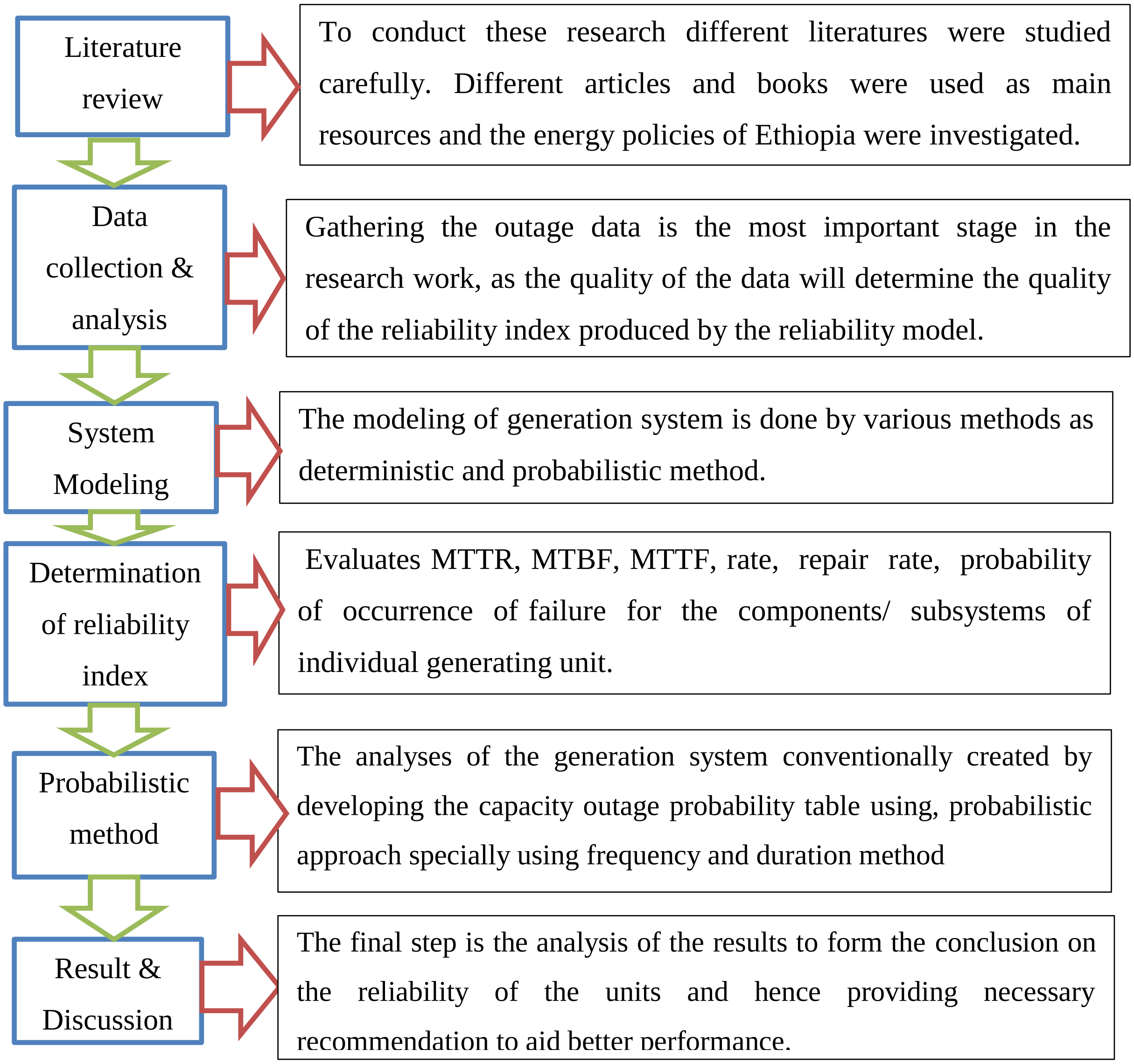
The general objective of this research is to evaluate the various defined failure states of Hydro power generation station (Beles hydropower generation station) over a period of Four years.

1.3.2. Specific objectives

- To study the Frequency of Scheduled maintenance of each individual generating unit of the station.
- To Evaluate MTTR, MTBF, MTTF, failure rate, repair rate and probability of occurrence of failure for individual generating unit.
- To carry out Markov model and State space diagram of hydro power station.
- To apply the common concepts of probability to find the overall reliability of hydro power station

1.4. Research methodology

There are two main categories of reliability evaluation techniques, namely analytical and simulation. Analytical techniques represent the system by a mathematical model and evaluate reliability indices by mathematical solutions. Simulation on the other hand, like Monte Carlo simulation methods, estimates the reliability indices by simulating the actual progression and random performance of the system. The method employed in this research is summarized as in the flow chart below.



To conduct these research different literatures were studied carefully. Different articles and books were used as main resources and the energy policies of Ethiopia were investigated.

Gathering the outage data is the most important stage in the research work, as the quality of the data will determine the quality of the reliability index produced by the reliability model.

The modeling of generation system is done by various methods as deterministic and probabilistic method.

Evaluates MTTR, MTBF, MTTF, rate, repair rate, probability of occurrence of failure for the components/ subsystems of individual generating unit.

The analyses of the generation system conventionally created by developing the capacity outage probability table using, probabilistic approach specially using frequency and duration method

The final step is the analysis of the results to form the conclusion on the reliability of the units and hence providing necessary recommendation to aid better performance.

Figure1.1Research methodology flow chart

1.5. Scope of the study

The study of this research centers on reliability and availability assessment of generating units in Beles hydropower station for the period of four years. This work includes solving mathematical equations involving failure rate repair rate availability etc. Based on unit’s outage data collected from the power station. By making use of various reliability index formulas reliability index table is developed for the period of the study. This table shows the outage rate the mean time to failure (MTTF), mean time to repair (MTTR), mean time between failure (MTBF) and unit’s availability. The result of the analysis shows the reliability parameter such as the overall probability and frequency of the unit failure.

1.6. Significance of the study

This study is presents a theoretical and practical implication for electric power reliability and availability and will show the causes and impacts of electric power interruptions and importance of managing power interruptions and lose and its urgency. The finding identifies the focal problem and priority areas for decision makers. Additionally, it will also provide a reliable data in relation to the cause of power interruption and lose for researchers, academics and students.it also provides system reliability improvement, secured operation of the system as well as for future planning and expansion of generation station in Ethiopia

1.7. Organization of the thesis

The report of this research is outlined as follows,

Chapter 1:- gives a general introduction of reliability assessment .a clear definition of the problem and the motivation the study as well as the method adopted to achieve the goal of the research are presented in this chapter.

Chapter 2:- reviews some literature relevant to the study. This chapter introduces reliability and Markov process, method of reliability evaluation of the different types of systems, the method used to build the generation capacity model and the method of generating system reliability evaluation is reviewed in this chapter.

Chapter 3:- describes the general system reliability evaluation and the method of system evaluation, the modelling of capacity outage probability table, generation system reliability indices formula as well as the factors influencing power system reliability evaluation.

Chapter 4:- presents the operational reliability evaluation of Beles generation station and the method used to obtained reliability indices as well as the analysis and the performance of each individual generating units

Chapter 5:- presents conclusions as well as recommendations for future studies. Finally the references used and appendices are presented at the end of the research.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Reliability has been defined as the probability that a system or device perform its function adequately for the period under specific operating condition. This definition is distinct from its qualitative general meaning as it applies to engineering device.it revolves around four major determinations via probability (uncertainty of the device),adequate performance , operating condition and specific period of time. Many researchers have made meaningful contribution on evaluating the reliability of power station using different approach.

Power generation plant reliability is the probability that it will not only generate electricity for its end-users without interruption but also, in an acceptable quality subject to design specifications [8]. Reliability of power generation system is a good indicator in planning for capacity expansion geared towards ensuring that the total installed capacity is sufficient to deliver adequate electricity as required. [9], presented various philosophical aspects concerning power system reliability and in particular adequacy and the concept of hierarchal levels in reliability evaluation. This work provided a frame work on which the discussion within the power industry and with the external groups can be ideally based. The paper also briefly comments on various methods that can be used to assess reliability. [10], analyzed the impacts of a flexible alternating current transmission system (FACTS) controller on reliability of composite power generation and transmission system .Here the conventional dc flow based linear programming model used in composite system reliability evaluation method is converted in to non-linear optimization model to include the impacts of flexible alternating current transmission system (FACTS) devices on reliability of power system. The model was tested on 24 buses IEEE-reliability test system (RTS) and an annualized reliability index calculated using the model .this is then compared with the index calculated without considering flexible alternating current transmission system (FACTS) devices. [11], Provided the Basic power Reliability concepts and stressed the need. [12] found the usage of the Markov approach for calculating the failure time measures such as availability, mean cycle time, and mean time to first failure to analyze repairable and also discussed various special techniques such as lumping states or decomposing the system into independent subsystems can simplify the analysis considerably for a large system. [13]used a Markov-chain model and the numerical difficulties associated with large transition-probability matrices were reduced by a systematic ordering of the system states and also described a technique for the systematic merging of processes corresponding to systems exhibiting symmetries. [14] Described the concept of frequency of failures during the useful life period was programmed by mathematical reliability model. It starts from the basic configuration component failure-rate data and uses the tie-set approach to carry out the reliability analysis of the system. [15] presented an approach for determining the effect of terminal station failures on station-originated outages and the results used to assess the reliability of the terminal stations themselves and as input data to a composite system reliability evaluation technique.

There occur failures at different components of the units this ultimately leads to the turn off of the unit and cause's considerable loss of availability of the units. To mitigate these limitations, in this paper three state Markov approach is used to evaluate the reliability and availability of the plant. However in this study the reliability and availability concept which is applicable generation aspects of power system is reviewed to enable as for evaluating the case study. Four units for Beles hydropower station are considered as the case studies the comparative study of the station are highlighted. Furthermore this work shows the reliability evaluation with a view to improve the generation and other system performance by applying probability theories using frequency and duration/ Markov/ approach and Statistical analysis.

2.2. Probability concept

The central concept in the theory of probability is the event or set. A set is a collection of objects or outcomes called elements. Sets are combined in various ways to form other sets. The elements of sets are taken from largest set called space S. probability is a numerical index $P(A)$ assigned to a set or events A as defined by ([16].

$$P(A) = \frac{NA}{N} \tag{2.1}$$

Where N is the number of possible objects of outcomes of the space and event A occurs in NA of these outcomes. $P(A)$ varies between zero and one which defines absolute impossibility and unity.

2.2.1. Set operation

There are relationships involving sets which can be proved with the help of appropriate Venn diagrams. These includes

a). **Subsets**: A set B is said to be a subset of another A if all element of B are also elements of A.

b). **Equality**: A set is said to be equal to another set B if and only if every element of A is an element of B and every element of B is an element of A.

c). **Sums**: the sum or union $(A + B)$ of two set $A\&B$ is another set whose element are all the elements of Aor B or both. It is easy to show that:

$$(A + B) + C = A + (B + C) \qquad (2.2)$$

d). **Product**: the product of intersection (AB) of two set A&B is another set consisting of all elements that are common to both A and B. it is easy to show that:

$$(AB)C = A(BC) \qquad (2.3)$$

It can also be provided that:

$$A(B + C) = AB + AC \qquad (2.4)$$

e). complements: the complements of a set A are another set consists of all elements of S that are not in A.

f).Difference: the difference (A-B) of two sets A and B is another set consisting of the element of A that are not in B. it is easy to show and important to note that:

$$(A - B) + B \,\#A \qquad (2.5)$$

2.2.2. Probability combination

The probability of occurrence of two or more events can be combined depending on the relationships that exist between the events. Two events A and B can either occur (A+B). An event A can also occur conditionally on the occurrence of another event B (A/B). Events can be either dependent or independent they can be mutually exclusive or not [17]. Table 2.1 shows how the probability of the different combination can be evaluated.

Table2.1 : Probability of occurrence of two events

Types of occurrence	Dependent evens	Independent and not Exclusive	Independent and Exclusive
Simultaneous (AB)	P(A/B) P(B)	P(A)P(B)	-
At least one P(A+B)	P(A)+P(B)-P(A/B)P(B)	P(A)+P(B)-P(A)P(B)	P(A)+P(B)
Condition P(A/B)	P(AB/P(B)	P(A)	-

2.2.3. Random variables

The theory of probability deals with the outcomes of a single experiment .in application one often deals with two or more experiments or with repeated performance of the same experiment from which emerges a range of values or outcomes. In order that probability theory can be applied to the occurrence of these outcomes, it is essential that they occur by chance, that is randomly in time or space or both. The parameter of event being measured may be defined as random variables.

One way of specifying the probability of a random variable is by means of density function. A density function *f(x)* of a random variable *x* is defined as the function that yields the probability that the random variable takes on any one of its admissible value. That is

$$F(x) = P \qquad (2.6)$$

A number of standard density functions are available from which one that suits intended application can be selected. This standard function includes binomial, Poisson, normal, Weibull and exponential functions. Sometimes it is not the probability of random variables taking on a specific value that is required but the probability that the random variable is less than or equal to a specific value. In such situation another function, the cumulative distribution function is made use of. The cumulative distribution function $F(a)$ is defined as the probability that the random variable is less than or equal to

$$F(a) = P(x \leq a) \qquad (2.7)$$

Clearly defined as

$$F(a) = P(x \leq a) = \int_{-\infty}^{a} f(x)dx \qquad (2.8)$$

$F(a)$ is therefore the area under the f(x) curve between limit -∞ and a, is the minimum value that $f(x)$can take. So that the probability of the random variable lying between any two values a, b is given by

$$\boldsymbol{P(a \leq x \leq b = \int_{a}^{b} f(x)dx} \qquad (2.9)$$

One other function that is used in the analysis of the probability of random variable which is extensively used in reliability evaluation is the hazard rate function**λ**(x).this is defined as probability that a given item on test will fall between a and (a+Δa) time when it has already survived up to the time a where (Δa)is a small time interval. that is

$$\lambda(\mathrm{x}) = \mathrm{P}(\mathrm{a} \leq \mathrm{x} \leq \frac{(\mathrm{a} + \Delta a)}{\mathrm{x}} \geq \mathrm{a}) \qquad (2.10)$$

$$\lambda(x) = \frac{f(x)}{1 - F(x)} \qquad (2.11)$$

In reliability ,the random variable is frequently the time and so the standard function that best suits it is the exponential function because it has only time as the independent variable (14). The most important factor for this function to be applicable is that the hazard rate should be constant in which case it is called failure. The density function $f(t)$ for an exponential function is given by

$$f(t) = \lambda \ell^{-\lambda t} \qquad (2.12)$$

Where $f(t)$ =probability of failure

t= operating time (independent variable)

λ= failure rate

e=base of natural logarithm

$$F(t) = \int_{0}^{t} f(t)dt = 1 - e^{-\lambda t} \qquad (2.13)$$

Since the minimum value that time can take, is zero, the next equation thus shows that the hazard rate for an exponential distribution is constant which the condition earlier stated.

$$\lambda(\mathrm{t}) = \frac{\mathrm{f(t)}}{1 - F(t)} = \lambda \qquad (2.14)$$

The probability value is the first index of reliability and in most cases it is considered most significant and sufficient index. However other indices also used includes

1. Expected number of failures in a specified period
2. Average time between failures
3. Expected down time
4. Expected loss in revenue due to failures
5. Expected loss in plant output to failure

2.3. Reliability concept

Reliability is the probability that a system or device will perform its prescribed function without failure, for a given period when operated correctly in a specified environment [18]. It should be noted that reliability is not the only performance criterion by which a device or system can be characterized. If a device fails it can be repaired (repairable system) and since it is not possible for a device to be used while it is being repaired on might measure its performance in terms of availability, which could be defined as the probability that a system or a device will be operational at any particular time. Another measure closely related to reliability and availability is the maintainability and is defined as the probability that a system will perform to specified condition within a given period when maintenance action is performed in accordance with prescribed procedure and resource. A device or system may be adequate but not reliable if it has poor maintainability.

2.4. System classification and method of reliability evaluation

System generally fall in to two class’s .there is one in which all the components of the system are considered operating for system success, for example a transmission network. Such systems are frequently represented as a network in which the system components are connected together either in series, parallel, meshed or a combination of these. Very often the resulting reliability network is not identical to the physical system in to reliability network utilizing the system operational logic and sound understanding of the physical behavior and requirement of the system [19]. The evaluation techniques applicable to this class of system are methods for translating the topology of the resulting reliability network in to a structure that consists only of a series and parallel components.

The second lass of system is the one in which some of the components may be in standby mode and can be switched in to operation at any desired instance, for example an electrical power generating unit. Such system are not easily represented by a network .the method of reliability evaluation often used are those that can give the possible combination of components states and their corresponding probabilities. Two such methods available in literature are the event tree method and Markov techniques.

2.2.4. Markov processes

A Markov process is a particular kind of stochastic process. A stochastic process is defined as discrete or continuous variation which develops in time a manner controlled by probabilistic laws [20]. A simple example of stochastic process is the ‘up’ and ‘down’ state occupied by an electrical power generation unit, with the time spent in each state being random variables as shown in figure [21].

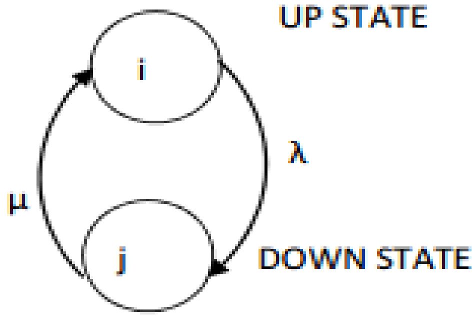


Figure2. 1: State space diagrams for a two state system

Where λ = unit failure rate

μ = unit repair rate and i & j the state transitions

There are two key characteristics of Markov process, which are its lack of memory and being stationary process. Lack of memory implies that the future states of the system are independent of all the past state except the immediately preceding one and completely independent of all the time spent in any state. By stationary process, it is implies that the probability of making a transition from one state to another is the same at all times in the past and future. There are four Markov process depending on whether the stats of the process are discrete or continuous and whether transition from one state to another can occur at discrete time interval or at any time. The electrical power generation system certainly falls in to the discrete state, continuous time class for the obvious reason that a power can operate fully, partially or down and transition between these states can occur at any time. These Markov transition rates, as they are often called, can be estimated from the systems past operational information.

2.2.5 Fault tree analysis

Fault tree analysis (FTA) is a top down, deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events. This analysis method is mainly used in the fields of safety engineering and reliability engineering to understand how systems can fail, to identify the best ways to reduce risk or to determine (or get a feeling for) event rates of a safety accident or a particular system level (functional) failure [22].

Fault tree analysis (FTA) is a tool with which protection engineers can easily compare the reliability of proposed protection of systems. FTA quantify the probability of the top event or sub top event of the fault tree a probability for each basic event (failure probability of every components) in the fault tree must be provided. These basic component probabilities are then propagated upward to the top event using Boolean relationships for the fault tree. Alternatively, the minimal cut sets can be generated from the fault tree and then used to quantify the top event or sub top event [23].

Fault tree construction is generally a complicated and time consuming task. Computer aided synthesis has attracted considerable attention and several methodologies have been proposed [24]. Fault Tree constriction use computer software is employed to develop and calculate fault tree. Such as Relex, Top event FTA profession, ITEM toolkit…etc.

2.5. Mathematical modeling

2.5.1. State space diagram

The first step towards the development of a mathematical model for the discrete state, continuous time process is to construct the systems state space diagram. A state space diagram is a representation of all possible states in which the system can reside with all relevant transition rates between states inserted.

2.5.2. Time dependent and limiting state probability

To develop a mathematical model for a discrete state continuous time process, let

$Pi(t)$ = probability that the system is in state i at time t

$Pj(t)$ = probability that the system is in state j at time t

Considering the transition for a time interval Δt, the probability of failures and repaire at this interval Δt is $\lambda . \Delta t$ and $\mu . \Delta t$ respectively.

Probability that the component is in state *i* at time t+Δt

$$p_i(t+\Delta t\ ) = p_i(t)[1-\lambda\Delta t] + p_j(t)[\mu\Delta t] \qquad (2.15)$$

Similarly, the probability that the system is in state j at time t+Δt is

$$p_t(t+\Delta t) = p_j(t)[1-\mu\Delta t] + pi(t)[\lambda\Delta t] \qquad (2.16)$$

Equation 2.15 and 2.16 can be written as

$$\frac{p_i(t+\Delta t)-p_i(t)}{(\Delta t)} = \lambda p_i(t) + p_j(t) \qquad (2.17)$$

$$\frac{p_j(t+\Delta t)-p_j(t)}{(\Delta t)} = \lambda p_i(t) - p_j(t) \qquad (2.18)$$

As

$\Delta t \to 0, LHS\ of\ equation\ 2.17\ is\ \frac{dpi(t)}{dt}\ \ or\ \dot{p}i(t) and\ LHS\ of\ equation\ 2.18\ is\ \frac{dpj(t)}{dt} or\ \dot{p}j(t)$

$$\begin{pmatrix} \dot{p}i(t) \\ \dot{p}j(t) \end{pmatrix} = [p_i(t)\ p_j(t)]\ \begin{bmatrix} -\lambda & \lambda \\ \mu & -\mu \end{bmatrix} \qquad (2.19)$$

Equation 2.19 can be solved by classical method or Laplace transform method. The solution is

$$p_i(t) = \frac{\mu}{\lambda+\mu}\left[p_i(0)+p_j(0)\right] + \frac{e^{-(\lambda+\mu)t}}{\lambda+\mu}\left[\lambda p_i(0) - \mu p_j(0)\right] \qquad (2.20)$$

$$p_j(t) = \frac{\lambda}{\lambda+\mu}\left[p_i(0)+p_j(0)\right] + \frac{e^{-(\lambda+\mu)t}}{\lambda+\mu}\left[\mu p_i(0) - \lambda p_j(0)\right] \qquad (2.21)$$

Where $pi(0)$ and $p_j(0)$ are the intial condition and $p_i(0) + p_j0) = 1$

If the process starts from state$i$, the system is in state i at time $0, p_i(t) = 1\ and\ p_j(t) = 0$. Then equation 2.20 and 2.21 simplified to

$$p_i(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda e^{-(\lambda+\mu)t}}{\lambda+\mu} \qquad (2.22)$$

$$p_j(t) = \frac{\lambda}{\lambda+\mu} + \frac{\lambda e^{-(\lambda+\mu)t}}{\lambda+\mu} \qquad (2.23)$$

Time dependent state probabilities or transient state probabilities as they are sometimes called, are needed for assessing the near future reliability. They can be obtained by substituting the appropriate time in the expressions for the time dependent state probabilities. Usually reliability is needed for system planning application, and their steady state probabilities are all that are required. One way of finding these steady state solutions is to find the general solution and take limit as time approaches infinity.

When $t \to \infty$, the probabilities are known as limiting state probability.

These are

$$p_i(\infty) = \frac{\mu}{\lambda+\mu} = \frac{MTTF}{MTTF+MTTR} \qquad (2.24)$$

$$p_j(\infty) = \frac{\lambda}{\lambda+\mu} = \frac{MTTR}{MTTF+MTTR} \qquad (2.25)$$

Where MTTF is mean time to failure and MTTR is mean time to repair (mean down time), $p_i(\infty)$is the availability and $p_j(\infty)$ is the unavailability of the component. These values are independent of the state from which the process starts.

2.5.3. State probabilities, frequencies and Durations

In most applications, state space models with constant transition rate are used. The process based on constant transition rate is essentially a homogeneous Markov process. To obtain the state probability $pi(t)$ as a function of time, the matrix deferential equation 2.26 must be solved [25].

$$\dot{p}(t) = p(t)A \qquad (2.26)$$

Where $\dot{p}(t)$ is a row vector consisting of the elements $\frac{dp1(t)}{dt}, \frac{dp2}{dt}, \dots, p(t)$ is a row vector consisting of the element $p_1(t), p_2(t), \dots, and\ A$ is the transition intensity matrix, with element $a_{ij} = \lambda_{ij}$ for $i \neq j$ and -$\sum_{i \neq j} \lambda_{ij}$

If only the long term (steady state) value of the probability p_i(t) are of interest , they can be obtained by much simpler task of solving the set of linear equation [26].

$$p_A = 0 \tag{2.27}$$

Where the element of the row vector p are long term state probabilities $p1, p2 \dots, and$ the row-vector 0 consists of zeros. The solution for P requires an individual equation, which is provided by the fact that the probability of all state must always add up to 1, that is [27]

$$\sum_i p_i = 1 \tag{2.28}$$

The frequency of encountering state i, *fi* is defined as the expected number of stays in (or arrival into, or departures from) *i* per unit time, computed over a long period.

By this definition, the concept of frequency is associated with the long term behavior of the process describing the system. The mean duration of the stays in state *i* must also be computed over a long period. In order to relate the frequency, probability and the mean duration of a given system state, the history of the system will be regarded as consisting of two alternating periods, the stays in *i* and the stays outside *i*. thus, the system is represented by a two state process whose state-space diagram is shown in figure2.3. Let the mean duration of the stays in state *i* beT_i, and that of the state outside $i,$ $\dot{T}_i$.

The mean cycle time, T_{ci} is then

$$T_{ci} = T_i + \dot{T}_i \tag{2.29}$$

From the definition of the state frequency it follows that, in long run f_i equals the reciprocal of the mean cycle time, that is;

$$f_i = \frac{1}{T_{ci}} \tag{2.30}$$

Multiplying equation 2.30 by T_i , the right hand side become $\frac{Ti}{Tci}$. This provide the long term state probabilities in a two state process and by definition of availability (A) and unavailability (u), $\frac{Ti}{Tci}$`equals p_i. Therefore,

$$fi = \frac{Pi}{Ti} \tag{2.31}$$

This is fundamental equation, which provides the relation between the three state parameters. To relate the frequencies fi mean duration Ti, and the transition rates in the system, the concept of the frequency of transfer from state *i* to state *j* is first introduced.

This frequency f_{ij} is defined as expected number of direct transfers from i to j per unit time. It can be written as

$$f_{ij} = \lambda_{ij} p_i \qquad (2.32)$$

Thus, the transition rate λ_{ij} is essentially a conditional frequency, the condition being that the system resides in state i. From the definition of fi and f_{ij} it follows that

$$f_i = \sum_{j \neq i} f_{ij} \qquad (2.33)$$

Substituting 2.32 in to 2.33

$$f_i = p_i \sum_{j \neq i} \lambda_{ij} \qquad (2.34)$$

Finally, combining 2.31 and 2.34, T_i can be expressed as

$$T_i = \frac{1}{\sum_{j \neq i} \lambda_{ij}} \qquad (2.35)$$

In other words the mean duration of the stay in any given state equals the reciprocal of the total rate of departures from that state. With the help of equation 2.27, 2.28, 2.34 and 2.35 all the indices can be computed from the transition rates that define a given system.

2.5.4. System of two independent components

The state space diagram of such system is illustrated in figure 2.2 with various transition rates indicated next to the transitions. According to the conventions, the failure rate (the reciprocal of the mean time to failures) are denoted by λ and the repair rates (the reciprocal of the mean component repair time) by μ with the subscripts referring to the appropriate component.

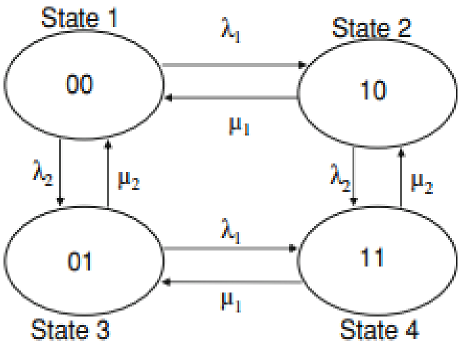


Figure2. 2: State space diagram for two state models

In the model of figure 2.2 the state probabilities are first computed. As in most application, only the long run solutions are sought. The transition intensity matrix A is

$$A = \begin{bmatrix} -(\mu_a + \mu_b) & \mu_b & \mu_a & 0 \\ \lambda_b & -(\mu_a + \lambda_b) & 0 & \mu_a \\ \lambda_a & 0 & -(\lambda_a + \mu_b) & \mu_b \\ 0 & \lambda_a & \lambda_b & -(\lambda_a + \lambda_b \end{bmatrix} \qquad (2.36)$$

To facilitate the construction of the matrix indicated for each entry are the state where the corresponding transition originates and where it ends. The set of linear equations 2.36 yielding the probabilities pi, are the following.

$$-(\mu_a + \mu_b)p_0 + \lambda_b p_1 + \lambda_a p_2 = 0 \qquad (2.37)$$

$$\mu_b p_0 - (\mu_a + \lambda_b)p_1 + \lambda_a p_3 = 0 \qquad (2.38)$$

$$\mu_a p_0 - (\lambda_a + \mu_b)p_2 + \lambda_b p_3 = 0 \qquad (2.39)$$

$$\mu_a p_1 + \mu_b p_2 - (\lambda_a + \lambda_b)p_3 = 0 \qquad (2.40)$$

These equations are obtained by proceeding column by column in the matrix A, multiplying each column vector by $p = [p_0, p_1, p_2, p_3]$, as required by 2.36. Since the four equations in 2.37 are not independent one can be omitted and it is replaced by

$$p_0 + p_1 + p_2 + p_3 = 1 \qquad (2.41)$$

The solution of 2.36and 2.38 is

$$p_0 = \frac{\lambda_b \lambda_a}{D}, p_1 = \frac{\lambda_a \mu_b}{D}, p_2 = \frac{\lambda_b \mu_a}{D}, p_3 = \frac{\mu_a \mu_b}{D} \qquad (2.42)$$

Where, ($D = (\lambda_a + \mu_a)(\lambda_b + \mu_b)$

We can obtain the results in 2.40 by direct reasoning, the availability (probability of success) of a single two state component is $A = \frac{\mu}{\lambda+\mu}$, and its unavailability (probability of failure), $u = \frac{\lambda}{\lambda+\mu}$.

For two independent components *a* and *b* the probability of both operational is $A_a A_b$, of *a* operational and *b* not operational is $A_a U_b$, of *b* operational and *a* not is $U_a A_b$, and of both having failed is $U_a U_b$. After substituting in to these terms the expression for A and U above, equation (2.39) are obtained. Equation 3.36 computes the mean duration of the stays in each state. Thus

$$T_0 = \frac{1}{\mu_a + \mu_b}, T_1 = \frac{1}{\lambda_a + \mu_b}, T_2 = \frac{1}{\mu_a + \lambda_b}, T_3 = \frac{1}{\lambda_a + \lambda_b} \qquad (2.43)$$

While equation 2.34 compute the frequency of encountering each state as

$$f_o = \frac{\lambda_a \lambda_b (\mu_a + \mu_b)}{D}, f_1 = \frac{\mu_a \lambda_b (\lambda_a + \mu_b)}{D}, f2 = \frac{\lambda_a \mu_b (\lambda_b + \mu_a)}{D}, f3 = \frac{\mu_a \mu_b (\lambda_a + \lambda_b)}{D}, \qquad (2.44)$$

2.6. Power system Reliability

Electric power has become an inevitable asset to consumers that its adequate and reliable provision had become essential. Reliability is and always has been one of the major factors in planning, design, operation and maintenance of electric power system [28]. The reliability of an electric supply system has been defined as the probability of providing the users with continuous service of satisfactory quality. The quality constraint refers to the requirement that the frequency and the voltage of the power supply should remain within prescribed tolerances. The actual degree of reliability experienced by a consumer could depend on the location of the customer and the aspect of the power network such as generation, transmission and distribution systems.

CHAPTER 3: GENERATION SYSTEM RELIABILITY EVALUATION

3.1. Introduction

Modern power systems in developed countries are usually very large highly integrated and complex. The numerous numbers of components and the complex interrelations between them makes evaluation of the overall system extremely tricky, as it would require very complicated analytical models. These models are not impossible to build but they are difficult to develop and also required excessive computational time. Furthermore, the result obtained is likely to be so vast that meaningful interpretation will be difficult if not possible. Due to these characteristics system are usually divided in to three main functional units namely generation, transmission and distribution subsystems. Basically, these subsystems are usually evaluated separately for better reliability performance [29]. This study however addressed only a portion of system reliability, on generation system reliability. This system concentrates on the performance of the generators where water is converted in to electricity before it has been transferred the transmission network [30]. Generators are subjected to unexpected outage or reduction in available capacity which can affect the system reliability, hence the need for its evaluation. System reliability is commonly interpreted as the probability of system staying in its operating state, performing its intended purpose adequately for the intended period of operation without failure under specific conditions.

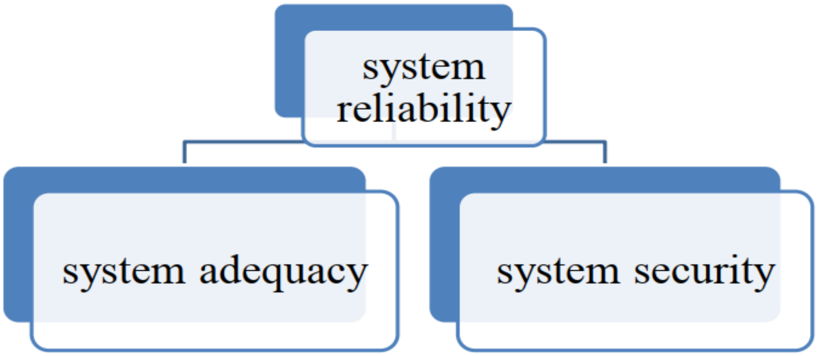


Figure3. 1Component of system reliability

System reliability is made up of two main components, system security and system adequacy. System security in this sense refers to the ability of the system to respond disturbances arising within that system [31].

However generation system security is the capability of the generators in enduring unexpected contingencies involving frequency and voltage anytime during the system operation. Security is a dynamic measure of response to unforeseen events. Adequacy on the other hand, considers the system in static condition and does not fluctuate from one moment to another, because it does not include system disturbances. It is probability of having enough capacity to remain secure at all times. In terms of generation an adequacy and its ability to meet the annual peak demand with the capacity under normal operating condition taking in to account both the scheduled and forced outages on the generators.

Put together, adequacy and security provides the overall reliability description of a generation system, which can be broadly described as the ability to supply the quantity and quality of electricity desired by the customer when needed. However the scope of this study only covers the system adequacy and not system security.

3.2. Generation system reliability evaluation methods

A general approach to electrical power generating system reliability assessment, determine one or more numbers of its reliability indices. A reliability index is defined quality that measures and quantifies some aspects of system reliability performance. [29]. A number of indices have been introduced in reliability studies over the past years to assist reliability evaluation and predictions. Reliability indices are extremely useful as it quantifies the reliability of the system, hence making the assessment more meaningful.

They are used to assess the reliability performance of generation system against some pre-determined criteria of reliability standards. Reliability indices used in the electric power industry can generally be grouped in to two broad categories.

I. Deterministic indices, which reflect postulated condition and
II. Probabilistic indices, which considers uncertainty inherent in power system operation

Probabilistic indices permit reliability evaluation by taking in to account the factors that influence reliability such as the capacity of individual unit and forced outage of each unit.

For the deterministic approach, two indices were used which are reserve margin and loss of largest unit in the system.

However there are generally two fundamental approaches used to calculate the risk indices in a probabilistic evaluation, the analytical method and the simulation method commonly known as Monte Carlo Simulation (MCS). Analytical techniques use mathematical and statistical models to represent the system elements. Monte Carlo Simulation, on the other hand, simulates the actual process and the random behavior of the system. The selection of the proper approach should be based on the desired type of evaluation and the particular system problems.

Probabilistic approaches however have more indices. According to [32] the indices can generally be categorized as follows.

Table3. 1: Probabilistic Reliability indices categories

No,	Index category	Example
1	Probabilistic	The reliability or the availability (probability of success)
2	Frequencies	The average number of failures per unit time
3	Mean duration	The mean time to the first failure(MTTF) The mean time between failure (MBTF) The mean duration of failures
4	Expectation	The average numbers of days in a year in system failure The average curtailment of energy per unit time because of power supply failure.

3.2.1 Analytical method of generating unit model

The conventional approach of generating capacity system evaluation is to develop a model for all the capacities from the system, using a convolving model, to obtain the all possible capacities of the power generating system. The capacities of generating units can be modeled like a discrete random variable, described as a probability mass function associated with a table that contains all the capacity states, in an ascending order, and its capacities probability.

Basic approach to evaluating generation capacity adequacy consists of three parts

- Generation model

- ➢ Load model
- ➢ Risk model

3.2.1.1 Generation Model

The simplest model for a generating unit for continuous operation is a Run-Fail-Repair-Run cycle that states that every generator has two states. They are Unit availability and Unit unavailability or forced outage rate (FOR). The unit availability means the long term probability that the generating unit will reside in on state and unit unavailability or FOR means the long term probability that the generating unit will reside in off state.

$$FOR = U = \frac{\lambda}{\lambda + \mu} = \frac{\sum[\,Down\ time]}{\sum[Down\ time]\ [+[up\ time]} \qquad (3.1)$$

$$A = \frac{\mu}{\mu + \lambda} = \frac{\sum[\,Up\ time]}{\sum[Down\ time]\ [+[up\ time]} \qquad (3.2\ \ )$$

Generation systems are modeled by three arrays: capacity outage levels (***X***), cumulative probability of capacity outages (***P***), and cumulative frequency of capacity outages (***F***) as follows:

- X_i = one of the discrete capacity outage levels
- P_i = probability of capacity outage greater than or equal to X_i
- F_i = frequency of capacity outage greater than or equal to X_i.

The generation system model is arranged in a tabular form with capacity outage levels sorted in ascending order. Table 3.2 indicates a generation system model in a tabular form. Index i is the number of capacity outage level in the generation system model.

Table3. 2: Generation system model

i	X_i=capacity outage level	P_i(capacity ≥ X_i)	F_i(capacity ≥ X_i)
1	X_1	P_1	F_1
2	X_2	P_2	F_2
3	X_3	P_3	F_3
…	…	…	…

Suppose there are *n* identical units installed in a system and that all units are independent:

$$P(X_k) = \binom{n}{k} r^k (1-r)^{n-k} \tag{3.3}$$

$$\mathrm{Pc}(X_k) = \sum_{\mathrm{k}\geq\mathrm{i}} \mathrm{P}(\mathrm{x}_k) \tag{3.4}$$

$$Fc(X_k) = P(x_k).\frac{K}{t_r} \tag{3.5}$$

When X_k denotes the level of outage capacity due to K failed units, r is the forced outage rate $P\ (X_k)$, the exact probability of k failed unit, t_r the repair time (MTTR) and $Pc\ (X_k)$, $F_c\ (X_k)$ are the cumulative probability and frequency respectively.

3.2.1.2 Load Model

Load model is formed by using daily or monthly or yearly peak loads via time in seconds or minutes or hours as shown in figure 3.2 where t_k is the time at outage of unit k, Q_k is the outage capacity.

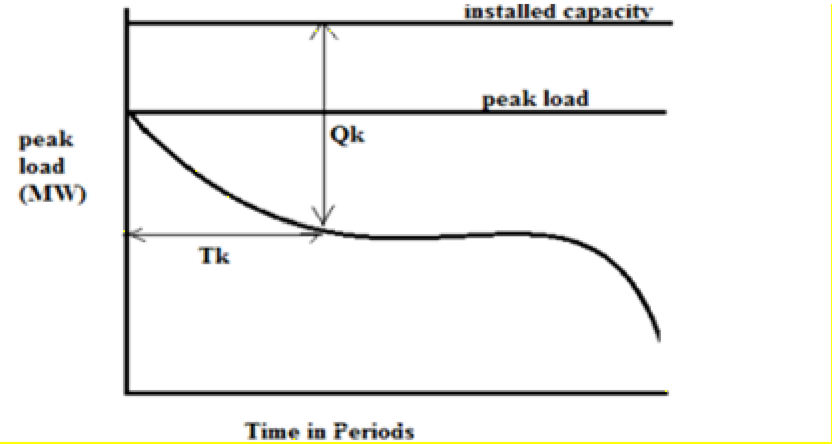


Figure3. 2: Typical load model

3.2.1.3 Risk Model

Risk model is to evaluate the risk indices such as LOLE, LOEE, EENS, Frequency and duration of systems. The equation below can be used to calculate the risk model (in hours) within the observation horizon (t):

Loss of load expectation (LOLE) can be obtained using the daily peak load variation curve. The period of study could be week, month or a year.

$$LOLE = \sum_{i=1}^{Nt} pf_i \tag{3.6}$$

The loss of energy expectation (LOEE) is the expected unsupplied energy due to generating inadequacy. The LOEE incorporates the severity of the deficiencies.

$$LOEE = \sum_{i=1}^{Nt} PNS_i \tag{3.7}$$

WherePNS_i, is the power not supplied and pf_irepresents the load probability of lost for hour t.

3.3.1. Capacity outage table for identical units

A capacity table is simply a probabilistic description of the possible capacity states of the system being evaluated.

Now consider a two unit system, with both units of capacity C. We can obtain the capacity outage table by basic reasoning, resulting in Table 3.3.

Table3. 3: Capacity Outage Table for 2 Identical Units

Capacity Outage	Probability
0	**A^2**
C	**AU**
C	**UA**
2C	**U^2**

Where, A and U are the availability and the forced outage rate or the unavailability of the system respectively.

It may also more formally obtain Table 3.3 by considering the fact that it provides the probability mass function (pmf) of the sum of two random variables. Define X_1 as the capacity outage random variable for unit1 and X_2 as the capacity outage random variable for unit2, with pmfs $f_{X1}(x)$ and $f_{X2}(x)$, each of which appear as in Figure 3.3, the desire $f_Y(y)$, the pmf of Y, where $Y=X_1+X_2$. Convolving $f_{X1}(x)$ with $f_{X2}(x)$, provides $f_Y(y)$.

$$f_Y(y) = \int_{-\infty}^{\infty} f_{x1}(t) f_{x2}(y-t)dt \qquad (3.8)$$

But, inspection of $fX1(x)$ and $fX2(x)$, as given by Figure 3.3, indicates that, since X_1 and X_2 are discrete random variables, their pmfs are comprised of impulses. Convolution of any function with an impulse function simply shifts and scales that function. The shift moves the origin of the original function to the location of the impulse, and the scale is by the value of the impulse. Figure 3.3 illustrates this idea for the case at hand.

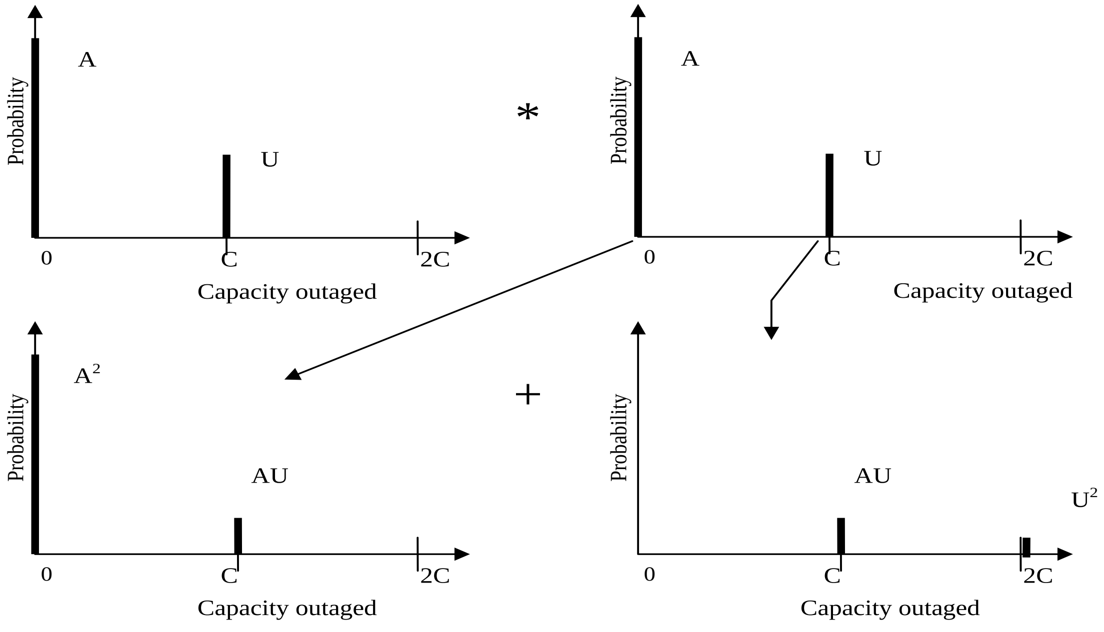


Figure3. 3: Convolution of Generator Outage Capacity pmfs

Figure3.4 shows the resultant pmf for the capacity outage for 2 identical units each of capacity C.

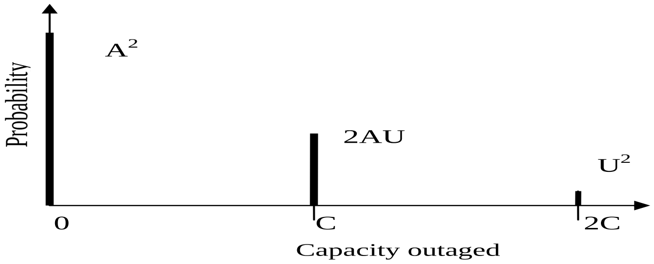


Figure3. 4: Pmf for Capacity Outage of 2 Unit examples

Figure 3.3 indicates there are only 3 states, but in Table 3.3 there are 4. One may reason from Table 3.3 that there are two possible ways of seeing a capacity outage of C, either unit 1 goes down or unit 2 goes down. Since these two states are the same, we may combine their probabilities, resulting in Table 3.4, which conforms to Figure 3.4

Table3. 4: Capacity Outage Table for 2 Identical Units with Frequencies and Durations

Capacity Outage	Probability	Frequency	Duration
0	A^2	$2\lambda A^2$	$\frac{1}{2\lambda}$
C	2AU	$2AU\mu\lambda$	$\frac{1}{\mu\lambda}$
2C	U^2	$2\mu U^2$	$\frac{1}{2\mu}$

3.4. Generation system Reliability indices formula

The reliability indices give glance picture of the reliability characteristics of device or system in general. The relationship between unit outage and some reliability parameters are specified in a number of literatures: These indices along with their formula are listed as follows [33].

Total service hours, $SH = 8760 - (SOH + FOH)$ (3.9)

Forced outage Rate, $FOR = \frac{FOH}{SH+FOH}$ (3.10)

Scheduled outage rate, $SOR = \frac{SOH}{SH+FOH}$ (3.11)

Outage hours, $FOR = FOH + SOH$ (3.12)

Mean time to failures (mean time up), $MTTF = \frac{SH}{N}$ (3.13)

Mean time to repair (mean time down) $MTTR = \frac{FOH}{N}$ (3.14)

Mean time between failures (period), $MTBF = MTTR + MTTF$ (3.15)

Frequency, $f = \frac{1}{MTBF}$ (3.16)

Failure rate, $\lambda = \frac{1}{MTTF}$ (3.17)

Repair rate, $\mu = \frac{1}{MTTR}$ (3.18)

Reliability, $R = \frac{SOH+SH}{8760hrs}$ (3.19)

Availability, $A = \frac{\mu}{\mu+\lambda}$ (3.20)

Unavailability, $U = \frac{\lambda}{\mu+\lambda}$ (3.21)

3.5. Factors influencing power system reliability

The factors influencing power system reliability can be broken down in to two categories. They are component statistics and environmental conditions.

3.5.1. Component statistics

A power system consists of various components, such as lines, cables, transformers, breaker, switches, reactors, and capacitors. Any single component outage may cause a partial or even entire system outage. The availability of functional component is characterized by failure rate and repair or replacement time.

3.5.1.1 Failure rate

Component failure can be divided in to aging failures and chance failures. Aging failure is a conditional failure that depends on the components history. Figure 3.5 shows a bath- tub curve of components failure rate changing during its life time. An aging failure can happen suddenly after a component enters in wear-out period. Figure 3.5 indicates that a component failure rate is not a constant. Failure rate distribution is different from component type to component type. Some expensive components like transformers come with a set of reliability data provided by the manufacturer, including the components life cycle statistical distribution [21] [34]. Nowadays, the infant mortality period of some expensive component is usually consumed by manufacturer so that when these components are put in to service they are already in a reliable state.

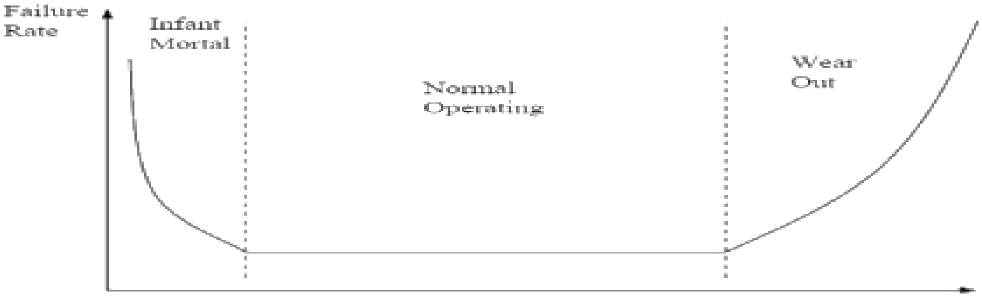


Figure3. 5: Bathtub curve of a component life

Chance failure is a random fatal failure. The failure rate in the normal operation period is a constant failure rate and it does not depend on a components age. Therefore, chance failure can be modeled as an exponential distribution.

3.5.1.2. Repair time

There is no good models for repair time (or down time), since the repair time for failed equipment depends upon many things, such as location, crew dispatch policy, different failed parts in a type of component and so on. One of the common practices is to use the exponential model, which assumes reparations are statistically independent events and the repair time can be represent by the global average. Historical data shows that the repair time is also affected by weather conditions. Stormy conditions usually prolong the process of customer down time.

3.5.2. Environmental condition

Power system components are exposed to various weather conditions and hazards. Animals, motor vehicle accidents, rain, ice and tree contacts can all lead to faults and failures. Environment dependent failures may be of short duration. However during such events the probabilities of failures of components increase dramatically. Many utility companies have given this increased attention, especially with weather dependent failures.

It is difficult to develop an accurate model for the catastrophic environment since its probability of occurrence and the impact range can only be based on a rough estimate.

Usually weather condition modeling is better designed than the other environmental conditions since historical weather data is always available. For example if the weather condition divided in to two basic states: normal and adverse, and the failure rates and repair rates of components for these two states are available, the system reliability can be weighted by the probability of the weather states.

CHAPTER 4: RELIABILITY EVALUATION OF BELES HYDROELECTRIC POWER STATION

4.1. General overview of Beles Hydroelectric power station

Beles hydropower station is one of the second largest and most modern power generation stations in Ethiopia which is located on the south west shores of Lake Tana. From the shores of Lake Tana, the project extends in a south westerly corridor 20 km in to the upper Beles valley. This project is a single stage power scheme with a total installed capacity of 460MW and an average annual generation capability of 2,050GWh per year. Apart from a 0.8 km Long approach channel, it develops completely underground for a length of about 20 km. a headrace tunnel (11.8 Km long) conveying water from lake Tana into an underground power house, accommodating four Francis turbine generator units, and then a tailrace tunnel (7.2Km long) discharges it into the Jehana river a small tributary of the Beles river, exploiting a total gross head of about 335m. After generate hydroelectric power, It also provides water for the irrigation of sugar industry in the downstream area. For the hydropower plant operation a minimum of 1784masl operation level is designed. The station has four generating units rated as 115MW each at a rated head of 315m. Each unit comprises a vertical Francis turbine unit controlled by electro-hydraulic governor.

For the last ten years, different types of faults have been occurred for each individual generating unit.

4.2. Outage data collection

Reliability assessment is one of the several required for decisions in the planning, design or operation of electric power systems [35]. For the normal operation of electric power systems, system outage data should be recorded and documented. The determination of the various components failure data (failure rate, repair time, switching times, and so on) depends on the collection of data and the statistical evaluation of the resulting data sample.

A comprehensive, structure and narrative procedure recommended by the institute of electrical and electronics engineers (IEEE) power engineering committee on recording generating unit outage was utilized to record all unit outages in the stations. This procedure, which can bring together statistical data that are normally gathered from a failure event, gives fourteen topical items which constitute a complete description of any specific failure. This procedure is known as Failure Event Record (FER) [36].

4.3. Computations of reliability indices

Components reliability indices are inputs to the system reliability studies and the validity of the results depends on how good this input information is. The determination of the various component failure data consists essentially of two steps: the collection of data and the statistical evaluation of the data. The evaluation of these data is done using analytical method (frequency and duration method), which adopt transition rate parameters of the generating units. A period of four years was covered based on the outage data obtained from Beles hydroelectric power station. In this section the yearly key performance indices and other parameters of the units between year 2014 and 2017 were presented. These tables are computed using of equation (3.9 to 3.21).

Table4. 1: Reliability indices of -2013/14

	Unit 1	Unit2	Unit3	Unit4
Forced outage hours (FOH)	2327.2	1365.2	1360.8	2209.6
Schedule outage hours(SOH)	194.4	202	276.4	467.2
Total period in the year (H)	8760	8760	8760	8760
Number of failures (N)	19	18	16	22
Service hours(SH)	6238.4	7192.8	7122.8	6085.2
Forced outage rate (FOR %)	26.566	15.584	15.534	25.223
Scheduled outage rate (SOR %)	2.219	2.30	3.155	5.333
Mean time to failure (MTTF)	338.568	410.822	462.450	297.745
Mean time to repair (MTTR)	122.484	75.844	85.050	100.436
Mean time between failure (MTBF)	461.052	486.666	547.500	398.181
Frequency (F)	0.002168	0.002054	0.001826	0.002511
Failure rate(λ)	0.002953	0.002434	0.002162	0.003358
Repair rate (µ)	0.008164	0.013184	0.011757	0.009956
Availability (A)	0.73437	0.84415	0.84467	0.74778
Unavailability (U)	0.26563	0.15584	0.15532	0.25221

Table4. 2: Reliability indices of -2014/15

	Unit 1	Unit2	Unit3	Unit4
Forced outage hours (FOH)	520.4	368.8	605.2	644.4
Schedule outage hours(SOH)	364.4	326.8	322.8	372.4
Total period in the year (H)	8760	8760	8760	8760
Number of failures (N)	14	11	10	14
Service hours(SH)	7875.2	8064.4	7832	7743.2
Forced outage rate (FOR %)	5.940	4.210	6.900	7.356
Scheduled outage rate (SOR %)	9.803	3.730	3.684	9.031
Mean time to failure (MTTF)	588.54	762.84	815.48	769.68
Mean time to repair (MTTR)	37.17	33.52	60.52	46.02
Mean time between failure (MTBF)	625.71	796.36	876	815.7
Frequency (F)	0.001598	0.001255	0.001141	0.001226
Failure rate(λ)	0.001699	0.001310	0.001226	0.001299
Repair rate (µ)	0.026901	0.029832	0.016523	0.021729
Availability (A)	0.940594	0.957934	0.930925	0.943590
Unavailability (U)	0.059405	0.042653	0.042594	0.056409

Table4. 3: Reliability indices of -2015/16

	Unit 1	Unit2	Unit3	Unit4
Forced outage hours (FOH)	1462.8	2112	1656	2184
Schedule outage hours(SOH)	200.4	346.1	684.2	860.2
Total period in the year (H)	8760	8760	8760	8760
Number of failures (N)	14	16	17	12
Service hours(SH)	7096.8	6301.9	6419.8	5715.8
Forced outage rate (FOR %)	16.69	24.10	18.90	24.93
Scheduled outage rate (SOR %)	2.29	3.95	7.81	9.82
Mean time to failure (MTTF)	521.3	415.5	417.9	548
Mean time to repair (MTTR)	104.48	132	97.42	182
Mean time between failure (MTBF)	625.8	547.5	515.3	730

Frequency (F)	0.001597	0.001826	0.001940	0.001369
Failure rate(λ)	0.001918	0.002406	0.002393	0.001824
Repair rate (μ)	0.009571	0.007575	0.010264	0.005494
Availability (A)	0.833057	0.758941	0.810934	0.750751
Unavailability (U)	0.166942	0.241058	0.189065	0.249248

Table4. 4: Reliability indices of -2016/17

	Unit 1	Unit2	Unit3	Unit4
Forced outage hours (FOH)	1200.8	2100	1449..2	1242
Schedule outage hours(SOH)	268.4	196.4	268.4	600.6
Total period in the year (H)	8760	8760	8760	8760
Number of failures (N)	17	23	28	15
Service hours(SH)	7290.8	6463.6	7042.9	6917.4
Forced outage rate (FOR %)	13.707	23.973	16.543	14.178
Scheduled outage rate (SOR %)	3.064	2.242	3.063	6.856
Mean time to failure (MTTF)	444.658	289.565	261.1	501.2
Mean time to repair (MTTR)	70.635	91.304	51.757	82.8
Mean time between failure (MTBF)	515.293	380.869	312.857	584
Frequency (F)	0.0019406	0.002625	0.003196	0.001712
Failure rate(λ)	0.0022489	0.003453	0.001382	0.001995
Repair rate (μ)	0.0141572	0.010952	0.019321	0.012077
Availability (A)	0.8629187	0.760274	0.933201	0.858218
Unavailability (U)	0.1370763	0.239031	0.66798	0.141780

Table4. 5: Average Reliability indices for Beles hydroelectric power plants from (2013-2016)

	Unit 1	Unit 2	Unit 3	Unit 4
Forced outage hours (FOH)	1377.8	1486.5	1267.8	1570
Schedule outage hours(SOH)	256.9	267.82	387.95	575.1
Total period in the year (H)	8760	8760	8760	8760
Number of failures (N)	16	17.25	17.75	15.75
Service hours(SH)	7125.3	7005.7	7104.4	6615.4
Forced outage rate (FOR %)	15.73	16.96	14.46	17.92
Scheduled outage rate (SOR %)	4.34	3.05	4.43	7.76
Mean time to failure (MTTF)	445.4	406.2	400.3	420.1
Mean time to repair (MTTR)	74.4	83.2	73.68	102.81
Mean time between failure (MTBF)	547.66	552.85	562.91	631.97
Frequency (F)	0.00182	0.00194	0.00202	0.001704
Failure rate(λ)	0.002204	0.002400	0.002025	0.002119
Repair rate (µ)	0.014698	0.015386	0.014466	0.012314
Availability (A)	0.843	0.831	0.887	0.826
Unavailability (U)	0.1526	0.1697	0.1134	0.1749

4.4 Program development

The analytical program was developed using the analytical method described earlier in this chapter. The structure, input data and output data are illustrated in the following.

4.4.1 Structure

Hardware Environment

Processor: Intel Pentium M, 1400 MHZ. RAM: 384 MB.

Software Environment Operating System: Windows 7 ultimate, version 2003.

Developing Environment: Visual basics 2010 express.

Flow chart for the program is shown in figure 4.1

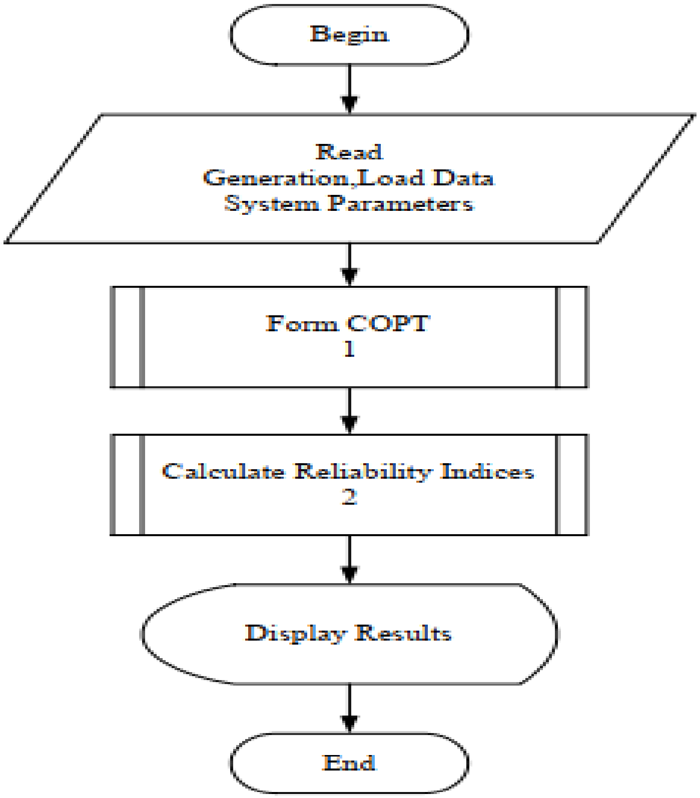
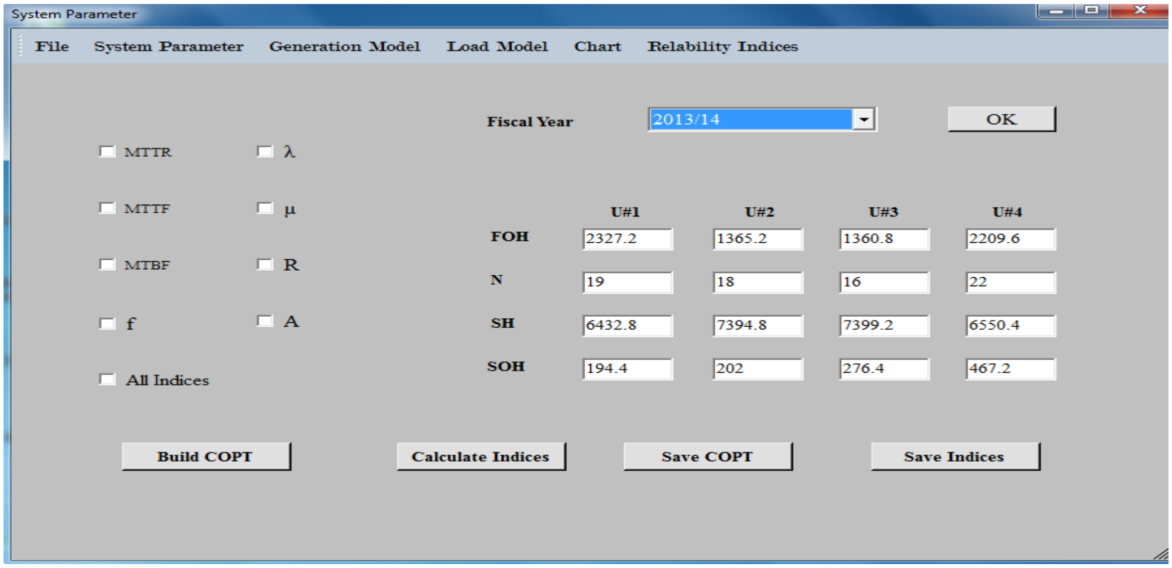


Figure4. 1: Flow chart for the program

4.4.2 Input Data

Three data segments are needed to perform generating capacity adequacy evaluation using the analytical program. These segments are designated as system parameters, generation data and load data.

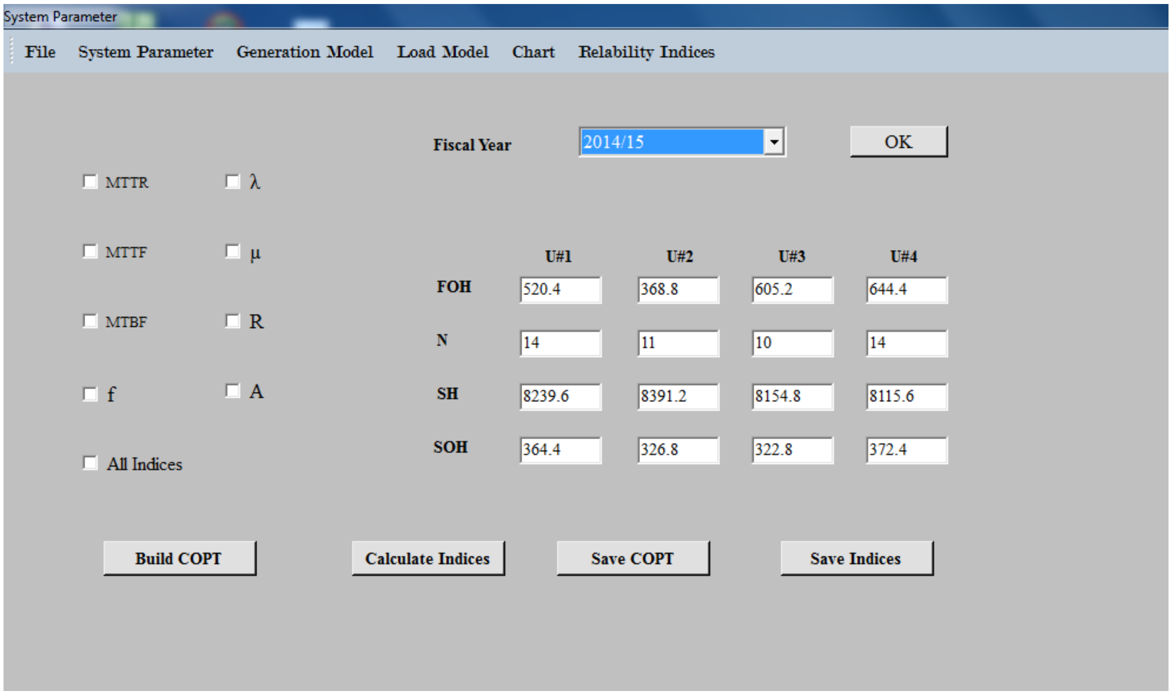
System Parameters: Figure 4.2 (a-d) shows the system parameters that need to be inputted and selecting the Reliability Indices to calculate from 2013/14 to 2016/17 respectively.



Fiscal Year: 2013/14

	U#1	U#2	U#3	U#4
FOH	2327.2	1365.2	1360.8	2209.6
N	19	18	16	22
SH	6432.8	7394.8	7399.2	6550.4
SOH	194.4	202	276.4	467.2

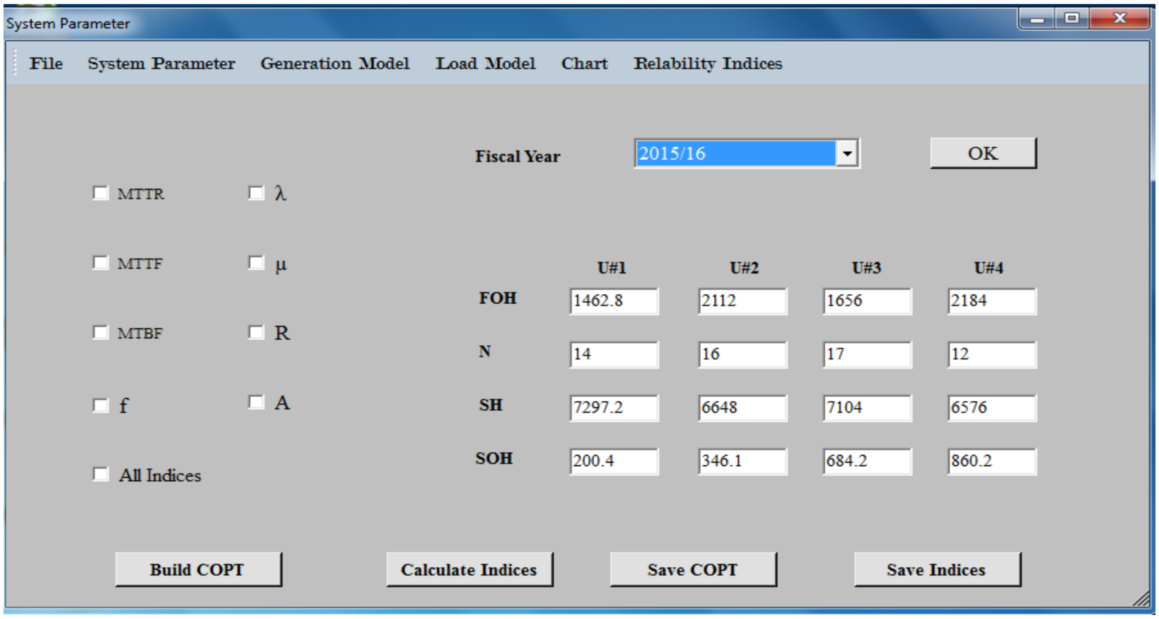
Figure4. 2(a): User interface to input the system parameters in the analytical program



Fiscal Year: 2014/15

	U#1	U#2	U#3	U#4
FOH	520.4	368.8	605.2	644.4
N	14	11	10	14
SH	8239.6	8391.2	8154.8	8115.6
SOH	364.4	326.8	322.8	372.4

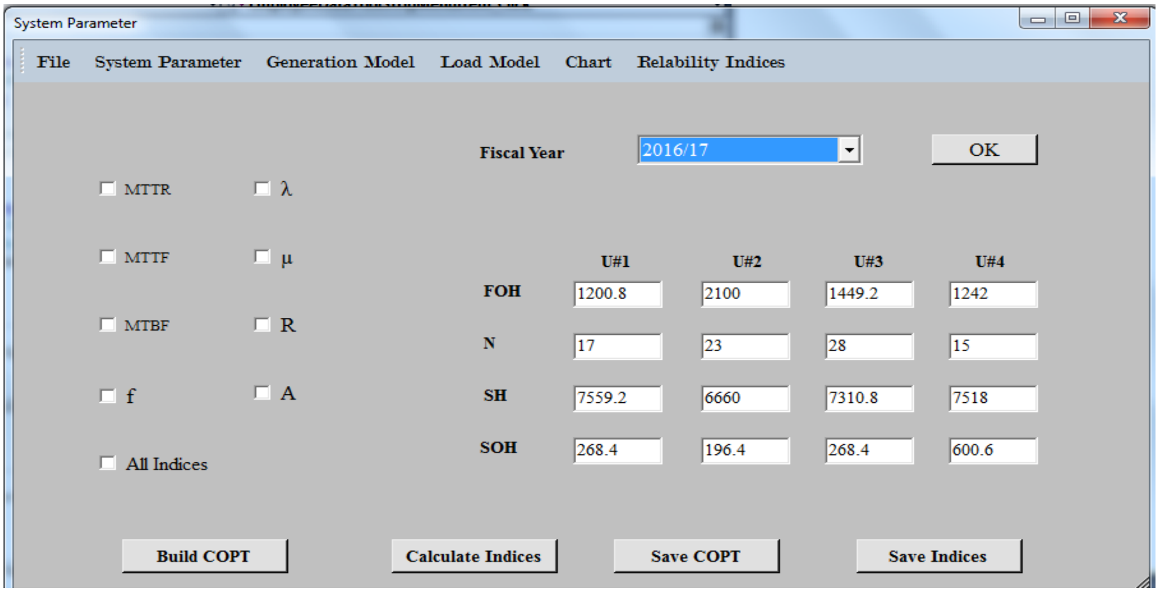
Figure4. 3 (b): User interface to input the system parameters in the analytical program



Fiscal Year 2015/16

	U#1	U#2	U#3	U#4
FOH	1462.8	2112	1656	2184
N	14	16	17	12
SH	7297.2	6648	7104	6576
SOH	200.4	346.1	684.2	860.2

Figure4. 4(c): User interface to input the system parameters in the analytical program



Fiscal Year 2016/17

	U#1	U#2	U#3	U#4
FOH	1200.8	2100	1449.2	1242
N	17	23	28	15
SH	7559.2	6660	7310.8	7518
SOH	268.4	196.4	268.4	600.6

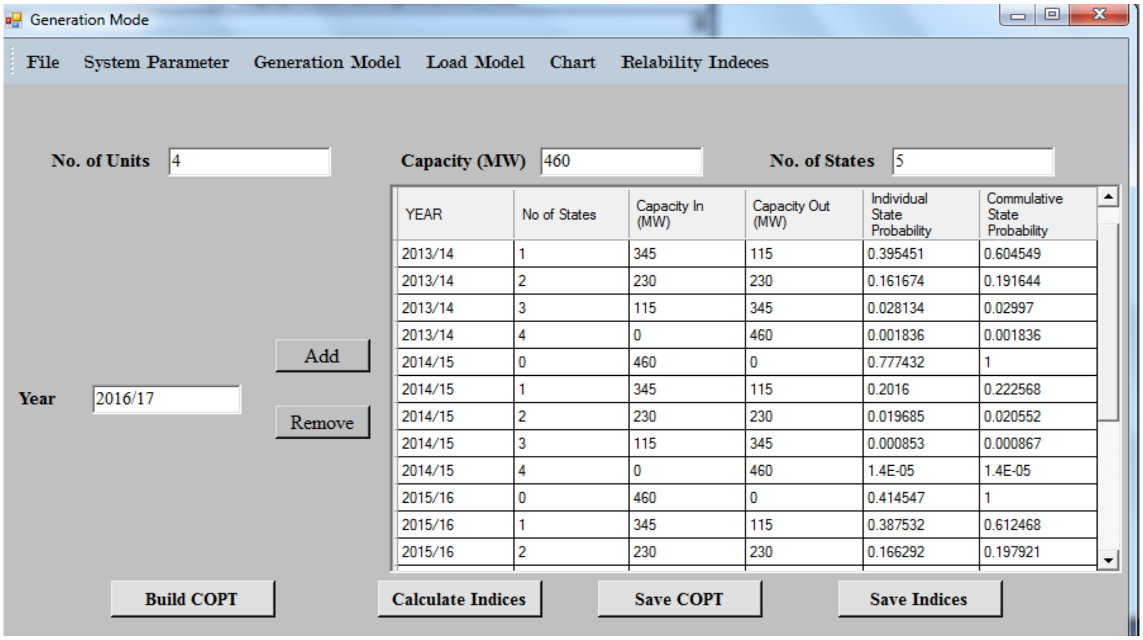
Figure4. 5(d): User interface to input the system parameters in the analytical program

Generation Data: - Figure 4.3 shows the required generation data.

Capacity -The unit capacity of this group of generating units.

No. of States- The number of the states of this group of generating units.

For each generating unit state, the capacity out of service and the associated probability are inputted.



No. of Units 4

Capacity (MW) 460

No. of States 5

Year 2016/17

YEAR	No of States	Capacity In (MW)	Capacity Out (MW)	Individual State Probability	Commulative State Probability
2013/14	1	345	115	0.395451	0.604549
2013/14	2	230	230	0.161674	0.191644
2013/14	3	115	345	0.028134	0.02997
2013/14	4	0	460	0.001836	0.001836
2014/15	0	460	0	0.777432	1
2014/15	1	345	115	0.2016	0.222568
2014/15	2	230	230	0.019685	0.020552
2014/15	3	115	345	0.000853	0.000867
2014/15	4	0	460	1.4E-05	1.4E-05
2015/16	0	460	0	0.414547	1
2015/16	1	345	115	0.387532	0.612468
2015/16	2	230	230	0.166292	0.197921

Figure4. 6: User interface to input the generation data in the analytical program

The following is the function of the buttons in the generation model page.

"Add": After the information for one unit of generating units is completely inputted, the "Add" button is pressed to include this group in the generating unit list.

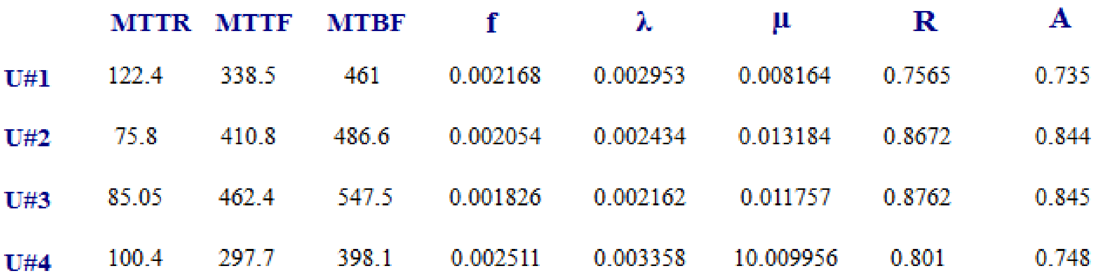
"Remove": Select the data of generating units to be removed. Pressing this button removes the data from the list.

"Save": After inputting the data for all generating units in the system, press this button and save the data to a specific file

4.4.3 Output Data

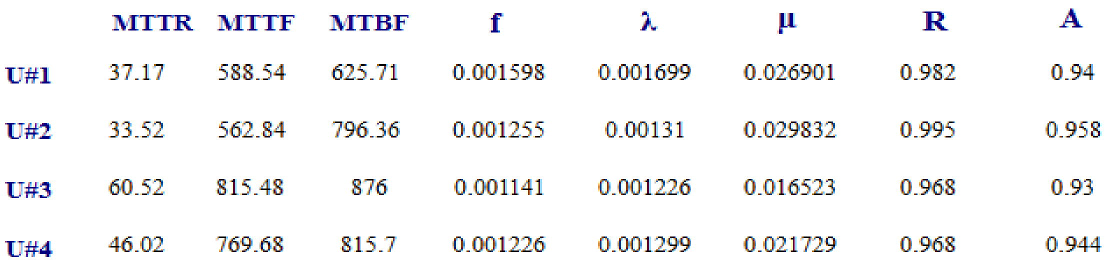
The program determines the COPT and the reliability indices for the system using the specified information. The maximum number of states for a COPT is 20. The output includes the capacity out, individual probability and cumulative probability for each state. The calculated reliability indices, MTTR, MTTF, MTBF and the failure & repair rates from the fiscal year 2013/14 to 2016/17 are shown in Figure 4.4.

Reliability calculated induces for 2013/14



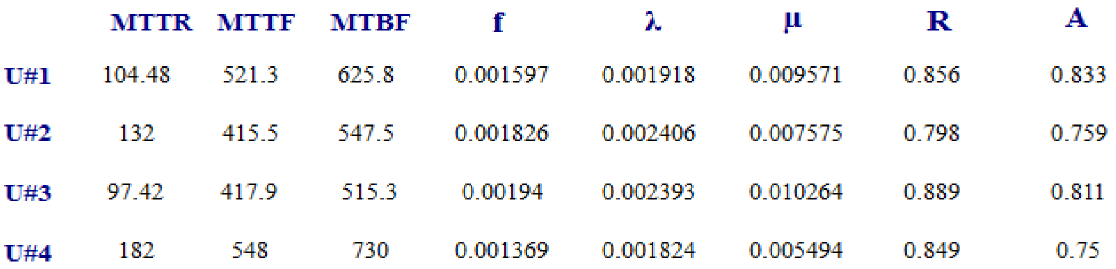
	MTTR	MTTF	MTBF	f	λ	μ	R	A
U#1	122.4	338.5	461	0.002168	0.002953	0.008164	0.7565	0.735
U#2	75.8	410.8	486.6	0.002054	0.002434	0.013184	0.8672	0.844
U#3	85.05	462.4	547.5	0.001826	0.002162	0.011757	0.8762	0.845
U#4	100.4	297.7	398.1	0.002511	0.003358	10.009956	0.801	0.748

Reliability calculated induces for 2014/15



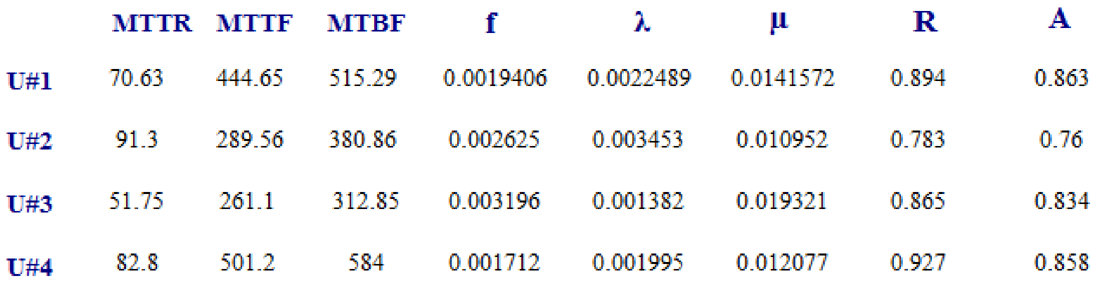
	MTTR	MTTF	MTBF	f	λ	μ	R	A
U#1	37.17	588.54	625.71	0.001598	0.001699	0.026901	0.982	0.94
U#2	33.52	562.84	796.36	0.001255	0.00131	0.029832	0.995	0.958
U#3	60.52	815.48	876	0.001141	0.001226	0.016523	0.968	0.93
U#4	46.02	769.68	815.7	0.001226	0.001299	0.021729	0.968	0.944

Reliability calculated induces for 2015/16



	MTTR	MTTF	MTBF	f	λ	μ	R	A
U#1	104.48	521.3	625.8	0.001597	0.001918	0.009571	0.856	0.833
U#2	132	415.5	547.5	0.001826	0.002406	0.007575	0.798	0.759
U#3	97.42	417.9	515.3	0.00194	0.002393	0.010264	0.889	0.811
U#4	182	548	730	0.001369	0.001824	0.005494	0.849	0.75

Reliability calculated induces for 2016/17



	MTTR	MTTF	MTBF	f	λ	μ	R	A
U#1	70.63	444.65	515.29	0.0019406	0.0022489	0.0141572	0.894	0.863
U#2	91.3	289.56	380.86	0.002625	0.003453	0.010952	0.783	0.76
U#3	51.75	261.1	312.85	0.003196	0.001382	0.019321	0.865	0.834
U#4	82.8	501.2	584	0.001712	0.001995	0.012077	0.927	0.858

Figure4. 7: The output of the COPT from the analytical program

For a system with n generating units which can either be in service or out of service, the total number of system states is 2^n and the total probabilities of these states must be equal to 1.0. Each unit is represented by one bit with a value of 1 or 0 which corresponds to in service or out of service state. The individual state probability is calculated using

$$Pg = \prod_{g=1}^{n} Pg \qquad (4.1)$$

For Beles hydroelectric power plant with 4 units, the possible state is 16 which are shown in table 4.6.

Table4. 6: Possible state of Beles HEPP

System state	Unit 1	Unit 2	Unit 3	Unit 4
1	1	1	1	1
2	0	1	1	1
3	0	0	1	1
4	0	0	0	1
5	0	0	0	0
6	1	0	1	1
7	1	1	1	0
8	1	0	0	0
9	1	0	0	1
10	1	1	0	1
11	0	1	0	1
12	1	1	0	0
13	0	1	1	0
14	1	0	1	0
15	0	0	1	0
16	0	1	0	0

It can be seen from Table 4.6 that

All units operating that is in stat 1 with full capacity of 460 MW

Three units operating in state 2, 6, 7 & 10 with a capacity of 345MW

Two units operating in state 3, 9, 11, 12, 13 & 14 with a capacity of 230 MW

One unit operating in state 4, 8, 15 & 16 with a capacity of 115 MW

All units failed in state 5 it is a down state

From the possible state of Beles hydropower station, at least three units are required for successful operation of the plant. The success probability of the plant is 0.8476.

When one unit operating in state 4, 8, 15 & 16 and when all units are in down state, that is in state five, the failure probability of the plant is 0. 1524.

4.5. Analysis of the operational data

Data used for this study are extracted from operation log book from 2013 to 2017. The data collected included running hours, planned outage hours, forced outage hours and grid interruptions. The results of the analysis are displayed in tables, graphs and charts. Table4.7. and 4.8 shows the summary of operational data obtained from the operations department of the plant from the period of Jun 2013 to Jun 2017 for each of the units. These data involve the yearly outage frequency (N), yearly forced outage hour (FOH), and yearly planned outage frequencies' (PN) and yearly outage hours (PHO) respectively.

Table4. 7: Summary of outage frequencies and forced outage hours

Power plant	Generating unit	Yearly forced outage frequency (N)				Yearly total forced outage hours (FOH)			
		2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017	2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017
Beles HEEP	Unit 1	19	14	14	17	2327	521	1463	1200
	Unit 2	18	11	16	23	1363	369	2112	2100
	Unit3	16	10	17	28	1361	605	1656	1449
	Unit4	22	14	12	15	2209	645	2184	1242

Table4. 8: Summary of planned outage hours and frequencies

Power plant	Generating unit	Yearly planned outage frequency (N)				Yearly total planned outage hours (POH)			
		2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017	2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017
Beles	Unit 1	12	13	16	12	194	859	200	268

HEP	Unit 2	14	16	12	12	202	326	346	196
	Unit3	14	13	12	14	276.4	323	684	268
	Unit4	16	12	15	12	467.2	791	860	600

The most basic parameter/index used in reliability computation is the failure rate (λ) which is the number of failures (shutdown) per unit time and repair rate (μ) which is the number of repairing (maintaining) of the unit per unit time? The failure rate and the repair rate of the units for the period of study are shown in Table 4.9.

Table4. 9: Failure rate and Repair rate of Beles hydroelectric power station units

Unit No.	2013/14		2014/15		2015/16		2016/17	
	Failure Rate(λ)	Repair Rate(μ)	Failure Rate(λ)	Repair Rate(μ)	Failure Rate(λ)	Repair Rate(μ)	Failure Rate(λ)	Repair Rate(μ)
1	0.002953	0.008164	0.001699	0.026901	0.001918	0.095710	0.002249	0.014157
2	0.002434	0.013184	0.001310	0.029832	0.002406	0.075750	0.003453	0.010952
3	0.002162	0.011757	0.001226	0.016523	0.002393	0.010264	0.001382	0.019321
4	0.003358	0.099560	0.001299	0.021729	0.001824	0.054940	0.001995	0.012077

Considering five state model, for the reliability system of Beles Power station having an identical units from 2013/14-2016/17, the state space diagram is shown in figure 4.5

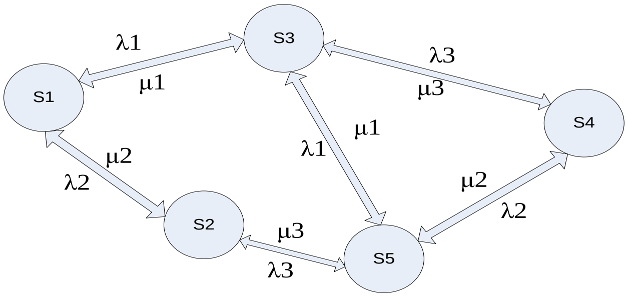


Figure4. 8: State-space diagram of four generators

The state transition intensity matrix is given by

$$\begin{bmatrix} -\kappa_{\mathbf{0}} & \mu_1 & \mu_2 & 0 & \mu_3 \\ \lambda_1 & -\kappa_1 & 0 & \mu_2 & 0 \\ \lambda_2 & 0 & -\kappa_2 & \mu_1 & 0 \\ 0 & \lambda_2 & \lambda_1 & -\kappa_3 & 0 \\ \lambda_3 & 0 & 0 & 0 & -\kappa_4 \end{bmatrix} \tag{4.2}$$

Where

$$K_0 = (\lambda_1 + \lambda_2 + \lambda_3)$$

$$K_1 = (\lambda_2 + \lambda_3 + \mu_1)$$

$$K_2 = (\lambda_1 + \lambda_3 + \mu_2)$$

$$K_3 = (\lambda_3 + \mu_1 + \mu_2)$$

$$K_4 = (\lambda_1 + \lambda_2 + \mu_3)$$

$$-K_0P_0 + \lambda_1P_1 + \lambda_2P_2 + \lambda_3P_4 = 0 \tag{4.3}$$

$$\mu_1P_0 - K_1P_1 + \lambda_2p_3 = 0 \tag{4.4}$$

$$\mu_2P_0 - K_2p_2 + \lambda_1p_3 = 0 \tag{4.5}$$

$$\mu_2P_1 + \mu_2P_2 - K_3P_3 = 0 \tag{4.6}$$

$$\mu_3P_0 - K_4P_4 = 0 \tag{4.7}$$

By omitting the first equation and replacing it with $P_0 + P_1 + p_{2+} + P_3 + P_4 = 1$, the solution of the steady state probabilities are:

$$P_0 = \frac{\lambda_1 + \lambda_2 + \lambda_3}{D} \tag{4.8}$$

$$P_1 = \frac{\lambda_2 + \lambda_3 + \mu_1}{D} \tag{4.9}$$

$$P_2 = \frac{\lambda_1 + \lambda_2 + \mu_2}{D} \tag{4.10}$$

$$P_3 = \frac{\lambda_3 + \mu_1 + \mu_2}{D} \tag{4.11}$$

$$P_4 = \frac{\lambda_1 + \lambda_2 + \mu_3}{D} \tag{4.12}$$

Where D=$(\lambda_1 + \lambda_2)(\lambda_1 + 2\mu_2) + (2\lambda_1\mu_1 + \mu_2(\mu_1 - \lambda_1) + \mu_2^2$

The steady state probabilities for 2013,2014,2015,2016 are presented in table 4.10

Table4. 10: Capacity outage probability table (COPT) of Beles HEPS

Year	State number	Capacity (MW)	Individual state probability	Cumulative state probability	Average hours in state per year
2013/14	4	460	0.30191	1.000000	2653.45
	3	345	0.21157	0.604549	1853.37
	2	230	0.18676	0.191644	1751.84
	1	115	0.18081	0.02997	1583.93
	0	0	0.17699	0.001836	1531.08
2014/15	4	460	0.32840	1.000000	2868.04
	3	345	0.21205	0.222568	1857.57
	2	230	0.16942	0.020552	1365.53
	1	115	0.14788	0.000867	1295.43
	0	0	0.14246	0.000014	1280.73
2015/16	4	460	0.28421	1.000000	2489.69
	3	345	0.21164	0.612468	1853.99
	2	230	0.18957	0.197921	1750.94
	1	115	0.18253	0.031629	1598.97
	0	0	0.18002	0.001982	1572.75
2016/17	4	460	0.27230	1.000000	2385.36
	3	345	0.21655	0.527700	1896.94
	2	230	0.17991	0.138009	1751.30
	1	115	0.11486	0.017436	1006.18
	0	0	0.10998	0.000855	954.69

From table4.10, Beles HEPS consists of four units and as the number of unit increases progressively during analysis, the system capacity output (MW) increases while capacity available (MW) decreases. The probability of individual state being failed decreases as the unit increases.

The system availability, the system unavailability, the frequency of system failure and the mean duration of the system failure of each year under study is obtained from equations 3.47, 3.48, 3.44, and 3.43 respectively in table 4.11

Table4. 11: System availability and unavailability for Beles HEPs units

Year	system availability	System Unavailability	Frequency of system failure	Mean duration of system failure(hours)
2013/14	0.792746	0.207254	0.002284	46.843
2014/15	0.943261	0.056739	0.024821	39.125
2015/16	0.800865	0.199135	0.002013	58.323
2016/17	0.853672	0.146328	0.002814	57.321

The overall capacity outage probability table (COPT) for the units under the period of study (2013/14-2016/17) can be obtained from the failure rate and repair rate table 4.5. This is presented in table 4.12.

Table4. 12: Average capacity outage probability table (COPT) for Beles HEPP (2013/14-2016/17)

State	Capacity	Steady state probabilities	Average hours in state per year
4	460	0.296704	2599.13
3	345	0.212953	1865.47
2	230	0.181415	1589.19
1	115	0.156564	1371.52
0	0	0.152364	1334.71

Hence, the overall system availabilities as

$$A_s = \sum_{j=B} P_j = P1 + P2 + P3 + P4 = 0.8476 \qquad (4.13)$$

While the overall system unavailability as

$$u_s = (1 - A_s) = \textstyle\sum_{j=F} P_j = 0.1524 \qquad (4.14)$$

The frequency of the system failure

$$f = (1 - A_s).\sum_{i=1}^{n} \mu_i = 1.98 * 10^{-4} \qquad (4.15)$$

And the mean duration of system failure

$$T_f = \frac{1}{\sum_{i=1}^{n} \mu i =} = 50.5\ hrs \qquad (4.16)$$

4.6. Performance analysis of individual units

Table4. 13: Annual unit Reliability and availability for the FY 2013/14-2016-17

FY	Unit 1		Unit 2		Unit3		Unit4	
	R	A	R	A	R	A	R	A
2013/14	75.65	73.5	86.72	84.4	87.62	84.5	80.10	74.8
2014/15	98.2	94.0	99.5	95.8	96.8	93.0	96.8	94.4
2015/16	85.6	83.3	79.8	75.9	88.9	81.1	84.9	75.0
2016/17	89.4	86.3	78.3	76.0	86.5	83.4	92.7	85.8

From table 4.13 for 2014/15 the plant has been operated in full capacity with minimum forced and schedule outage.

Table4. 14: Average key performance indices of units from the period of study 2013/14-2016/17

Key performance indices	Unit 1	Unit 2	Unit3	Unit4
MTBF	547.66	552.85	562.91	631.970
MTTR	74.400	83.20	73.680	102.810
MTTF	473.300	469.68	489.23	529.150
FOR	0.15700	0.169	0.1450	0.17900
Reliability (R)	0.87212	0.86080	0.89955	0.88625
Availability (A)	0.843	0.831	0.887	0.826

A major determinant of reliability and availability of a plant is the failure rate which gives a reasonable measure of the stability of the plant units and indicates the economic effectiveness of repairs. Throughout the time of investigation in this study, availability, reliability and other parameters needed to be considered fluctuate and could not reach the required expected benchmark.

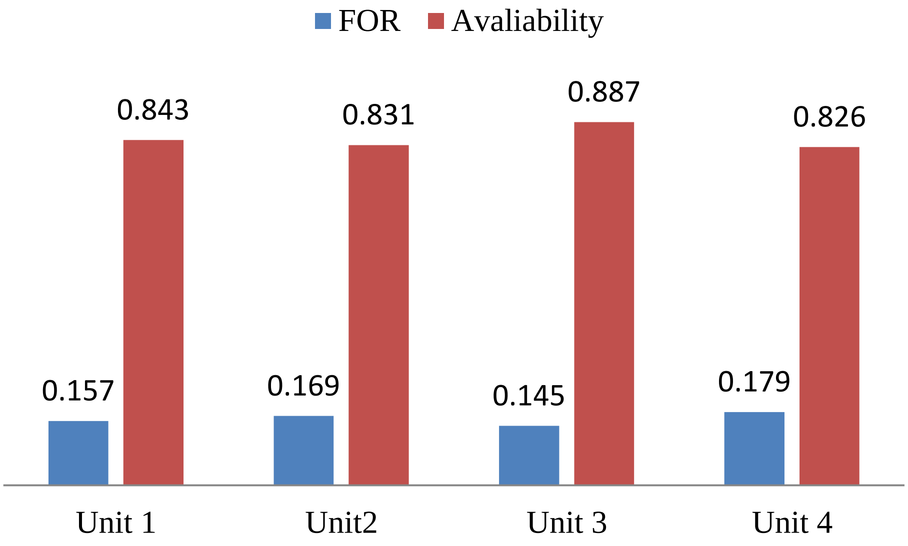


Figure4. 9: Relationship between Availability and forced outage rate

The relationship between availability and forced outage rate of the units, it reveals that the lower the FOR of each unit the higher availability.

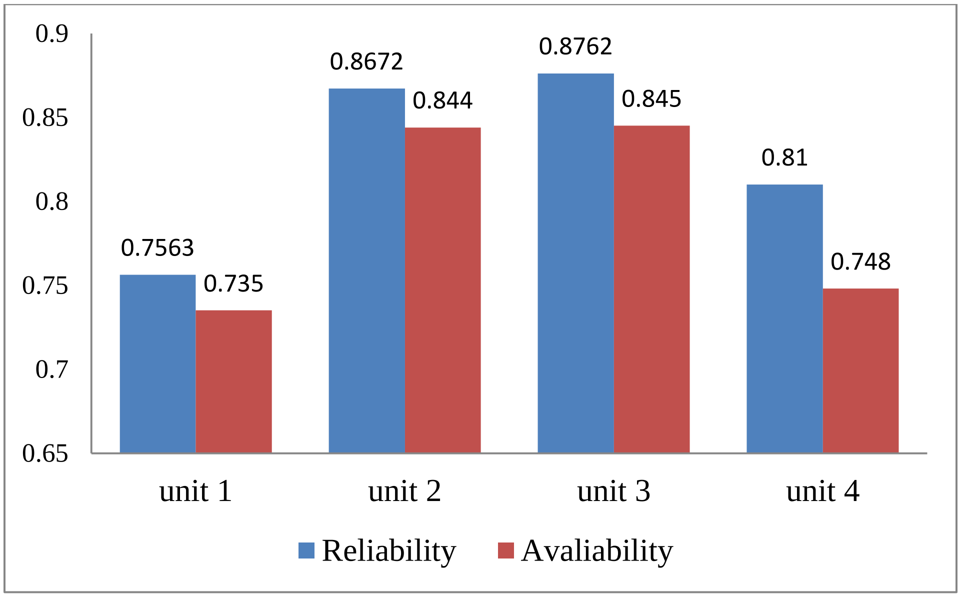


Figure4. 10: Reliability and Availability of units for FY 2013/14

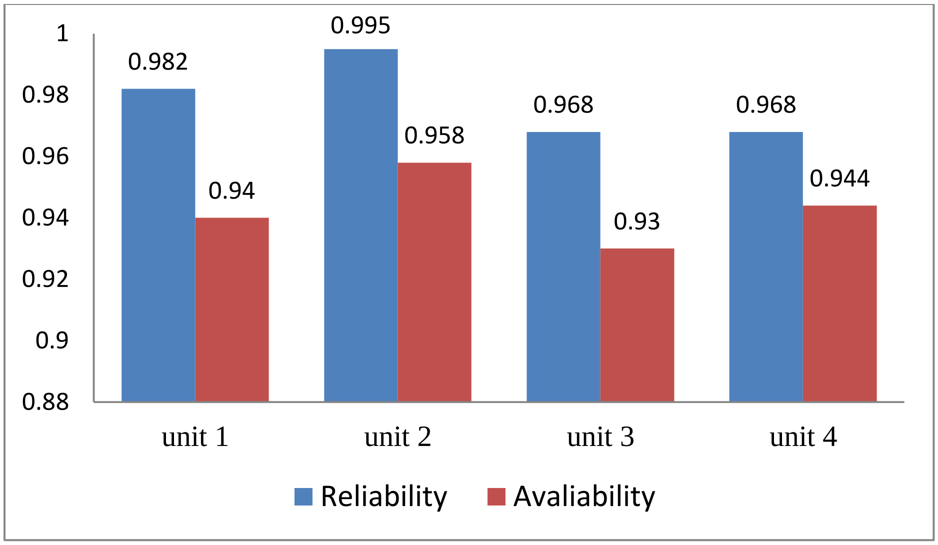


Figure4. 11: Reliability and Availability of units for FY 2014/15

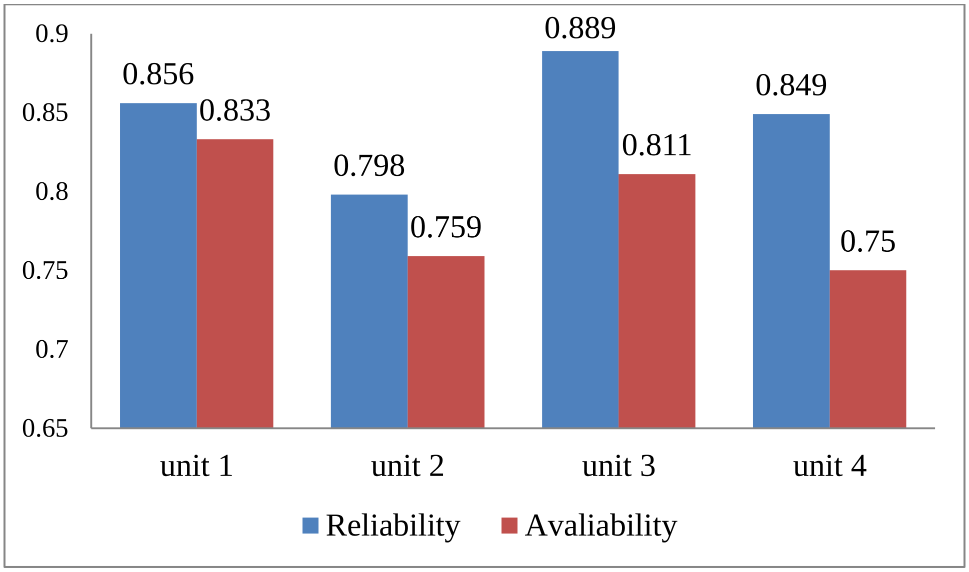


Figure4. 12: Reliability and Availability of units for FY 2015/16

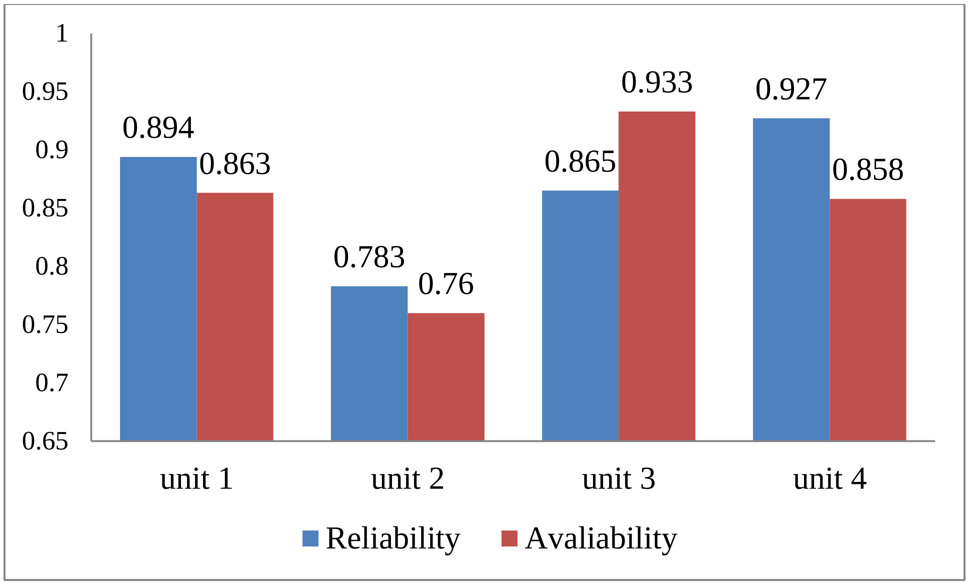


Figure4. 13: Reliability and Availability of units for FY 2016/17

From figure 4.7 -4.10 the reliability and reliability indices analysis carried out on each individual units within the period of study.

The major factor responsible for these high values in reliability and availability were their high MTBF and Low MTTR. This suggests that the lower the MTTR, the higher the up time and ultimately the availability of a unit .However, for all units except unit 2 in 2014/15,the higher values of reliability and availability from the study were below the benchmark as 98 % and above. The plant is made up of four individual and identical units. The overall performance of the plant depends on the performances of each of these units.

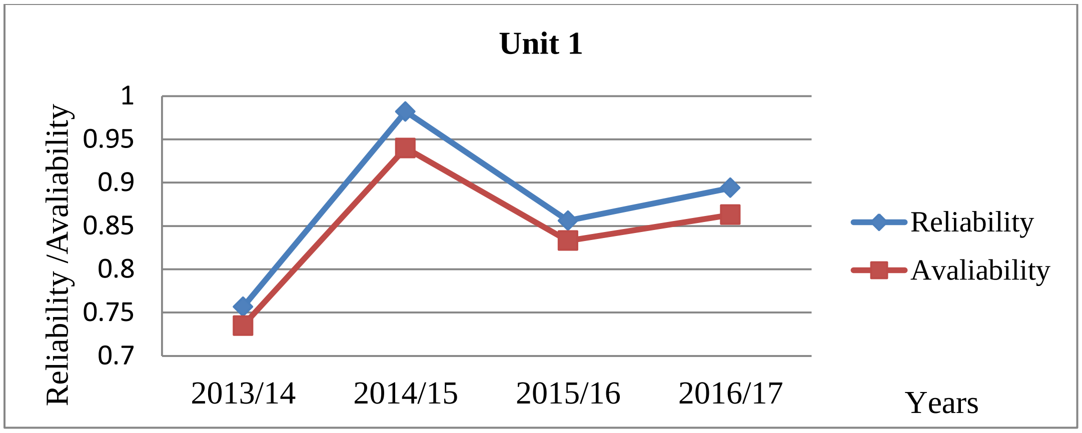


Figure4. 14: Annual Reliability and Availability of unit No.1 for FY 2013/14-2016/17

Figure 4.11 above shows that the poor performance of the unit in 2013/14.As compared to the other years the frequency of interruption was high in this year .this is due to fault frequently occurring on the grid. Hence the overall system reliability and availability was 0.872% and 0.842% respectively during the period of study which is considerably below the international standard value of 0.98% and above.

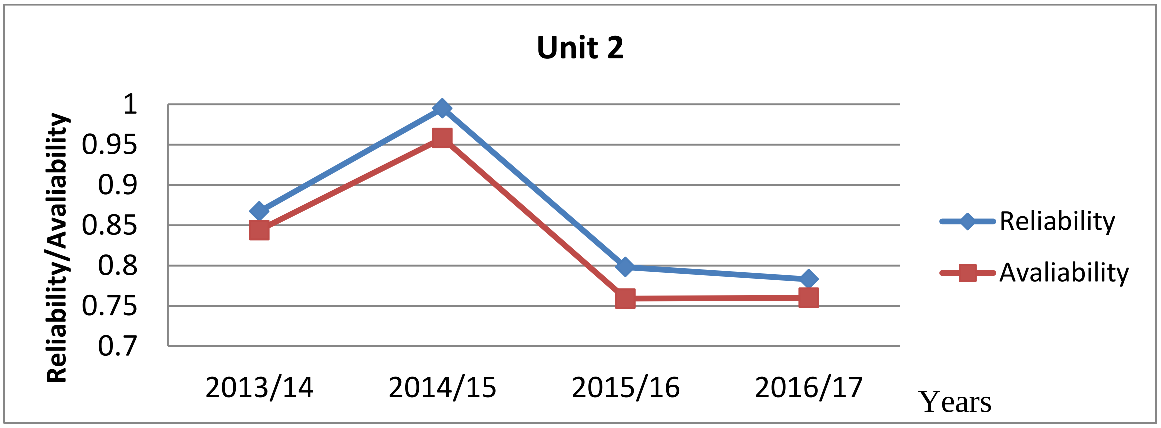


Figure4. 15: Annual Reliability and Availability of unit No.2 for FY 2013/14-2016/17

Figure 4.12 shows that the poor performance of the unit in 2015/16.As compared to the other years the frequency of interruption was 16 and the total outage hour was 2112hrs shown in table 4.1.this is mainly due to fault occurring on the main inlet valve of the locking device, control voltage lost due malfunction of the Battery and other external factors of the system. Hence the overall system reliability and availability was 0.86% and

0.83% respectively during the period of study which is much below the international standard value of 0.98% and above.

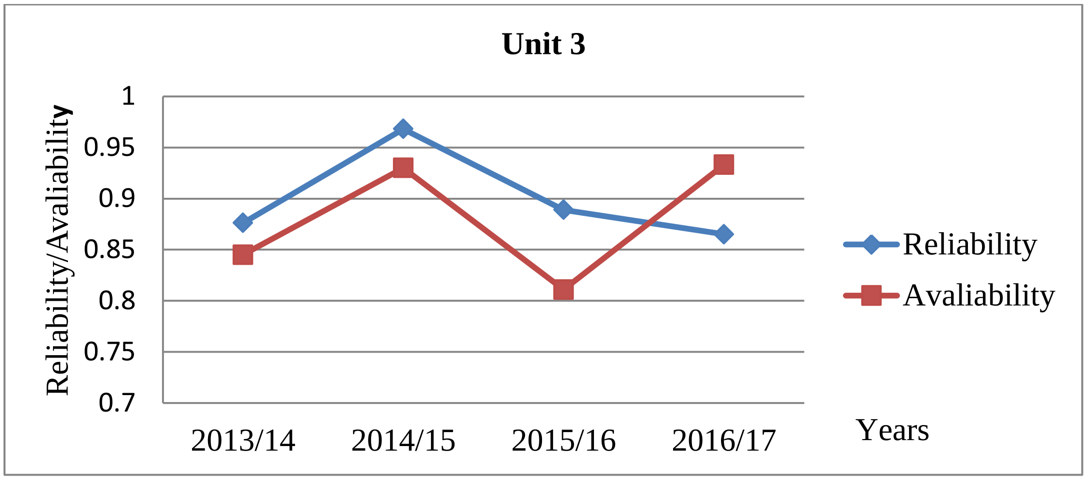


Figure4. 16: Annual Reliability and Availability of unit No.3 for FY 2013/14-2016/17

Figure 4.13 shows that the poor performance of the unit in 2015/16. As compared to the other years the frequency of interruption was 17 and the total outage hour was 1656 hrs. shown in table 4.1.this is mainly facing the problem of breaking of regulating ring due to continuous underload operation of the unit and leads vibration and cavitation effects of the turbine runner, control voltage lost due malfunction of the Battery and other external factor. Delivery for run of machines in isolation mode is available in unit 3 for the backup supply in station while main transmission system fails. Hence unit 3 has been seen running continuously even in the absence of system in order to get immediate back up supply. Hence the overall system reliability and availability was 0.899% and 0.855% respectively during the period of study which is considerably below the international standard value of 0.98% and above.

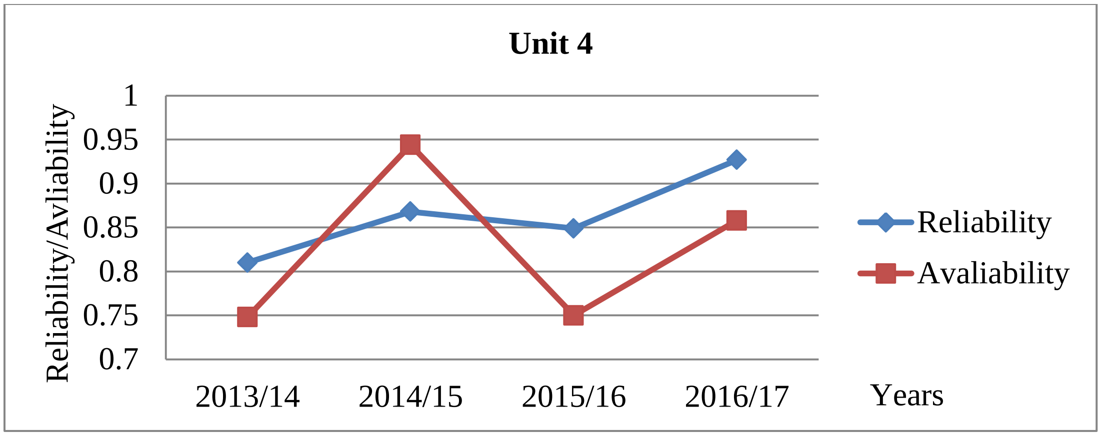


Figure4. 17: Annual Reliability and Availability of unit No.4 for FY 2013/14-2016/17

Figure 4.14 above shows that the poor performance of the unit in 2013/14 and 2015/16.As compared to the other years the frequency of interruption was high in this year .this is due to fault repetitively occurring on the grid, control voltage lost due to malfunction of the battery and other internal and external outages. Hence the overall system reliability and availability was 0.888% and 0.8476% respectively during the period of study which is much below the international standard value of 0.98% and above.

According to the study, year by year Assessment shows that the performance of the plant was best in 2014/15.

Generally, the typical values for Forced Outage Rates of generating units tend to range between 15% and 18%, which depends on other factors such as unit type, size and age of plant components.

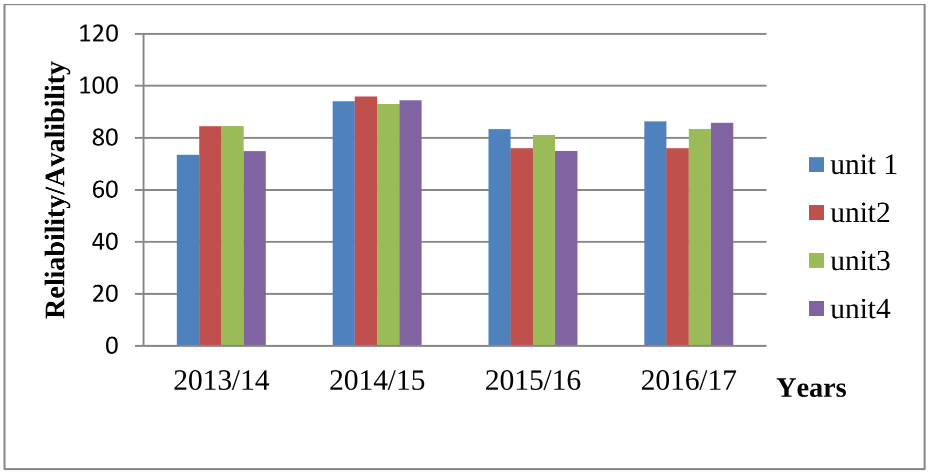


Figure4.25: Annual Reliability and Availability of unit No.4 for FY 2013/14-2016/17

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The operational reliability evaluation of Beles Hydroelectric Power Plant has been carried out in this study. Based on results obtained using key performance indices, the plant had an overall poor performance. For instance, the average overall availability and reliability in the four-year span was 84.45% and 87.97% respectively. Compare these with the international best practices of 98% and above for reliability [37]. Two major reasons have been discovered to be responsible for this poor performance: Line restriction by the system operator due to poor wheeling capacity of the grid has been major factor responsible for the poor performance of the plant. The frequent partial and total collapses of the grid often experienced in the country makes it impossible for generating companies to increase their capacity without a corresponding increase in the Wheeling capacity of the national grid. This is mainly due to fault frequently occurring on the grid and under load operation affect the operating life time of the machine. Another major problem affecting the plant's performance is the unavailability of spare parts required for proper running maintenance to be carried out. There is a poor inventory of spare parts and lack of competent manpower to carry out major maintenance operations in the event of sudden breakdown. The availability of the units can be improved if a proper maintenance plan is drawn for the units and strictly followed. The performance of the plant has been found to be affected not only by management, maintenance and operational practices but also by the activities of the National load dispatch Centre (LDC), transmission and distribution system. To improve electricity generation of the Plant there has to be an improvement in O&M practices, provision of a robust inventory of spare parts, training and retraining of the O&M staff to be able to carry out major maintenance activities, increasing the wheeling capacity of the grid, reduction in distribution losses and improved revenue collection by the distribution offices. Since the challenges facing the plant is not merely localized, it is therefore of utmost importance that all sectors of the electricity value chain be made to operate more efficiently to ensure improved electricity supply which will enhance rapid industrialization of the country and improvement in the socio-economic lives of the citizens.

5.2. Recommendations

The presented work can be extended in following area:

- Development of program for calculation of LOLP, LOLE and other reliability indices.
- Security analysis of generation system.
- Reliability evaluation of power system for transient conditions.
- Reliability of complete system which includes generation, transmission and distribution.

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APPENDICES

Code for the COPT development using Visual basics software

```
Operational Reliability evaluation of hydroelectric power stations
By Woldemariam Worku
Dim str As String
    str = "select * from sysparm where (Fiscalyr = '" & ComboBox1.Text & "')"
    Dim cmd As OleDbCommand = New OleDbCommand(str, myConnection)
    dr = cmd.ExecuteReader()
    While (dr.Read())
       TextBox1.Text = dr("U1FOH").ToString
      TextBox5.Text = dr("U1N").ToString
      TextBox9.Text = dr("U1SH").ToString
      TextBox13.Text = dr("U1SOH").ToString
      TextBox2.Text = dr("U2FOH").ToString
      TextBox6.Text = dr("U2N").ToString
      TextBox10.Text = dr("U2SH").ToString
      TextBox14.Text = dr("U2SOH").ToString
      TextBox3.Text = dr("U3FOH").ToString
      TextBox7.Text = dr("U3N").ToString
      TextBox11.Text = dr("U3SH").ToString
      TextBox15.Text = dr("U3SOH").ToString
      TextBox4.Text = dr("U4FOH").ToString
      TextBox8.Text = dr("U4N").ToString
      TextBox12.Text = dr("U4SH").ToString
      TextBox16.Text = dr("U4SOH").ToString
    End While
    myConnection.Close()
  End Sub
```

```
Private Sub ColumnToolStripMenuItem1_Click(sender As System.Object, e As System.EventArgs) Handles ColumnToolStripMenuItem1.Click
        chart.Show()
    End Sub
        If (TextBox4.Text = "2013/14") Then
            Me.DataGridView1.Rows.Add(TextBox4.Text, "0", 460, 0, 0.412905, 1)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "1", 345, 115, 0.395451, 0.604549)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "2", 230, 230, 0.161674, 0.191644)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "3", 115, 345, 0.028134, 0.02997)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "4", 0, 460, 0.001836, 0.001836)
            ElseIf (TextBox4.Text = "2014/15") Then
            Me.DataGridView1.Rows.Add(TextBox4.Text, "0", 460, 0, 0.777432, 1)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "1", 345, 115, 0.2016, 0.222568)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "2", 230, 230, 0.019685, 0.020552)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "3", 115, 345, 0.000853, 0.000867)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "4", 0, 460, 0.000014, 0.000014)
        ElseIf (TextBox4.Text = "2015/16") Then
            Me.DataGridView1.Rows.Add(TextBox4.Text, "0", 460, 0, 0.414547, 1)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "1", 345, 115, 0.387532, 0.612468)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "2", 230, 230, 0.166292, 0.197921)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "3", 115, 345, 0.029647, 0.031629)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "4", 0, 460, 0.001982, 0.001982)
        ElseIf (TextBox4.Text = "2016/17") Then
```

```
            Me.DataGridView1.Rows.Add(TextBox4.Text, "0", 460, 0, 0.472301, 1)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "1", 345, 115, 0.389691, 0.5277)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "2", 230, 230, 0.120573,
0.138009)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "3", 115, 345, 0.016581,
0.017436)
            Me.DataGridView1.Rows.Add(TextBox4.Text, "4", 0, 460, 0.000855, 0.000855)
        Else
            MessageBox.Show("The Fiscal Year Is Empty Or Wrong", "Error",
MessageBoxButtons.OK, MessageBoxIcon.Error)
        End If
    End Sub
    DataSource=H:\EIMS\EIMS\ore.accdb")
        myConnToAccess.Open()
        ds = New DataSet
        tables = ds.Tables
        da = New OleDbDataAdapter("SELECT Fiscalyr from sysparm", myConnToAccess)
        da.Fill(ds, "sysparm")
        Dim view1 As New DataView(tables(0))
        With CB1
            .DataSource = ds.Tables("sysparm")
            .DisplayMember = "Fiscalyr"
            .ValueMember = "Fiscalyr"
            .SelectedIndex = 0
            CB1.Focus()
        End With
        provider = "Provider=Microsoft.ACE.OLEDB.12.0;Data Source="
        dataFile = "H:\EIMS\EIMS\ore.accdb"
        connString = provider & dataFile
        myConnection.ConnectionString = connString
    End Sub
```

```
    Private Sub Button1_Click(sender As System.Object, e As System.EventArgs) Handles CRTLD.Click
        '2013/14
        If (CB1.Text = "2013/14") Then
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit1", " 0.7565")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit1", "0.735")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 2", "0.8672")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 2", "0.844")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 3", "0.8762")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 3", "0.845")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 4", "0.8010")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 4", "0.748")

            '2014/15
        ElseIf (CB1.Text = "2014/15") Then
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit1", " 0.565")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit1", "0.35")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 2", "0.672")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 2", "0.844")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 3", "0.762")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 3", "0.45")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 4", "0.010")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 4", "0.48")

            '2015/16
        ElseIf (CB1.Text = "2015/16") Then
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit1", " 0.765")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit1", "0.75")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 2", "0.872")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 2", "0.84")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 3", "0.862")
```

```
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 3", "0.85")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 4", "0.810")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 4", "0.78")

            '2016/17
        ElseIf (CB1.Text = "2016/17") Then
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit1", " 0.755")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit1", "0.73")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 2", "0.862")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 2", "0.84")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 3", "0.876")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 3", "0.84")
            Me.Chart1.Series("Reliabilty").Points.AddXY("Unit 4", "0.801")
            Me.Chart1.Series("Availabilty").Points.AddXY("Unit 4", "0.74")
        End If
    End Sub
End Class
```