RELIABILITY EVALUATION OF TWO MAJOR HYDRO ELECTRIC POWER STATIONS IN NIGERIA: KAINJI AND SHIRORO

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M.Eng/SEET/2008/1900

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DECLARATION

I, Olatomiwa, Lanre Joseph (M.ENG/SEET/2008/1900) declare that this thesis titled "Reliability Evaluation of Two Major Hydro Electric Power Stations in Nigeria: Kanji and Shiroro", is written by me and has not been previously submitted to the University or similar institution for the purpose of award of higher degree.

05/12/2011

Signature & Date

Olatomiwa, Lanre Joseph
(Student)

CERTIFICATION

This thesis titled "Reliability Evaluation of Two Major Hydro Electric Power Stations in Nigeria: Kainji and Shiroro" by Olatomiwa, Lanre Joseph (M.Eng/SEET/2008/1900) meets the regulations governing the award of the degree of Master of Engineering (M.Eng) of the Federal University of Technology, Minna and is approved for its contribution to scientific knowledge and literary presentation.

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DEDICATION

This thesis is dedicated to God Almighty for His grace, love, mercy, strength and inspiration throughout the course of this work.

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ABSTRACT

This research aims at evaluating the reliability performance of two units each from Shiroro and Kainji hydro electric power stations of Nigeria. The result of this study intends to provide the basis for planning generation expansion of hydro electric power stations. Herein reliability evaluation based on the Frequency and Duration (F & D) approach was adopted. A set of reliability parameters which quantify generating unit reliability, were computed for each unit using the annual outage durations for the periods of study (2005-2009). The system failure probability (unavailability), frequency of system failure (F_F), and the mean duration of system failure (T_F) for each unit were obtained and fully discussed. The reliability of the individual unit was also computed for the periods of study. The result obtained gives an overview of the general reliability performance of the stations considered, this will assist in generating capacity planning, criteria for future designs and operation of hydro electric power stations. The study generally shows that generating units at Kainji Hydro Power Stations have not been adequately maintained as compared with Shiroro units, leading to frequent and delayed forced outage of the units at Kainji. This indicates unreliable performance of the individual units and the entire stations at large.

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ABBREVIATIONS AND SYMBOLS

EFOH	Equivalent Forced Outage Hours
EFOR	Equivalent Forced Outage Rate
EOPE	Emergency Operating Procedure Expectation
ELCC	Effective Load Carrying Capacity
FACTS	Flexible Alternating Current Transmission System
FER	Failure Event Record
FOH	Forced Outage Hour
FOR	Forced Outage Rate
FCE	Firm Capacity Equivalent
F & D	Frequency and Duration
H	Total period. (usually one year, 8760hrs)
IEEE	Institute of Electrical Electronics Engineers
IG	Intake Gate
LOE	Loss of Energy
LOLP	Loss of Load Probability
LOEP	Loss of Energy Probability
LU	Loss of Largest Generation Unit
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MW	Megawatts
NF	Number of Failures
NR	Number of Repairs
NSO	Number of Scheduled Outages
NFO	Number of Forced Outages
PHCN	Power Holding Company of Nigeria
SH	Service Hours
SOH	Scheduled Outage Hours
SOR	Scheduled Outage Rate
λ	Failure Rate
μ	Repair Rate

p_0	Steady-state probability of state 0
p_1	Steady-state probability of state 1
p_2	Steady-state probability of state 2
p_3	Steady-state probability of state 3
q_1	Limiting unavailability of unit 1
q_2	*Limiting unavailability of unit 2*

GLOSSARY

Identification: The identifying data are the station, the unit and the date of report.

Outage Data: The following are entered under this topical item, utility outage number starting with the first outage event of each year and numbered sequentially by start time throughout the year. Event cause code, type of event, outage start time, outage end time and the hours waiting which is the time during which the unit is down and nothing is being done on it, for example, the period of awaiting the arrival of spare parts. Others are the hours worked on primary cause, hours worked on the major equipment which may be the same as the hours worked on primary cause, capacity before and after outage and reduction from available capacity.

Equipment: The failed equipment is uniquely identified

Problem; A brief description of the failure is entered. The severity of the failure is included in the format as check off entries.

Failure Mode: This is the effect by which a failure is observed. A number of failure modes that are common in the industry are included as check off entries.

Manner of Detection: The means by which the failure is detected is recorded. Common means of detection are included in the format as check off entries.

Failure Appearance: What is seen in the way of physical appearance is recorded. The phrase 'functional failure' is recorded when no physical failure is observed.

Failure Mechanism: This is the chemical or mechanical process which results in the failure. Some common processes are included in the format as check off entries.

Immediate Activity Phase: The unit state at the time of failure is recorded under this topical item. The possible unit states are included in the format as check off entries. Also the system phases that apply to any activity underway at the location and at the time of failure are recorded. Possible system phases are also included as check off entries.

Precipitating Factor(s): Factors that precipitated the failure are recorded here. If there are several alternatives, then each alternative is entered followed by a question mark.

Contributing Activity Phase(s): Under this topical item, the most appropriate unit state at the time of failure and the (once removed) system phase are recorded. The unit states and the system phases are included in the format as check off entries.

Contributing Factor(s): One or a combination of the following contributing factors are recorded:

a) Normal aging, which indicates that prior life span of the equipment, has been reached with normal wear out.
b) Random failure, which recognizes that the failure occurs during useful life of the equipment and therefore the failure, is by chance.
c) Systematic, which include design, manufacturing, engineering or environmental causes.
d) Human factor such as incorrect operating procedure and installation, poor planning, etc.

These four categories are written in the format as check off entries with write in spaces also provided.

Effect: The effect on the unit's output and efficiency is recorded here.

Disposition. This is the immediate corrective action taken to restore normalcy.

Outage: An outage describes the state of a component when it is not available to perform its intended function due to some event directly associated with that component. An outage may or may not cause an interruption of service to consumers depending on system configuration.

Partial outage: This describes a component state where the capacity of the component to perform its function is reduced but not completely eliminated.

Total outage: is an outage where the component is completely incapable of performing its function.

Forced outage: is an outage that results from emergency conditions directly associated with a component, requiring that component be taken out of service immediately, either automatically or as soon as switching operations can be performed, or an outage caused by improper operation of equipment or human error.

Scheduled outage: is an outage that results when a component is deliberately taken out of service at a selected time, usually for purposes of constructive, preventive maintenance, or repair. The key test to determine if an outage should be classified as forced or scheduled is as follow; if it is possible to defer the outage when such deferment is desirable, the outage is a scheduled outage; otherwise, the outage is a forced outage.

Transient forced outage: This is a component outage whose cause is immediately self-clearing so that the affected component can be restored to service either automatically or as soon as a switch or a circuit breaker can be restored or a fuse replaced.

Persistent forced outage: This is component outage whose cause is not immediately self-clearing, but must be corrected by eliminating the hazard or by replacing or repairing the affected component before it can be returned to service.

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND TO THE STUDY

The high rate of electricity demand requires stable and continuous supply of electrical power to consumers However, the electrical power supply in our country has been erratic and unreliable Therefore the operational performance of the overall power system of our nation needs improvement.

Generating stations form an important and integral part of the overall power system and their reliabilit depends on the reliability of the overall electricity supply. 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 demands adequately for the period of time intended. Improving the availability of existing units is as important as improving the reliability expectation of each units during the planning phase. These two are mutually supportive; design reliability impacts major changes in existing units, and information about operating availability is important to the system designers in both developing and developed countries.

The reliability concept applicable to the generation aspect of power systems will be reviewed to enable us have basis for evaluating our case studies. This work will show the reliability evaluation with a view to improve the generation and other system performance by applying probability theories and statistical analysis. Two units each from Kainji and Shiroro Hydro power station will be consider as our case studies, being one of the oldest and newest respectively in order to give room for comparison.

The results expected would include the basic reliability indices, which will give an overview of the general reliability performance and the long-term predictive indices that can assist in long-term system planning.

1.2 OBJECTIVES

The objectives of this research work are:

(i) To evaluate the reliability of two units each, of the two major hydro electric power stations in Nigeria: Kainji and Shiroro.

(ii) To develop reliability model and state-space diagram for the hydro electric power stations.

1.3 PROBLEM STATEMENT/MOTIVATION

Over the years, it has been observed that the energy generated by the major hydro-power stations in Nigeria does not meet up with the load demands. Consumers of electricity, both domestic and industrial have been experiencing incessant power-cut or failures that have cost implications in terms of appliances damaged and loss of production, even goodwill that cannot be quantified. Furthermore, faults inherent in the long operation of these stations and aging of their associated auxiliary equipment often lead to forced outages of the units, thereby minimizing the reliability performance of these stations. Consequently, these necessitate a research on evaluating the reliability performance of Nigerian hydro power stations (Kainji and Shiroro).

1.4 METHODOLOGY

Reliability evaluation is one of the several inputs required for decisions in the planning, design and operation of power systems. For the operation of power systems, for instance, systems outage data has to be collected. The determination of various component failure data consists essentially of two steps: collections of data and statistical evaluation of the resulting data samples. The method adopted to achieve the reliability evaluation of the two major Hydro Electric power stations in Nigeria includes the followings;

1. Collection of outage data,
2. Statistical evaluation of the resulting data samples using Frequency and Duration Method.
3. Conclusion based on the results obtained from the Reliability indices and the probability table.

Gathering the outage data is the most important stage in this research work as the quality of the data will determine the quality of the reliability indices produced by the reliability models. Therefore, in any project, sufficient time must be allocated to data collection. Scheduling of data collection takes into account the amount of detail and confidentiality of the data required. Firstly, the input data required to build the reliability models and the sources for these data are identified. Most at times, the data found are in raw form, which means that they are not in the form that is ready to be used directly in the reliability model. Hence, the relevant data are extracted and converted to suit the reliability model. In order to present these data (outages) in a narrative format, the Failure Event Record (FER) was used as a format for outage data of the hydro power stations being considered. This format is shown in Appendix D.

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 of the units and the entire stations at large.

1.5 SCOPE OF STUDY

The subject matter of this thesis is to assess the reliability of generating units in Kainji and Shiroro Hydro Power Stations for the period of five (5) years (2005-2009). This work include solving mathematical equations involving failure rate, repair rate, availability etc. on the basis of units outage data to be collected from these power stations. By making use of various reliability indices formulas, reliability indices tables will be develop for the period of the study. These tables will show the outage rate, the Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), Mean Time between Failure (MTBF) and the units' availability.

The result of the analysis will show the reliability parameters such as, the overall probability and the frequency of the unit failure.

1.6 ORGANIZATION OF THESIS

The report of this thesis is outlined as follows; the first chapter gives a general introduction of reliability assessment. A clear definition of the problem and the motivation of this study as well as the methods adopted to achieve the goal of the research are presented in this chapter. Chapter two reviews some literature relevant to the thesis. This chapter introduces reliability and Markov processes. 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 also reviewed in this chapter. Chapter three describes the method of data collection and the techniques used for the computation of reliability indices. Chapter four presents the results obtained from the analysis, while chapter five presents the general discussions on the research, observations, conclusions as well as recommendations for further studies. Finally, the references used and appendices are presented at the end of the report.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Reliability has been defined as the probability that a system or device performs its function adequately for the period of time under specified operating conditions. This definition is distinct from its qualitative general meaning as it applies to engineering devices, it revolves round four major determinants, viz. probability (uncertainty of the device), adequate performance, operating conditions and specified period of time. For instance, if the average life span of electrical equipment is given as two years (17520hrs) in an ambient temperature of 70°C. A brand of the equipment that functions for 17520hrs under the same condition implies a reliable performance and intuitively denotes a probability close to 100%. 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 systems) and since it is not possible for a device to be used while it is being repaired, one might also measure its performance in terms of Availability, which could be defined as the probability that a system or device will be operational at any particular time Many researchers have made meaningful contributions on evaluating the reliability of some power stations using different approaches.

Valdma *et al* (2007) studied the reliability of electric power generation in power systems with thermal and wind power plants. This study evaluates the principles of reliability of electric power generation with wind power plants treated as a non-stationary stochastic process. The probability, uncertain probability and fuzzy probability models of reliability and their applications to the analysis of electric power generation reliability were introduced. Allan *et al* (1988), presented various philosophical aspects concerning power system reliability and, in particular, adequacy and the concept of hierarchical levels in reliability evaluation. Their works provided a framework on which the discussions within the power industry and with external groups can be ideally based. The paper also briefly comments on the various methods that can be used to assess reliability. Vernaa *et al* (2004), analyzed the impacts of a flexible alternating current transmission system (FACTS) controller on reliability of composite power generation and transmission system, where the conventional dc flow-based linear programming model used in composite system reliability evaluation method is converted in to a non-linear optimization model to include the impact of flexible alternating current transmission system (FACTS) devices on reliability of power system. The model was tested on 24-bus IEEE-reliability test system (RTS) and an annualized reliability index calculated using the model, this is then compared with the indices calculated without considering flexible alternating current transmission System (FACTS) devices. Billinton *et al*(1990) provided the basic power reliability concepts and stressed the need. Moslebi *et al* (1993), described the direct method for evaluation of bulk power system reliability, that is, solution algorithm in which the algorithm is divided into five major steps. Telsons (1975), examined the consideration that should determine sensible reliability levels for electric generation systems. He explained that providing excess electrical generation capacity for reliability purposes has an economic cost. Ehnberg *et al* (2004), investigated the generation reliability for power systems entirely based on renewable energy sources. The stochastic models for solar and wind powers were used together with simpler models of small scale hydro power and storage. The load model is deterministic and based on industrial activities with a maximum load of 28kW, and further analyzed 38 cases with different supply configurations with the aid of simulation using the Monte-Carlo simulation. He concluded that a system with more than one sources has a higher availability. Burgio (2008), estimated the evaluation of the reliability of power system in presence of photovoltaic and wind power generation plants and uninterrupted power supply (UPS). Their study was aimed at reducing the critical loads loss due to long interruption of the main supply, using the power produced by renewable sources. It was observed that the critical load loss greatly depends on many stochastic variables, such as, main supply interruptions, battery capacity and weather condition. D'Annunzio *et al* (2005), evaluate the reliability impact of wind power penetration using the basic loss of load probability (LOLP) and expectation concepts. In the paper, the reliability impacts of various levels of wind power penetration were investigated and compared with conventional fossil-based units. The results of the comparison shows that, at wind penetration levels of less than 5 percent, the reliability impact of the wind farm is comparable to the impact of an energy equivalent of a conventional unit. However, for penetration levels greater than 5 percent, the wind farm is less efficient in reducing the loss of energy (LOE) than its energy of an equivalent unit. Guven (1977), presents a combined model for daily scheduling, taking into account the effects of possible supply shortages of electric power generation with optimal reliability. The optimization procedure comprises dynamic and heuristic programming routines for cost minimization and stochastic models for treating supply reliability. In one of the latest works on the reliability of power systems, Adler (1980), presented the mathematical methods and their underlying principles for calculating the probability of outages of generating equipment. Equations were developed for various types of generating units while formulae were also presented for the probabilities of multiple full outages as well as combination of full and partial outages. In a related work, Wang (1967), presented a method of calculating the probability of outages of a generating unit from recorded outage data. Nwohu (2007), in his paper presented an economic framework that can be used to optimize electric power system reliability. He investigated the cost models that take into account the economic analysis of system reliability; this can also be periodically updated to improve overall reliability of electric power system.

However, in this thesis, the reliability concept applicable to generation aspect of power systems is reviewed to enable us have basis for evaluating the case studies. Two units each from Kainji and Shiroro Hydro power stations are considered as the case studies, and the comparative study of the stations is 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 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 a largest set called space S.

Probability is a numerical index P(A) assigned to a set or events A as defined by (Papoulis,1965).

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

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 which defines absolute impossibility and unity which defines absolutely certainty.

2.2.1 Set Operation: There are relationships involving sets which can be proved with the help of appropriate Venn diagrams. These are:

(i) **Subsets:** A set B is said to be a subset of another A if all elements of B are also elements of A. this is written in the form.

$B \subset A$ or $A \supset B$

If $C \subset B$ and $B \subset A$ then $C \subset A$. Also for any set A, $A \subset A$, $0 \subset A$ and $A \subset S$ where 0 is the set with zero element.

(iii) **Equality:** A set A 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.

(iv) **Sums:** The sum or union (A + B) of two sets A and B is another set whose elements are all the elements of A or of B or of both. It is easy to show that

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

(v) **Product:** The product of intersection (AB) of two sets A and B is another set consisting of all elements that are common to both A and B It is easy to show that:

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

It can also be shown that:

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

(vi) **Complements:** The complement $\bar{A}$ of a set A is another set consisting of all elements of S that are not in A.

(vii) **Difference:** The difference (A - B) of two sets A and B is another set consisting of the elements of A that are not in B It is easy to show and important to note that:

$$(A - B) + B \neq A \quad (2.5)$$

2.2.2 Probability Combination: The probability of occurrence of two or more events can be combined together 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 either be mutually exclusive on not. Table 2.1 shows how the probabilities of the different combination can be evaluated

Table 2.1: Probability of occurrence of two events

Type of occurrence	Dependent Events	Independent and not Exclusive	Independent and Exclusive
Simultaneous (AB)	$P(A/B)\,P(B)$	$P(A)\,P(B)$	-
At least one $P(A+B)$	$P(A)+P(B) - P(A/B)P(B)$	$P(A)+(PB) - P(A)P(B)$	$P(A) + P(B)$
Conditional $P(A/B)$	$P(AB/P(B)$	$P(A)$	-

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 outcome. 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 then be defined as a random variable.

One way of specifying the probability of a random variable is by means of a 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:

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

A number of standard density functions are available, from which one that suits intended application can be selected. These standard functions include binomial, Poisson, normal, Weibull and exponential functions. Sometimes it is not the probability of the random variable 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 a 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 a.(Papoulis,1965).

$$F(a) = P(x \leq a) \tag{2.7}$$

Clearly defined as:

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

F(a) is therefore the area under the f(x) curve between limit - ∞ and a, where - ∞ 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:

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

One other function that is used in the analysis of the probability of a random variable which is extensively used in reliability evaluation is the hazard rate function λ(x), defined as the probability that a given item on test will fail 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.

$$\lambda(x) = P\ (a \leq x \leq (a+\Delta a) |\ x \geq a) \tag{2.10}$$

λ(x) is generally expressed as.

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

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 (Lipson, 1973). 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:

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

where, f(t) = probability of failure

t = operating time (independent variable)

λ = failure rate

e = base of natural logarithms

$$F(t) = \int_0^t f(t)dt = 1 - e^{-\lambda t} \qquad (2.13)$$

Since the minimum value that time can take is zero.

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

Equation (2.14) shows that the hazard rate for an exponential distribution is constant which is the condition stated earlier.

The probability value is the first index of reliability and in most cases it is considered to be most significant and sufficient index. However, many other indices are also used some are:

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 failure

5. Expected loss in plant output due to failure.

2.3 RELIABILITY CONCEPT

Reliability is the probability that a system or device will perform its prescribed duty without failure, for a given period of time, when operated correctly in a specified environment. 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 systems) and since it is not possible for a device to be used while it is being repaired, one might also measure its performance in terms of availability, which could be defined as the probability that a system or 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 resources. A device or system may be adequate but not reliable if it has poor maintainability.

2.4 SYSTEM CLASSIFICATION AND METHOD OF RELIABILITY EVALUATION

Systems generally fall into two classes. 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, but the analyst should be able to translate the physical system into a reliability network utilizing the system operational logic and a sound understanding of the physical behaviour and requirements of the system.

The evaluation techniques applicable to this class of systems are methods for translating the topology of the resulting reliability network into a structure that consists only of series and parallel components.

The second class of systems is one in which some of the components may be in standby mode and can be switched into operation at any desired instance, for example an electric power generating unit. Such systems are not easily represented by a network. The methods 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 methods and Markov techniques (Billinton*et al.* 1983).

2.4.1 Event Tree Method:

The event tree and the Markov techniques are conceptually the same and both can be applied to systems with continuously operating components as well. An event tree is a pictorial representation of all possible events which can occur in a system.

Consider a system of three components A, B and C. Define R_i as the probability that component i is operating and Q_i the probability that component i is down. The event tree for this system is shown in Fig. 2.1.

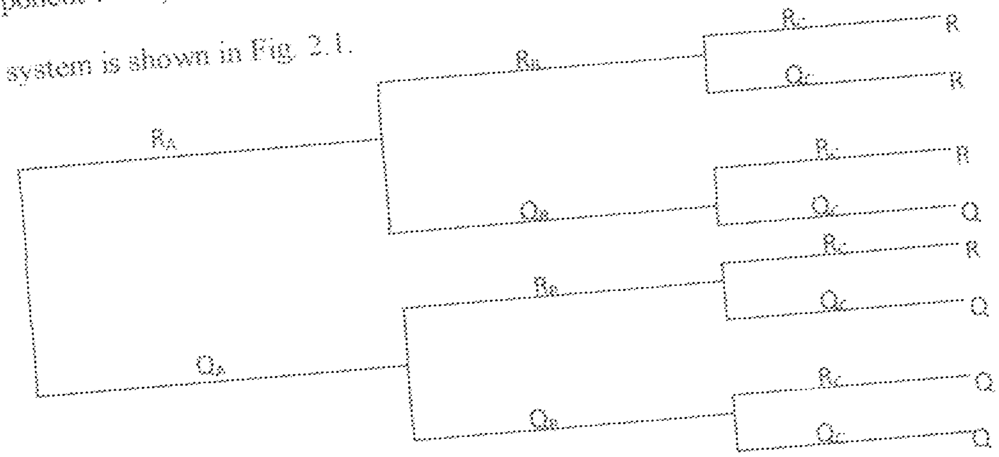

Fig. 2.1: Three component system event tree.

The probability of occurrence of each path is the product of the appropriate event probabilities. Since all paths are mutually exclusive, the probability of a particular system outcome can be evaluated by summing the path probabilities leading to that outcome. If, for example, the failure of any two components in the three components sample system results in system failure, then the system outcome caused by the occurrence of each path is shown in Fig. 2.1 with R for system operation and Q for system failure. Then the system reliability R_S, is the sum of probabilities of the R paths. The number of individual paths of the event tree for a system of n component with m component states is m^n paths correspond to the m^n possible states of the system and the probability of each state can be conveniently computed using Markov technique. Markov technique, which is the method used here, is also discussed in this session.

2.4.2 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 in a manner controlled by probabilistic laws. A simple example of stochastic process is the 'up' and 'down' states occupied by an electric power generating unit, with the time spent in each state being random variables as shown in Figure 2.2 (Biggerstaff *et al*, 1969)

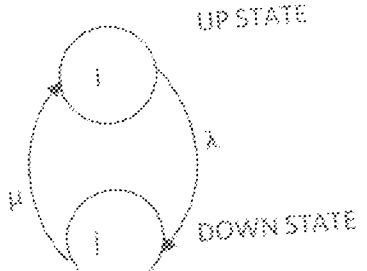

Fig. 2.2: State space diagram for a two state system.

There are two key characteristics of a Markov process which are: its lack of memory and being a stationary process. Lack of memory implies that the future states of the system are independent of all past states except the immediately preceding one and completely independent of the time spent in any state. By stationary process, it is implied that the probability of making a transition from one state to another is the same at all times in the past and future. Basically there are four Markov processes depending on whether the states of the processes are discrete or continuous and whether transition from one state to another can occur at discrete time intervals or at any time. The electric power generating system certainly falls into 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.

In this continuous time process, the probability that the system moves to a new state is a function of the rate of departure from the present state to the new state. These Markov transition rates, as they are often called, can be estimated from the systems past operational information.

2.5 MATHEMATICAL MODELLING

2.5.1 State Space Diagram

The first step towards the development of a mathematical model for the discrete state, continuous time processes is to construct the system`s 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. Figure 2.2 shows the state space diagram of a single repairable component whose failure and repair rate are characterized by exponential distribution.

2.5.2 Time Dependent and Limiting State probabilities

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

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

$P_j(t)$ = probability that system is in state j at time t.

Considering the transitions for a time interval Δt, the probabilities of failure and repair at this interval Δt are λ.Δt and μ.Δt respectively.

Probability that the component is in state 'i' at time t + Δt

= [probability that the system is in state 'i' at time t][probability that the state does not change from i to j in time Δt] + [probability that the system is in state j at time t][probability that the system is repaired in time Δt] (Rausand *et al*. 2004).

Thus

$$P_i(t + \Delta t) = P_i(t)[1 - \lambda\Delta t] + P_j(t)[\mu\Delta t] \tag{2.15}$$

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

$$P_j(t + \Delta t) = P_j(t)[1 - \mu\Delta t] + P_i(t)[\lambda\Delta t] \tag{2.16}$$

Equation (2.15) and (2.16) can be written as:

$$\frac{P_i(t + \Delta t) - P_i(t)}{\Delta t} = -\lambda P_i(t) + P_j(t) \tag{2.17}$$

$$\frac{P_j(t + \Delta t) - P_j(t)}{\Delta t} = \lambda P_i(t) - P_j(t) \tag{2.18}$$

As $\Delta t \to 0, LHS\ of\ equation\ (2.17)\ is\ \frac{dP_i(t)}{dt}\ or\ P_i{}'(t)$

and$LHS\ of\ equation\ (2.18)\ is\ \frac{dP_j(t)}{dt}\ or\ P_j{}'(t)$

$$\text{thus}\begin{bmatrix} P_i{}'(t) \\ P_j{}'(t) \end{bmatrix} = [P_i(t) \quad P_j(t)]\begin{bmatrix} -\lambda & \lambda \\ \mu & -\mu \end{bmatrix} \tag{2.19}$$

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 $P_i(0)$ *and* $P_j(0)$ are the initial conditions and $P_i(0) + P_j(0) = 1$

if the process starts from state i, i.e., the system is in state i at time 0, $P_i(0) = 1$ and $P_j(0) = 0$

Then equations (2.20) and (2.21) simplify 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. Often times, 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:

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

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

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 rates are used. The process based on constant transition rates is, essentially, a homogeneous Markov process. To obtain the state probabilities $P_i(t)$ as a functions of time, the matrix differential equation:

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

must be solved, where $\dot{P}(t)$ is a row-vector consisting of the elements $dp_1(t)/dt, dp_2(t)/dt, \ldots$; p(t) is a row-vector consisting of the element $p_1(t)$, $p_2(t)$,.....; 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 probabilities $P_i(t)$ are of interest, they can be obtained by much simpler task of solving the set of linear equations

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

where the element of row-vector p are long-term state probabilities p_1, p_2,...., and the row-vector 0 consists of zeros. The solution for p requires an additional equation, which is provided by the fact that the probabilities of all state must always add up to 1; that is,

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

The frequency of encountering state i, f_i is defined as the expected number of stays in (or arrivals 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 of time

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 Figure 2.3.

Let the mean duration of the stays in state i be T_i, and that of the state outside i, T_i'. The mean cycle time, T_{ci} is then:

$$T_{ci} = T_i + T'_i \tag{2.29}$$

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) byT_i, the right-hand side become T_i/T_{ci}. This provide the long-term state probabilities in a two-state process, and by definitions of Availability (A) and Unavailability ($\bar{A}$), T_i/T_{ci} equals p_i. Therefore,

$$f_i = \frac{p_i}{T_i} \tag{2.31}$$

This is fundamental equation, which provides the relation between the three state parameters

To relate the frequencies f_i, mean durations T_i, 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:

$$f_{ij} = \lambda_{ij} p_i \tag{2.32}$$

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 f_i and f_{ij} it follows, that:

$$f_i = \sum_{j \neq i} f_{ij} \tag{2.33}$$

Substituting (2.32) into (2.33),

$$f_i = p_i \sum_{j \neq i} \lambda_{ij} \tag{2.34}$$

Finally, combining (2.31) and (2.34), T_i can be expressed as:

$$T_i = \frac{1}{\sum_{j \neq i} \lambda_{ij}} \tag{2.35}$$

Put in words, the mean duration of the stays in any given state equals the reciprocal of the total rate of departures from that state. With the help of equations (2.27), (2.28), (2.34) and (2.35), all the state 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 2.3, with various transition rates indicated next to the transitions. According to the conventions, the failure rates (the reciprocals of the mean time to failure) are denoted by λ, and the repair rates (the reciprocal of the mean component repair times) by μ, with the subscripts referring to the appropriate component.

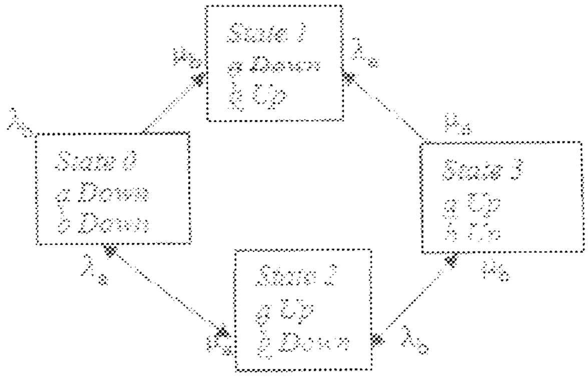

Figure 2.3: State-space diagram for two independent components.

In the model of Figure 2.3, the state probabilities are first computed. As in most applications, only the long-run solutions are sought. The transition intensity matrix A is:

$$A = \begin{array}{c|cccc} & 0 & 1 & 2 & 3 \\ \hline 0 & -(\mu_a+\mu_b) & \mu_b & \mu_a & 0 \\ 1 & \lambda_b & -(\mu_a+\lambda_b) & 0 & \mu_a \\ 2 & \lambda_a & 0 & -(\lambda_a+\mu_b) & \mu_b \\ 3 & 0 & \lambda_a & \lambda_b & -(\lambda_a+\lambda_b) \end{array} \tag{2.36}$$

To facilitate the construction of the matrix, indicated for each entry are the states where the corresponding transition originates and where it ends. The set of linear equations (2.27), yielding the probabilities p_i, are the following:

$$-(\mu_a+\mu_b)p_0+\lambda_b p_1+\lambda_a p_2=0 \tag{2.37a}$$

$$\mu_b p_0-(\mu_a+\lambda_b)p_1+\lambda_a p_3=0 \tag{2.37b}$$

$$\mu_a p_0-(\lambda_a+\mu_b)p_2+\lambda_b p_3=0 \tag{2.37c}$$

$$\mu_a p_1+\mu_b p_2-(\lambda_a+\lambda_b)p_3=0 \tag{2.37d}$$

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

$$p_0 + p_1 + p_2 + p_3 = 1 \qquad (2.38)$$

The solution of (2.26) and (2.38) is:

$$p_0 = \frac{\lambda_a \lambda_a}{D}, \quad p_1 = \frac{\lambda_a \mu_b}{D}, \; p_2 = \frac{\lambda_b \mu_a}{D}, \; p_3 = \frac{\mu_a \mu_b}{D} \qquad (2.39)$$

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

We can obtain the results in (2.39) by direct reasoning; the Availability (probability of success) of a single two-state component is $A = \mu/(\lambda + \mu)$, and its Unavailability (probability of failure), $\ddot{A} = \lambda/(\lambda + \mu)$

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 $A_a \ddot{A}_b$, of b operational and a not is $\ddot{A}_a A_b$, and of both having failed is $\ddot{A}_a \ddot{A}_b$. After substituting into these terms the expressions for **A** and $\ddot{A}$ above, equations (2.39) are obtained.

The mean durations of the stays in each state are computed by (2.36). Thus,

$$T_0 = \frac{1}{\mu_a + \mu_b}, T_1 = \frac{1}{\lambda_a + \mu_b}, T_2 = \frac{1}{\mu_a + \lambda_b}, T_3 = \frac{1}{\lambda_a + \lambda_b} \qquad (2.40)$$

The frequencies of encountering each state are computed by (2.34), as;

$$f_0 = \frac{\lambda_a \lambda_b (\mu_a + \mu_b)}{D}, f_1 = \frac{\mu_a \lambda_b (\lambda_a + \mu_b)}{D}, f_2 = \frac{\lambda_a \mu_b (\lambda_b + \mu_a)}{D},$$

$$f_3 = \frac{\mu_a \mu_b (\lambda_a + \lambda_b)}{D} \qquad (2.41)$$

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 the planning, design, operation and maintenance of electric power systems. 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 consumer and the aspect of the power network such as generation, transmission and distribution systems.

2.6.1 Generation System Reliability

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 extremely difficult to develop and would require excessive computing time. Furthermore, the results obtained are likely to be so vast that meaningful interpretation will be difficult, if not impossible (Billinton *et al*, 1983). Due to these characteristics, systems are normally divided into three main functional zones, namely generation, transmission and distribution system. Typically, the zones are evaluated separately for better measures of reliability in terms of making appropriate assumptions and flexibility in failure criteria selection. They can then be combined into higher hierarchica levels to convey a more wholesome performance of the system.

This thesis however, only addresses a portion of the system reliability which is the generation system reliability. Generation system reliability concentrates on the performance of the generators where fuel is converted to, electricity before entering the transmission system.

Generators are subjected to forced outages or reduction in available capacity, which can affect the system reliability and hence must be evaluated. System reliability is commonly interpreted as the probability of that system staying in the operating state, performing its intended purpose adequately for a period of time without failures under required conditions (Endrenyi, 1978). System reliability is made up of two main components, security and adequacy (Figure 2.4).

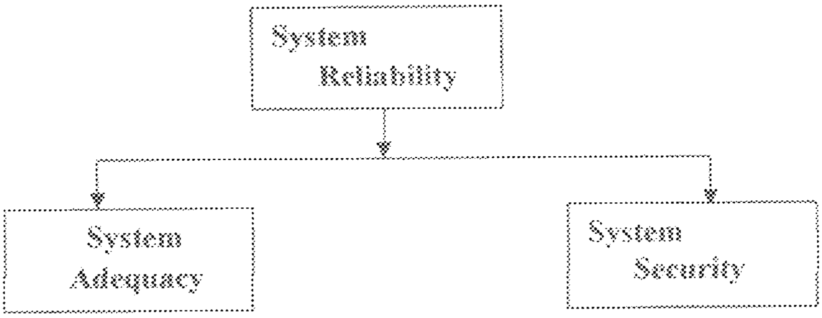

Figure 2.4: Components of system reliability.

Security relates to the ability of the system to withstand sudden disturbances such as faults and loss of system elements (Stoft,2000). Generally, generation system security is the capability of the generators in enduring unexpected contingencies involving frequency and voltage anytime during system operation. Security is a dynamic measure of response to the unforeseen events. Adequacy on the other hand, considers the system in static conditions and does not fluctuate from one minute to another as it does not include system disturbances (Allan *et al*,1988). It is the property of having enough capacity to remain secue almost all the time. Interms of generation, an adequate generation system is a matter of Installed capacity and ability to meet the annual peak demand with the capacity under normal operating conditions, taking into account scheduled and reasonably forced outages of generators (Stoft, 2000). Together, adequacy and security provides the overall reliability description of the generation system, which can be broadly described as the ability to supply the quantity and quality of electricity desired by the customer when it is needed. Nevertheless, the scope of this study only covers the generation system adequacy and not system security. It is however assumed that the security requirements will be met if the system has adequate capacity reserves. One way to improve system reliability is by installing new and better components or through incorporation of more redundancy in the system design. In generation system, redundancy is achieved by installing more generating capacity than normally required (Endrenyi, 1978).

In generation system, the reliability study of interest is usually termed as generating system adequacy assessment. For this exercise, the models developed do not represent the entire power system. It only includes the generating units whereas the rest of the system is assumed to be perfectly reliable as long as there is sufficient power generation available to meet the demand (Endrenyi,1978).Therefore ,transmission system which is directly connected to the generation system is ignored and treated merely as a load point as shown in (Figure 2.5).

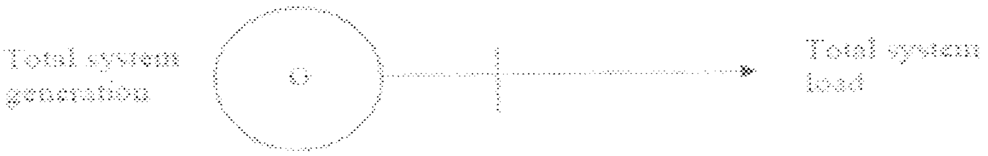

Figure 2.5 Conventional System Model.

This particular study examines the total generation in the system in order to determine its adequacy in meeting the system demand. The system is adequate if it is able to meet the system load requirement and at the same time have excess capacity to cater for planned and forced outage events. Planned or scheduled outage is an outage that resulted from a generator that is deliberately taken out of service at a predetermined time for the purpose of maintenance or repair. Meanwhile, forced outage is when a generator of the system has been taken out of service as a result of emergency conditions.

2.6.2 Generation System Reliability Indices

A general approach to an electric power generating system reliability assessment is to determine one or a number of its reliability indices. A reliability index is defined as a quantity that measures and quantifies some aspects of system reliability performance (Rausand *et al*, 2004). A number of indices have been introduced in reliability studies over the past years to assist reliability evaluations 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 a generation system against some predetermined criteria of reliability standards.

Reliability indices used in the electric power industry can generally be grouped into two broad categories:

(i) Deterministic indices which reflect postulated conditions and

(ii) Probabilistic indices which consider uncertainty inherent in power system operation.

Probabilistic indices permit reliability evaluation by taking into account the factors that influence reliability such as the capacity of individual unit and the forced outages of each unit. For the deterministic approach, two indices were used which are reserve margin and loss of largest unit in the system. Probabilistic approaches, however, have more indices. According to Endrenyi, (1978) the indices can generally be categorized as follows (Table 2.2):

Table 2.2: Reliability Indices categories

No	**Index Category**		**Example**
1	Probabilities	-	The reliability or the availability (probability of success)
2	Frequencies	-	The average number of failures per unit time
3	Mean durations	-	The mean time to the first failure (MTTF),
		-	The mean time between failures (MTBF),
		-	The mean duration of failures
4	Expectation	-	The average number of days in a year when a system failure occurs.
		-	The average curtailment of energy per unit time as a result of power systems failure.

In generation system reliability, common indices used are:

1. Loss of Load Probability (LOLP)
2. Loss of Load Expectations (LOLE)
3. Loss of Energy Probability (LOEP)
4. Loss of Energy Expectations (LOEE)
5. Expected Energy Not Served (EENS)
6. Loss of Load Frequency (LOLF)
7. Loss of Load Duration (LOLD)

Most of these indices are expected values of random variable. They provide valid adequacy indicators that reflect various factors such as system component availability and capacity, load characteristics and uncertainty, system configurations and operational conditions, etc. Figure 2.6 summarises the typical indices used in power system evaluations according to the approaches taken by Phoon (2000).

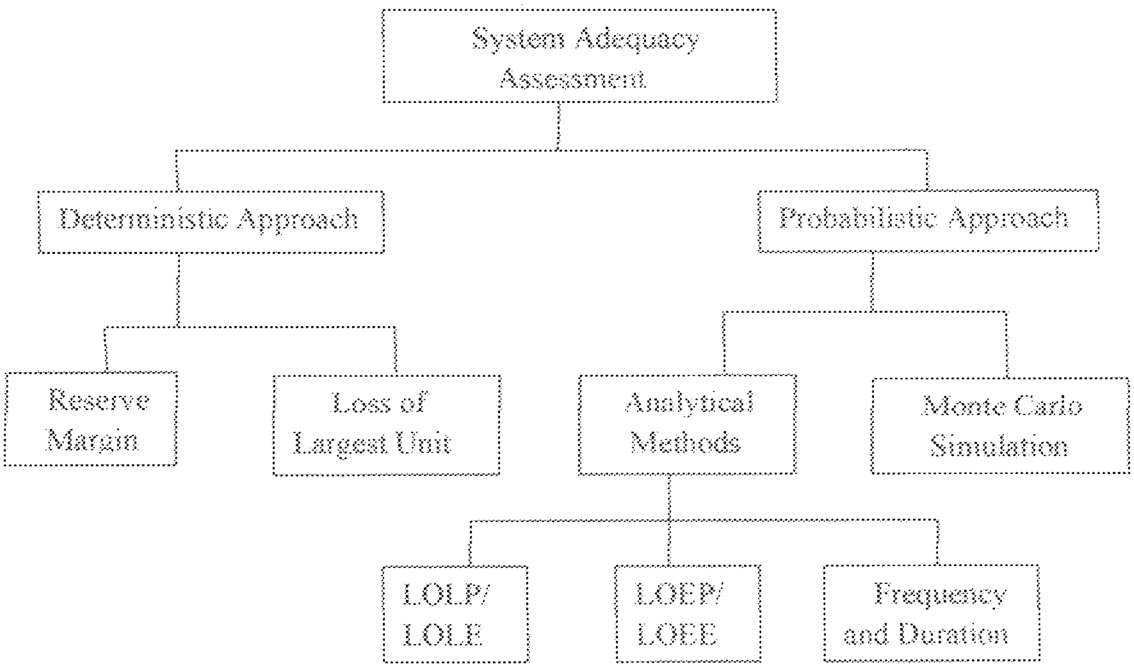

Figure 2.6: Typical generation reliability assessment indices.

2.6.2.1 Reserve Margin

Reserve margin is defined as the percentage of excess installed capacity (inclusive of interconnection capacities) over the annual peak demand. It is a measure used in the deterministic approach in evaluating system reliability. This method compares the adequacy of reserve requirements in totally different systems solely based on the system peak load. Equation (2.42) gives the formula to calculate the reserve margin of a power system.

$$\text{Reserve Margine} = \frac{\text{Installed Capacity (MW)} - \text{Peak Demand (MW)}}{\text{Peak Demand (MW)}} X\,100\% \qquad (2.42)$$

Typically, the reserve margin used ranges from 15 percent to 20 percent. Plant additions are made only when the reserve margin drops below the target level (Stoft, 2000). Reserve margin is therefore the easiest to understand and used in quantifying generation system adequacy. Nevertheless, in the reserve margin calculation, installed capacities are used. Installed Capacity is defined as the maximum possible capacity. Typically, they are assumed to be the same as the nameplate ratings. Although this capacity might be accurate during the early years of the operation, the total output generated by each unit decreases with service time due to wear and tear. The actual capability of a unit is given by derated capacity, which is defined as the maximum capacity of a plant that can be obtained as a result of plant deterioration over the operating years. Therefore, reserve margin is often an overestimate of the available margin in the system and does not reflect the true margin. Hence, in large systems, reserve margin alone is not sufficient to provide a reflective reliability assessment. Moreover, it measures the system statically causing the stochastic nature of demand, component failures and system behaviour to be excluded from the evaluation. As a result, reliability analysis based solely on reserve margin could cause insufficient generation and underinvestment in generation expansion. Therefore, most utilities have shifted to probabilistic analysis as it takes into account the failure rate of different plant and sizes, thus represents the system better.

2.6.2.2 Loss of Largest Unit

This method simply compares system peak demand with the generation capacity when the largest generation unit is unavailable. In larger system however, more than one generating unit is assumed to be unavailable when carrying out the reliability study. The remaining capacity after the loss of the largest generating unit is then known as the firm capacity and this can be given by equation (2.43).

$$Firm\ Capacity = \sum (C_i - C_1) \qquad (2.43)$$

where $C_i \geq C_1$ and $i = 2, \ldots, I$

This method suffers from many drawbacks. Firstly, it does not take into account the probability (availability) of the generating units. It also takes no account of the actual size of the system as it treats the units in sets depending on their capacity. Last but not least, any new additions of larger unit(s) only mean that the firm capacity increases by the size of the largest set before the capacity expansion (Stoft, 2000). As a result, the loss of largest unit approach is very inadequate and can be misleading. It is however used in some developing countries. A better indicator of system reliability can be obtained from indices generated through probabilistic analysis such as loss-of- load, loss-of-energy and frequency and duration methods.

2.6.2.3 Loss of Load Method

Loss of load occurs when the system demand exceeds the available generating capacity in the system during operation. The probability of this happening is called the loss of load probability (LOLP). Endrenyi (1978), defined loss of load probability as the probability of the system load exceeding available generating capacity under the assumption that the peak load of each day lasts all day. Meanwhile, definition given by Wang, (1980) for LOLP is the probability of the effective system capacity not meeting the load demand, which can be written as equation (2.44).

$$LOLP = P\,(X > R) \qquad (2.44)$$

where, X = System Outage Capacity

R = C-L = System Reserve Capacity

C = System Effective Capacity

L = Maximum Load

Generally, LOLP is obtained by combining the probability of generation capacity states with the daily or hourly peak demand probability. The number of days in a year whereby the daily peak load is unmet by the generation system is then assessed (Endrenyi, 1978). Alternatively, the hourly peak which is the peak load for each of the 24 hours a day is used instead of the daily peak, producing a more accurate representation of the stochastic nature of demand in the system. Consequently, the same system could be described by two or more values of LOLP, depending on how the calculation is done.

The overall LOLP of a system can be calculated using equation (2.45).

$$LOLP = \sum_{j} P[C = C_j]P[L > C_j] = \sum_{j} \frac{p_j T_j}{100} \qquad (2.45)$$

where,		
	P	is the probability of
	C	is the available generation capacity
	Cj	is the remaining generation capacity
	Pj	is the probability of capacity outage
	Tj	is the percentage of time when the load exceeds Cj
	L	is the expected load

The percentage of time when the load exceeds the remaining generation capacity can be obtained from the load model as discussed in the next section.

Ever since its introduction, LOLP index has gained recognition and is widely used as a reliability criterion as well as a measure to reliability of a system. Its popularity is contributed by the fact that it is relatively easy to compute and it also provides simplified comparison of reliability (Stoft, 2000). Nonetheless, it must be highlighted that even though LOLP and LOLE can be used to describe the adequacy of generation in a bulk power system, it cannot be used as the sole measure of power system reliability. This is because, calculation of LOLP does not include a model of the reliability of the power delivery system, namely transmission and distribution, where the majority of outages actually occurs. Furthermore, there are several shortcomings with the use of LOLP in reliability evaluations. Firstly, the LOLP provides no indication of the severity of load shedding either in MW or in percentage terms. It also does not give indication of its duration or frequency of shortfalls, which are important parameters in quantifying reliability. Instead, LOLP, given in days per year, mainly indicates the number of days in a year that the generation system will not be able to meet the system demand. As a result, the frequency of load shedding may be higher than this figure in case of double peaked daily load curves and in systems, which employ units with higher failure rates but short repair duration. As an expected value, LOLP is also not able to differentiate between a large supply shortage and several small and brief ones (Stoft, 2000). Moreover, as the load model used in LOLP derivation is often the cumulative curve of daily peak loads, the variations of load within a day are not recognised. Consequently, the LOLP value produced is rather a crude approximation of the actual system failure probability

Apart from that, this type of load model prevents the calculation of the system failure frequency (Endrenyi, 1978). Besides that, LOLP also does not include additional emergency support that is available to one area from another or emergency measures that can be taken by the control area operators in order to maintain system reliability (Stoft, 2000)

LOLP is not very useful when it comes to comparing the reliability of different utilities or systems, particularly if they have different shapes of the load curve and peak duration. It is also not necessarily an accurate predictor of the resulting incidence of electricity shortages. Nevertheless, LOLP is still an important reliability index and is useful in providing the first estimation of the generation system reliability.

2.6.2.4 Loss of Energy Method

An alternative to loss of load method in generation capacity reliability assessment is the loss of energy method. This is the ratio, E, of the expected amount of energy not supplied during some long period of observation to the total energy required during same period. Using the same notations in the Loss of Load Probability (LOLP) method, the loss of energy is given by:

$$E = \sum_{i} \frac{p_i \int_0^{t_i} (L - C_i)dt}{\int_0^{t} L\,dt} \qquad (2.46)$$

where, t is the 100% of time for which the load exceeds L (i.e peak load demand).

In some ways, the loss of energy index has more physical significance than the loss-of-load probability index. This is because it is able to show the severity of an event even if the probabilities and frequencies are the same. A higher value of loss-of-energy index is obtained for the more serious events than for the marginal failures. Hence, it can measure the amount of inconvenience and loss to the customer.

Nevertheless the true loss of energy cannot be accurately computed on the basis of the cumulative load curve of daily peaks. As a result, loss-of-energy index is seldom used in generation reliability studies for long term planning exercises. It is however used in several production cost evaluation programs using suitable load models (Endrenyi, 1978).

2.6.2.5 Frequency and Duration (F&D) Method

The F&D method produces a set of useful reliability indices when the frequency of interruption over a specified period is of interest. This is because it provides a reliability indication for specific customers or load points.

The frequency and duration method is based on Markov theory, but requires some more information regarding the system than the calculation of the Generation Capacity Outage Table. i.e outage data and the system capacity. The method also gives the average frequency and duration of interruptions as the title indicates. The method needs input data like failure rate and repair time of the components. A state-space approach is applied to the sets of units present in the system in the reliability evaluation using the F&D method, this approach, presents the system in its states and the possible transition between states. This method also adopts the transition rate parameters λ and μ of generating units. This means that each possible combination of units in up or down states defines a capacity state of the system, which are then classified according to their available capacity, the relevant state probabilities and of course their transition states (Rausand *et al*, 2004).

This method can easily be shown with a simple example of a power station with two generators, 1 and 2. Each generator can have two states: a functioning state (1) and a faulty state (0). A generator is considered to be in the failed state (0) also during repair. Assuming Generator 1 is supplying 100MW when it is functioning and 0MW when it is not functioning and Generator 2 is supplying 50MW when it is functioning and 0MW when it is not functioning.

The possible states of the system are shown in Table 2.3 below.

Table 2.3: Possible State of the Generators

System State	State of Generator 1	State of Generator 2	System Output
3	1	1	150MW
2	1	0	100MW
1	0	1	50MW
0	0	0	0MW

Source : Rausand *et al*, 2004

We assume that the generators fail independent of each other and that they are operated on a continuous basis. The failure rates of the generators can be represented as follows.

Let λ_1 = Failure rate of generator 1

and λ_2 = Failure rate of generator 2

The two generators are assumed to be repaired independent of each other, by two independent repair crews. The repair rates of the generators can be represented as follows.

Let μ_1 = Repair rate of generator 1

and μ_2 = Repair rate of generator 2

The corresponding state- space diagram is shown in Fig.2.7.

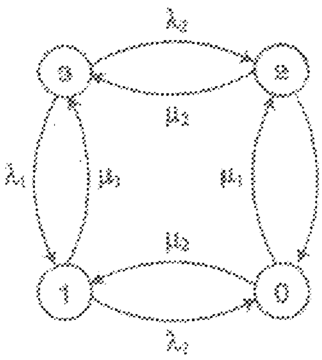

Figure 2.7: State-Space Diagram.

The transition matrix is

$$A = \begin{pmatrix} -(\mu_1 + \mu_2) & \mu_2 & \mu_1 & 0 \\ \lambda_2 & -(\lambda_2 + \mu_1) & 0 & \mu_1 \\ \lambda_1 & 0 & -(\lambda_1 + \mu_2) & \mu_2 \\ 0 & \lambda_1 & \lambda_2 & -(\lambda_1 + \lambda_2) \end{pmatrix} \quad (2.47)$$

We can use equation (2.27) to find the steady-state probabilities P_j for j = 0,1,2,3 and we obtained the following equation:

$$\begin{aligned} -(\mu_1 + \mu_2)P_o + \lambda_2 P_1 + \lambda_1 P_2 &= 0 \\ \mu_2 P_0 - (\lambda_2 + \mu_1)P_1 + \lambda_1 P_3 &= 0 \\ \mu_1 P_o - (\lambda_1 + \mu_2)P_2 + \lambda_2 P_3 &= 0 \\ P_o + P_1 + P_2 + P_3 &= 1 \end{aligned}$$

Note that we use three of the steady-state equations from (2.27) and in addition the fact that $P_o + P_1 + P_2 + P_3 = 1$. Note also that we may choose any of the four steady-state equations and get the same solution

The solutions are:

Table 2.5: Capacity Outage Probability Table (COPT)

System State	System Output	Steady-State Probability	Average Hours in State per year	Frequency of Occurrence
3	150MW	0.9932	8700.3	4.0×10^{-4}
2	100MW	4.08×10^{-3}	35.8	3.4×10^{-4}
1	50MW	2.72×10^{-3}	23.8	1.2×10^{-4}
0	0MW	1.12×10^{-5}	0.1	1.4×10^{-6}

The structure in the above example is functioning when at least one of its two generators is functioning. When the system is in state 1, 2 or 3 the system is functioning, while state 0 corresponds to system failure.

The average system availability is

$$A_s = \sum_{j \in B} P_j = P_1 + P_2 + P_3 = 1 - q_1 q_2 \tag{2.58}$$

where B denote the subset of states in which the system is functioning.

The average system unavailability is:

$$\overline{A_s} = (1 - A_s) = \sum_{j \in F} P_j = P_0 = q_1 q_2 \tag{2.60}$$

where F denote the states in which the system failed. The frequency of system failures f_f is equal to the visit frequency of state 0, which is

$$f_f = f_o = P_o(\mu_1 + \mu_2) = (1 - A_s)(\mu_1 + \mu_2) \tag{2.61}$$

The mean duration of a system failure T_f in this case equal to the mean duration of stay in state 0. Thus

$$T_f = T_o = \frac{1}{\mu_1 + \mu_2} = \frac{(1 - A_s)}{f_f} \tag{2.62}$$

For a parallel structure of n independent components, the above results may be generalized as follows:

System Unavailability. $1 - A_s = \prod_{i=1}^{n} q_i = \prod_{i=1}^{n} \frac{\lambda_i}{\lambda_i + \mu_i}$ (2.63)

Frequency of system failure. $f_f = (1 - A_s).\sum_{i=1}^{n} \mu_i$. (2.64)

Mean duration of a system failure. $T_f = \frac{1}{\sum_{i=1}^{n} \mu_i}$ (2.65)

The mean functioning time (up-time) E(U)$_p$ of the parallel structure can be determined from

$$1 - A_s = \frac{T_f}{T_f + E(U)_p}$$

Hence $E(U)_p = \frac{T_f A_s}{1 - A_s} = \frac{1 - \prod_{i=1}^{n} \frac{\lambda_i}{(\lambda_i + \mu_i)}}{\prod_{i=1}^{n} \frac{\lambda_i}{(\lambda_i + \mu_i)} \sum_{j=1}^{n} \mu_j}$ (2.66)

When the component availabilities are very high (i.e $\lambda_i << \mu_i$ for all i = 1, 2,..... , n)

then $\frac{\lambda_i}{\lambda_i + \mu_i} = \frac{\lambda_i \cdot MTTR_i}{1 + \lambda_i \cdot MTTR_i} \approx \lambda_i MTTR_i$

the frequency f$_f$ of system failures can now be approximated as

$$f_f = (1 - A_s) \cdot \sum_{i=1}^{n} \mu_i = \prod_{i=1}^{n} \frac{\lambda_i}{(\lambda_i + \mu_i)} \cdot \sum_{i=1}^{n} \mu_i \approx \prod \lambda_i \cdot MTTR_i \cdot \sum_{j=1}^{n} \frac{1}{MTTR_j} \qquad (2.67)$$

For two components/generators equation (2.67) reduces to

$$f_f = \lambda_1 \lambda_2 \cdot (MTTR_1 + MTTR_2) \tag{2.68}$$

2.7 RELIABILITY INDICES FORMULAS

The reliability indices give an "at-a-glance" picture of the reliability characteristics of devices or systems in general. The relationship between unit outages and some reliability parameters are specified in a number of literatures: (Papadapoulous, 1983), (Hapur *et al*, 1977), and (Wang, 1980). These indices along with their formulae are listed as follows:

$$1.\ Forced\ Outage\ Rate,\ FOR = \frac{FOH}{SH + OH} \tag{2.69}$$

$$2.\ Schedule\ Outage\ Rate,\ SOR = \frac{SOH}{SH + OH} \tag{2.70}$$

$$3.\ Outage\ Hour.\ OH = FOH + SOH \tag{2.71}$$

$$4.\ Mean\ Time\ To\ Failure\ (mean\ up\ time),\ MTTF = \frac{SH}{N} \tag{2.72}$$

$$5\ Mean\ Time\ To\ \mathrm{Re}\,pair\ (mean\ down\ time),\ MTTR = \frac{FOH}{N} \tag{2.73}$$

$$6.\ Mean\ Time\ Between\ Failure\ (period),\ MTBF = MTTF + MTTR \tag{2.74}$$

$$7.\ Frequency\ (f) = \frac{1}{MTBF} \tag{2.75}$$

$$8.\ Failure\ Rate\ (\lambda) = \frac{1}{MTTF} \tag{2.76}$$

$$9.\ \mathrm{Re}\,pair\ Rate\ (\mu) = \frac{1}{MTTR} \tag{2.77}$$

$$10.\ Availability\ (A) = \frac{\mu}{\mu + \lambda} \tag{2.78}$$

$$11.\ Unavailability\ (\bar{A}) = \frac{\lambda}{\mu + \lambda} \tag{2.79}$$

2.8 FACTORS INFLUENCING POWER SYSTEM RELIABILITY

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

2.8.1 Component Statistics

A power system consists of various components, such as lines, cables, transformers, breakers, 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 rates and repair or replacement time.

2.8.1.1Failure rate

Component failures can be divided into aging failures and chance failures. Aging failure is a conditional failure that depends on the component's history. Figure 2.8 shows a bath- tub curve of a component's failure rate change during its life time. An aging failure can happen suddenly after a component enters its Wear-out period. Figure 2.8 indicates that a component failure rate is not a constant. Failure rate distributions are 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 component's life cycle statistical distribution. Nowadays, the infant mortality period of some expensive components is usually consumed by manufacturers so that when these components are put into service they are already in a reliable state

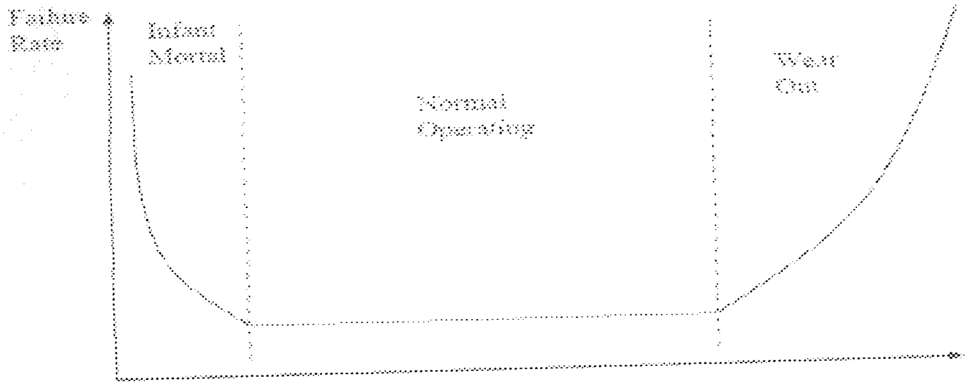

Figure 2.8 Bath-tub curve of a component`s life

Chance failure is a random fatal failure. We notice from Figure 2.9 that the failure rate in the normal operation period is a constant failure rate, and it does not depend on a component`s age. Therefore, chance failure can be modeled as an exponential distribution. Exponential distribution is the only distribution that has a constant failure rate. This statistic usually can be obtained under normal operating conditions from the manufacturer. However, loading and environmental conditions often contribute to equipment failures. Failure rates for operating under abnormal conditions are difficult for manufacturers to provide.

2.8.1.2 Repair Time

There are 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.

2.8.2 Environmental Conditions

Power system components are exposed to various weather conditions and hazards. Animals, motor vehicle accidents, rain, ice, and tree contact can all lead to faults and failures. Environment dependent failures may be of short duration. However, during such events, the probability of failure of components increases 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 we divide the weather conditions into two basic states: normal and adverse, and the failure rates and repair times of components for these two states are available, the system reliability can be evaluated separately for the two weather states and the resulting reliability indices can be weighted by the probability of the weather states.

3.2 OUTAGE DATA COLLECTION

Reliability assessment is one of the several inputs required for decisions in the planning, design or operation of electric power systems. For the normal operation of electric power systems, systems outage data should be recorded and documented. The determination of the various component failure data (failure rates, repair times, switching times, and so on) depends on the collection of data and the statistical evaluation of the resulting data samples. A comprehensive, structured and narrative procedure recommended by the Institute of Electrical and Electronics Engineers (IEEE) power generation committee on recording generating unit outages 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) and it is as shown in Appendix D.

3.3 COMPUTATION OF RELIABILITY INDICES

Components reliability indices are input 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 Frequency and Duration method which adopt transition rate parameters of the generating units. A period of five (5) years was covered based on the outage data obtained from Kainji and Shiroro Power Stations. In this section, (see Table 3.1 and Table 3.2) a compilation of number of failure, N and outage hour, OH was shown. The yearly reliability parameter of the units' availability between year 2005 and 2009 is shown in Table 3.3 through Table 3.12. These tables are

Table 3.3 : Shiroro Reliability Indices – 2005

	UNITS	
	411G1	411G2
Forced Outage Hour (FOH)	402.27	3695.63
Schedule Outage Hour (SOH)	0	0
Total Period(H)	8760	8760
Number of Failures (N)	22	20
Service Hours (SH)	8357.73	5064.37
Forced Outage Rate (FOR%)	4.5921233	42.187557
Schedule Outage Rate (SOR%)	0	0
Time To Failure (MTTF)	379.89682	253.2185
Mean Time To Repair (MTTR)	18.285	184.7815
Mean Time Between Failure (MTBF)	398.18182	438
Frequency (F)	0.0025114	0.0022831
Failure Rate (λ)	0.0026323	0.0039492
Repair Rate (μ)	0.0546896	0.0054118
Availability (A)	0.9540788	0.5781244
Unavailability (U)	0.0459212	0.4218756

Table 3.4 : Shiroro Reliability Indices – 2006

	UNITS	
	411G1	411G2
Forced Outage Hour (FOH)	56.78	121.6
Schedule Outage Hour (SOH)	0	0
Total Period(H)	8760	8760
Number of Failures (N)	15	32
Service Hours (SH)	8703.22	8638.4
Forced Outage Rate (FOR%)	0.6481735	1.3881279
Schedule Outage Rate (SOR%)	0	0
Mean Time To Failure (MTTF)	580.21467	269.95
Mean Time To Repair (MTTR)	3.7853333	3.8
Mean Time Between Failure (MTBF)	584	273.75
Frequency (F)	0.0017123	0.003653
Failure Rate (λ)	0.0017235	0.0037044
Repair Rate (μ)	0.2641775	0.2631579
Availability (A)	0.9935183	0.9861187
Unavailability (U)	0.0064817	0.0138813

Table 3.5 : Shiroro Reliability Indices – 2007

	UNITS	
	411G1	**411G2**
Forced Outage Hour (FOH)	126.38	95.15
Schedule Outage Hour (SOH)	0	8.27
Total Period(H)	8760	8760
Number of Failures (N)	27	19
Service Hours (SH)	8633.62	8656.58
Forced Outage Rate (FOR%)	1.4426941	1.0861872
Schedule Outage Rate (SOR%)	0	0.0944064
Mean Time To Failure (MTTF)	319.7637	455.60947
Mean Time To Repair (MTTR)	4.6807407	5.0078947
Mean Time Between Failure (MTBF)	324.44444	460.61737
Frequency (F)	0.0030822	0.002171
Failure Rate (λ)	0.0031273	0.0021949
Repair Rate (μ)	0.2136414	0.1996847
Availability (A)	0.9855731	0.9891279
Unavailability (U)	0.0144269	0.0108721

Table 3.6 : Shiroro Reliability Indices – 2008

	UNITS	
	411G1	**411G2**
Forced Outage Hour (FOH)	69.66	66.4
Schedule Outage Hour (SOH)	145.2	0
Total Period(H)	8760	8760
Number of Failures (N)	22	15
Service Hours (SH)	8545.14	8693.6
Forced Outage Rate (FOR%)	0.7952055	0.7579909
Schedule Outage Rate (SOR%)	1.6575342	0
Mean Time To Failure (MTTF)	388.41545	579.57333
Mean Time To Repair (MTTR)	3.1663636	4.4266667
Mean Time Between Failure (MTBF)	391.58182	584
Frequency (F)	0.0025537	0.0017123
Failure Rate (λ)	0.0025746	0.0017254
Repair Rate (μ)	0.3158197	0.2259036
Availability (A)	0.9919139	0.9924201
Unavailability (U)	0.0080861	0.0075799

Table 3.7 : Shiroro Reliability Indices – 2009

	UNITS	
	411G1	**411G2**
Forced Outage Hour (FOH)	59.35	62.43
Schedule Outage Hour (SOH)	257.49	737.41
Total Period(H)	8760	8760
Number of Failures (N)	19	7
Service Hours (SH)	8443.16	7960.16
Forced Outage Rate (FOR%)	0.6775114	0.7126712
Schedule Outage Rate (SOR%)	2.9393836	8.4179224
Mean Time To Failure (MTTF)	444.37684	1137.1657
Mean Time To Repair (MTTR)	3.1236842	8.9185714
Mean Time Between Failure (MTBF)	447.50053	1146.0843
Frequency (F)	0.0022346	0.0008725
Failure Rate (λ)	0.0022503	0.0008794
Repair Rate (μ)	0.3201348	0.1121256
Availability (A)	0.9930197	0.9922182
Unavailability (U)	0.0069803	0.0077818

Table 3.8 : Kainji Reliability Indices – 2008

	UNITS	
	1G7	**1G8**
Forced Outage Hour (FOH)	6573.72	180.92
Schedule Outage Hour (SOH)	3	73
Total Period(H)	8760	8760
Number of Failures (N)	35	12
Service Hours (SH)	2183.28	8506.08
Forced Outage Rate (FOR%)	75.042466	2.0652968
Schedule Outage Rate (SOR%)	0.0342466	0.8333333
Mean Time To Failure (MTTF)	62.379429	708.84
Mean Time To Repair (MTTR)	187.82057	15.076667
Mean Time Between Failure (MTBF)	250.2	723.91667
Frequency (F)	0.0039968	0.0013814
Failure Rate (λ)	0.0160309	0.0014108
Repair Rate (μ)	0.0053242	0.0663277
Availability (A)	0.2493183	0.9791735
Unavailability (U)	0.7506817	0.0208265

Table 3.9 : Kainji Reliability Indices – 2006

	UNITS	
	1G7	1G8
Forced Outage Hour (FOH)	1239.53	8046.78
Schedule Outage Hour (SOH)	84	615
Total Period(H)	8760	8760
Number of Failures (N)	62	24
Service Hours (SH)	7436.47	98.22
Forced Outage Rate (FOR%)	14.149886	91.858219
Schedule Outage Rate (SOR%)	0.9589041	7.0205479
Mean Time To Failure (MTTF)	119.94306	4.0925
Mean Time To Repair (MTTR)	19.992419	335.2825
Mean Time Between Failure (MTBF)	139.93548	339.375
Frequency (F)	0.0071462	0.0029466
Failure Rate (λ)	0.0083373	0.2443494
Repair Rate (μ)	0.050019	0.0029826
Availability (A)	0.8571312	0.0120589
Unavailability (U)	0.1428688	0.9879411

Table 3.10 : Kainji Reliability Indices – 2007

	UNITS	
	1G7	1G8
Forced Outage Hour (FOH)	1945.9	74.22
Schedule Outage Hour (SOH)	54	254
Total Period(H)	8760	8760
Number of Failures (N)	28	31
Service Hours (SH)	6760.1	8431.78
Forced Outage Rate (FOR%)	22.21347	0.8472603
Schedule Outage Rate (SOR%)	0.6164384	2.8995434
Mean Time To Failure (MTTF)	241.43214	271.9929
Mean Time To Repair (MTTR)	69.496429	2.3941935
Mean Time Between Failure (MTBF)	310.92857	274.3871
Frequency (F)	0.0032162	0.0036445
Failure Rate (λ)	0.004142	0.0036766
Repair Rate (μ)	0.0143892	0.4176772
Availability (A)	0.7764875	0.9912744
Unavailability (U)	0.2235125	0.0087256

Table 3.11 : Kainji Reliability Indices – 2008

	UNITS	
	1G7	1G8
Forced Outage Hour (FOH)	6258	262.3
Schedule Outage Hour (SOH)	0	41.35
Total Period(H)	8760	8760
Number of Failures (N)	5	51
Service Hours (SH)	2502	8456.35
Forced Outage Rate (FOR%)	71.438356	2.9942922
Schedule Outage Rate (SOR%)	0	0.472032
Mean Time To Failure (MTTF)	500.4	165.81078
Mean Time To Repair (MTTR)	1251.6	5.1431373
Mean Time Between Failure (MTBF)	1752	170.95392
Frequency (F)	0.0005708	0.0058495
Failure Rate (λ)	0.0019984	0.006031
Repair Rate (μ)	0.000799	0.1944339
Availability (A)	0.2856164	0.9699151
Unavailability (U)	0.7143836	0.0300849

Table 3.12 : Kainji Reliability Indices – 2009

	UNITS	
	1G7	1G8
Forced Outage Hour (FOH)	8760	243.7
Schedule Outage Hour (SOH)	0	42.76
Total Period(H)	8760	8760
Number of Failures (N)	1	56
Service Hours (SH)	0	8473.54
Forced Outage Rate (FOR%)	100	2.7819635
Schedule Outage Rate (SOR%)	0	0.4881279
Mean Time To Failure (MTTF)	0	151.31321
Mean Time To Repair (MTTR)	8760	4.3517857
Mean Time Between Failure (MTBF)	8760	155.665
Frequency (F)	0.0001142	0.0064241
Failure Rate (λ)	-	0.0066088
Repair Rate (μ)	0.0001142	0.2297907
Availability (A)	--	0.9720439
Unavailability (U)	-	0.0279561

Table 3.13: Average Reliability Indices for Shiroro Units
(2005-2009)

	UNITS	
	4111G1	**4111G2**
Forced Outage Hour (FOH)	714.84	4041.21
Schedule Outage Hour (SOH)	402.69	745.68
Total Period(H)	43800	43800
Number of Failures (N)	105	93
Service Hours (SH)	42682.47	39013.11
Forced Outage Rate (FOR%)	1.6320548	9.2265068
Schedule Outage Rate (SOR%)	0.9193836	1.7024658
Mean Time To Failure (MTTF)	406.49971	419.49581
Mean Time To Repair (MTTR)	6.808	43.453871
Mean Time Between Failure (MTBF)	413.30771	462.94968
Frequency (F)	0.0024195	0.0021601
Failure Rate (λ)	0.00246	0.0023838
Repair Rate (μ)	0.146886	0.0230129
Availability (A)	0.983528	0.9061369
Unavailability (u)	0.016472	0.0938631

Table 3.14: Average Reliability Indices for Kainji Units
(2005-2009)

	UNITS	
	1G7	**1G8**
Forced Outage Hour (FOH)	24777.15	8807.92
Schedule Outage Hour (SOH)	141	1026.11
Total Period(H)	43800	43800
Number of Failures (N)	131	174
Service Hours (SH)	18881.85	33965.97
Forced Outage Rate (FOR%)	56.568836	20.109406
Schedule Outage Rate (SOR%)	0.3219178	2.3427169
Mean Time To Failure (MTTF)	144.13626	195.20672
Mean Time To Repair (MTTR)	189.13855	50.62023
Mean Time Between Failure (MTBF)	333.27481	245.82695
Frequency (F)	0.0030005	0.0040679
Failure Rate (λ)	0.0069379	0.0051228
Repair Rate (μ)	0.0052871	0.0197549
Availability (A)	0.4324847	0.7940819
Unavailability (U)	0.5675153	0.2059181

CHAPTER FOUR

4.0 RESULTS

This chapter presents the results obtained from the analysis of the two case studies considered.

4.1 SHIRORO UNITS

Table 4.1 shows the failure rate and the repair rate of Shiroro units during the period of study.

Table 4.1: Failure Rate and Repair Rate for Shiroro Units

Year	Units	Failure Rate (λ)	Repair Rate (μ)
2005	411G1	0.0026	0.0547
	411G2	0.0040	0.0054
2006	411G1	0.0017	0.2642
	411G2	0.0037	0.2632
2007	411G1	0.0031	0.2136
	411G2	0.0022	0.1997
2008	411G1	0.0026	0.3158
	411G2	0.0017	0.2259
2009	411G1	0.0022	0.3201
	411G2	0.0009	0.1121

Source: PHCN Shiroro Hydro Power Station Generating Units' Outages Report (2009)

Considering the reliability indices for Shiroro units 411G1 and 411G2 from 2005-2009 (table 4.1).

The state space diagram for Shiroro Units 411G1 and 411G2 is designed as depicted in Figure 4.1

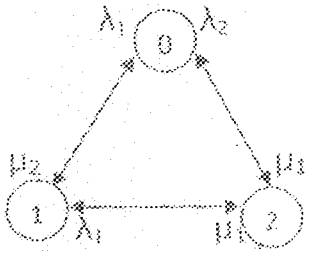

Figure 4.1: State-Space Diagram for Shiroro Units 411G1 and 411G2

The state-transition intensity matrix is given by:

$$A = \begin{bmatrix} -(\mu_1 + \mu_2) & \mu_2 & \mu_1 \\ \lambda_1 & -(\lambda_1 + \mu_2) & \mu_2 \\ \lambda_2 & \lambda_1 & -(\lambda_1 + \lambda_2) \end{bmatrix} \qquad (4.1)$$

Equation (2.27) becomes

$$\left.\begin{aligned} -(\mu_1 + \mu_2)P_0 + \lambda_1 P_1 + \lambda_2 P_2 = 0 \\ \mu_2 P_0 - (\lambda_1 + \mu_2)P_1 + \lambda_1 P_2 = 0 \\ \mu_1 P_0 + \mu_2 P_1 - (\lambda_1 + \lambda_2)P_2 = 0 \end{aligned}\right\} \qquad (4.2)$$

By omitting the first equation and replacing it with $P_0 + P_1 + P_2 = 1$, the solution of the steady state probabilities are:
where $D = (\lambda_1 + \lambda_2)(\lambda_1 + 2\mu_2) + 2\lambda_1\mu_1 + \mu_2(\mu_1 - \lambda_1) + \mu_2^2$

$$P_0 = \frac{(\lambda_1 + \lambda_2)(\lambda_1 + \mu_2) - \lambda_1\mu_2}{D}, \qquad P_1 = \frac{\lambda_1\mu_1 + \mu_2(\lambda_1 + \lambda_2)}{D}, \qquad P_2 = \frac{\mu_2^2 + \mu_1(\lambda_1 + \mu_2)}{D} \qquad (4.3)$$

The steady- state probabilities for 2005, 2006, 2007, 2008 and 2009 are presented in Table 4.2.

Table 4.2: Capacity Outage Probability Table (COPT) for Shiroro Units

Year	State No.	Capacity (MW)	Steady-State Probabilities	Average hour in state per year
2005	2	300	0.6830	5983.08
	1	150	0.2603	2280.23
	0	0	0.0567	496.69
2006	2	300	0.9800	8584.8
	1	150	0.0131	114.76
	0	0	0.0069	60.44
2007	2	300	0.9743	8534.87
	1	150	0.0204	178.704
	0	0	0.0053	46.428
2008	2	300	0.9825	8606.70
	1	150	0.0143	125.268
	0	0	0.0032	28.032
2009	2	300	0.9770	8558.52
	1	150	0.0209	183.084
	0	0	0.0021	18.396

Source: PHCN Shiroro Hydro Power Station Generating Units' Outages Report (2009)

Note: State 0 = State when both units are not operational

State 1 = State when only one of the units is operational

State 2 = State when both units are operational

The system availability, the system unavailability, the frequency of system failure and the mean duration of system failure of each year under study as obtained from equations (2.60), (2.57), (2.61) and (2.62) respectively, are presented in Table 4.3.

Table 4.3: System Availability and Unavailability for Shiroro Units

Year	System Availability	System Unavailability	Frequency of System Failure	Mean Duration of System Failure (hours)
2005	0.9433	0.0567	3.4077×10^{-3}	16.638
2006	0.9931	0.0069	3.6391×10^{-3}	1.8960
2007	0.9947	0.0053	2.1905×10^{-3}	2.4195
2008	0.9968	0.0032	1.7330×10^{-3}	1.8460
2009	0.9979	0.0021	9.0762×10^{-4}	2.3137

The overall Capacity Outage Probability Table (COPT) for the entire Shiroro units under the period of study (2005-2009) is obtained from the failure rate and repair rate of Table 3.14 and this is presented in Table 4.4.

Table 4.4: Average Capacity Outage Probability Table (COPT) for Shiroro Units (2005-2009)

State	Capacity	Steady-State Probabilities	Average hour in state per year
2	300	0.8865	7765.74
1	150	0.0995	871.62
0	0	0.0140	122.46

Hence, th overall system availability as obtained from equation (2.60) is:

$$A_s = \sum_{j \in S} P_j = P_1 + P_2 = 0.9860$$

while the overal system unavailability is: $\overline{A_s} = (1 - A_s) = \sum_{i \in F} P_i = P_0 = 0.0140.$

while the overall system unavailability is: $\overline{A_s} = (1 - A_s) = \sum_{i=1} P_i = P_0 = 0.0140.$

the frequency of system failure as obtained from equation (2.61) is:

$$f_f = (1 - A_s).\sum_{i=1}^{n} \mu_i = 2.3786 \times 10^{-3}$$

And the mean duration of system failure $T_f = \dfrac{1}{\sum_{i=1}^{n} \mu_i} = 5.888 hours$

4.2 KAINJI UNITS

Table 4.5 shows the failure rate and the repair rate of Kainji units during the period of study.

Table 4.5: Failure Rate and Repair Rate for Kainji Units

Year	Units	Failure Rate (λ)	Repair Rate (μ)
2005	1G7	0.0160	0.0053
	1G8	0.0014	0.0663
2006	1G7	0.0083	0.0500
	1G8	0.2444	0.0030
2007	1G7	0.0041	0.0144
	1G8	0.0037	0.4177
2008	1G7	0.0020	0.0008
	1G8	0.0060	0.1944
2009	1G7	-	0.0001
	1G8	0.0066	0.2298

Source: PHCN Kainji Hydro Power Station Generating Units' Outages Report (2009)

Considering the reliability indices for Kainji units 1G7 and 1G8 from 2005-2009 (Table 4.5).

The state space diagram of Kainji Units 1G7 and 1G8 is shown in Figure 4.2.

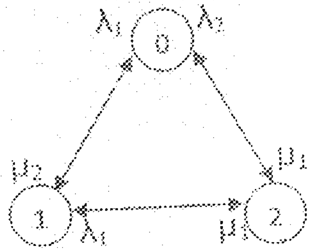

Figure 4.2: State-Space Diagram for Kainji Units 1G7 and 1G8

The state-transition intensity matrix is given by:

$$A = \begin{bmatrix} -(\mu_1 + \mu_2) & \mu_2 & \mu_1 \\ \lambda_1 & -(\lambda_1 + \mu_2) & \mu_2 \\ \lambda_2 & \lambda_1 & -(\lambda_1 + \lambda_2) \end{bmatrix} \tag{4.4}$$

$$\left.\begin{aligned} -(\mu_1 + \mu_2)P_0 + \lambda_1 P_1 + \lambda_2 P_2 = 0 \\ \mu_2 P_0 - (\lambda_1 + \mu_2)P_1 + \lambda_1 P_2 = 0 \\ \mu_1 P_0 + \mu_2 P_1 - (\lambda_1 + \lambda_2)P_2 = 0 \end{aligned}\right\} \tag{4.5}$$

By omitting the first equation and replacing it with $P_0 + P_1 + P_2 = 1$, the solution of the steady state probabilities are:

$$P_0 = \frac{(\lambda_1 + \lambda_2)(\lambda_1 + \mu_2) - \lambda_1\mu_2}{D}, \qquad P_1 = \frac{\lambda_1\mu_1 + \mu_2(\lambda_1 + \lambda_2)}{D}, \qquad P_2 = \frac{\mu_1^2 + \mu_1(\lambda_1 + \mu_1)}{D} \tag{4.6}$$

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 2005, 2006, 2007, 2008 and 2009 are presented in Table 4.6.

Table 4.6: Capacity Outage Probability Table (COPT) for Kainji Units

Year	State No.	Capacity (MW)	Steady-State Probabilities	Average hour in state per year
2005	2	160	0.7502	6571.752
	1	80	0.1922	1683.672
	0	0	0.0576	504.576
2006	2	160	0.1253	1097.628
	1	80	0.2563	2245.188
	0	0	0.6184	5417.184
2007	2	160	0.9736	8526.736
	1	80	0.0179	156.804
	0	0	0.0085	74.46
2008	2	160	0.9326	8169.576
	1	80	0.0383	335.508
	0	0	0.0291	254.916
2009	2	160	0.0000	0.0000
	1	80	0.9721	8515.598
	0	0	0.0279	244.56

Source: PHCN Kainji Hydro Power Station Generating Units' Outages Report (2009)

The system availability, the system unavailability, the frequency of system failure and the mean duration of system failure of each year under study is obtained from equations (2.60), (2.57), (2.61) and (2.62) respectively. This is presented in Table 4.7.

Table 4.7: System Availability and Unavailability for Kainji Units

Year	System Availability	System Unavailability	Frequency of System Failure	Mean Duration of System Failure (hours)
2005	0.9424	0.0576	4.1242×10^{-3}	13.966
2006	0.3816	0.6184	3.2770×10^{-2}	18.868
2007	0.9915	0.0085	3.6730×10^{-3}	2.3140
2008	0.9709	0.0291	5.6800×10^{-3}	5.1220
2009	0.9721	0.0279	6.414×10^{-3}	4.3497

The overall Capacity Outage Probability Table (COPT) for the entire Kainji units under the period of study (2005-2009) is obtained from the failure rate and repair rate in Table 3.15, and this is presented in Table 4.8.

Table 4.8: Average Capacity Outage Probability Table (COPT) for Kainji Units (2005-2009)

State	Capacity	Steady-State Probabilities	Average hour in state per year
2	160	0.1854	1624.104
1	80	0.2765	2422.14
0	0	0.5381	4713.756

Hence, the overall system availability as obtained from equation (2.60) is:

$$A_s = \sum_{j \in R} P_j = P_1 + P_2 = 0.4619$$

while the overall system unavailability is: $\overline{A_s} = (1 - A_s) = \sum_{j \in F} P_j = P_0 = 0.5381.$

the frequency of system failure as obtained from equation (2.61) is:

$$f_f = (1 - A_s).\sum_{i=1}^{n} \mu_i = 13.5 \times 10^{-3}$$

And the mean duration of system failure $T_f = \dfrac{1}{\sum_{i=1}^{n} \mu_i} = 39.84 hours$

Figure 4.3 to 4.8 graphically represents the relationship between FOR and Availability of both Kainji and Shiroro units under the period of study.

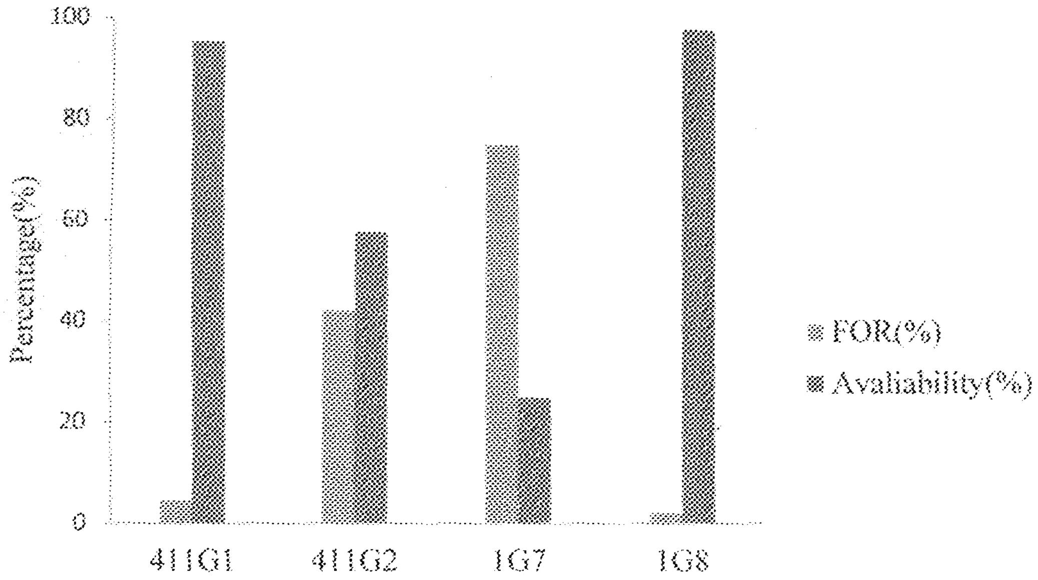

Fig. 4.3: Relationship between FOR and Availability of Shiroro & Kainji Units (2005)

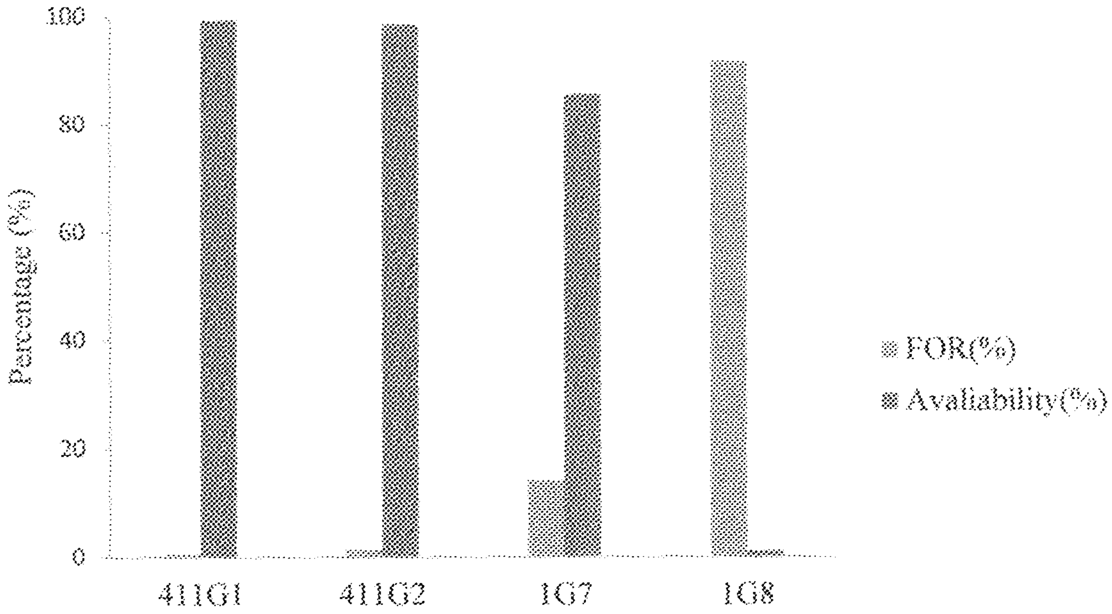

Fig. 4.4: Relationship between FOR and Availability of Shiroro & Kainji Units (2006)

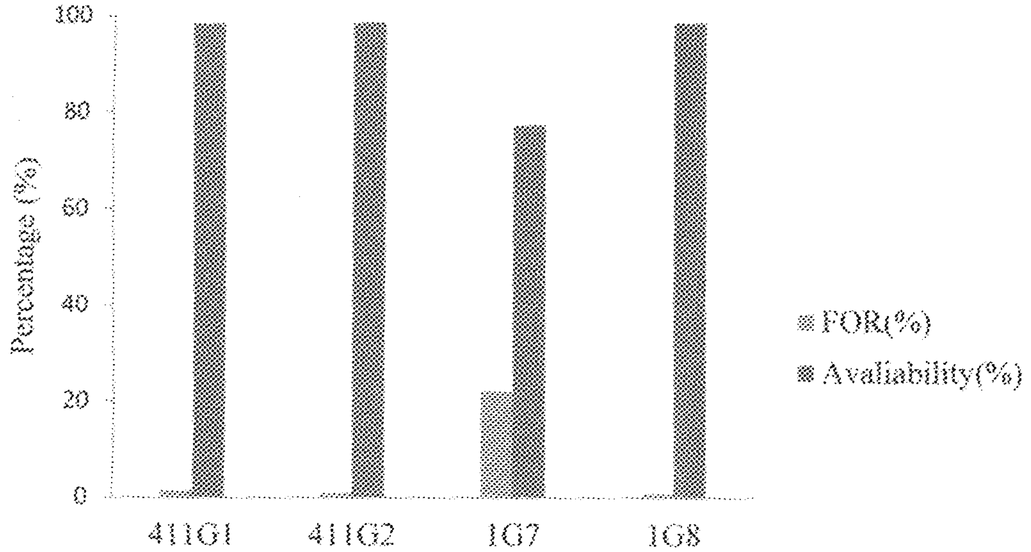

Fig. 4.5: Relationship between FOR and Availability of Shiroro & Kainji Units (2007)

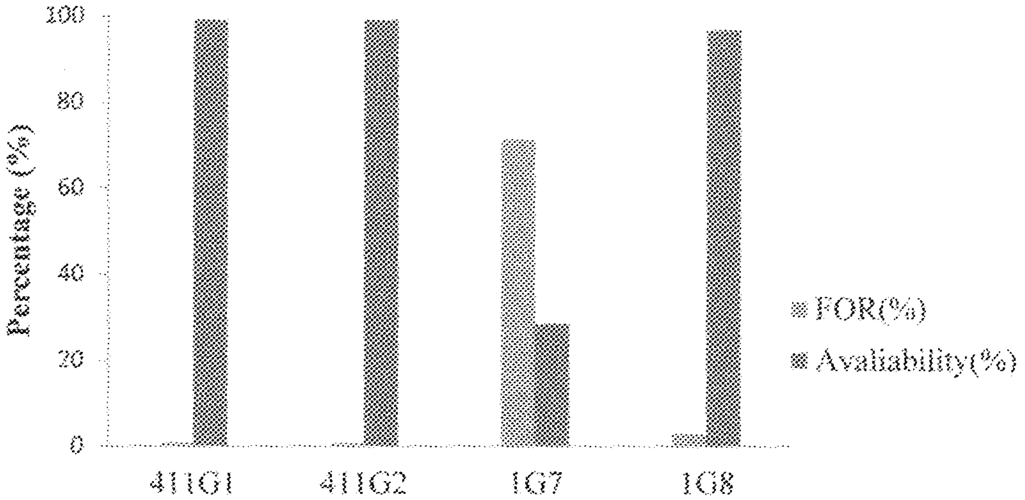

Fig. 4.6: Relationship between FOR and Availability of Shiroro & Kainji Units (2008)

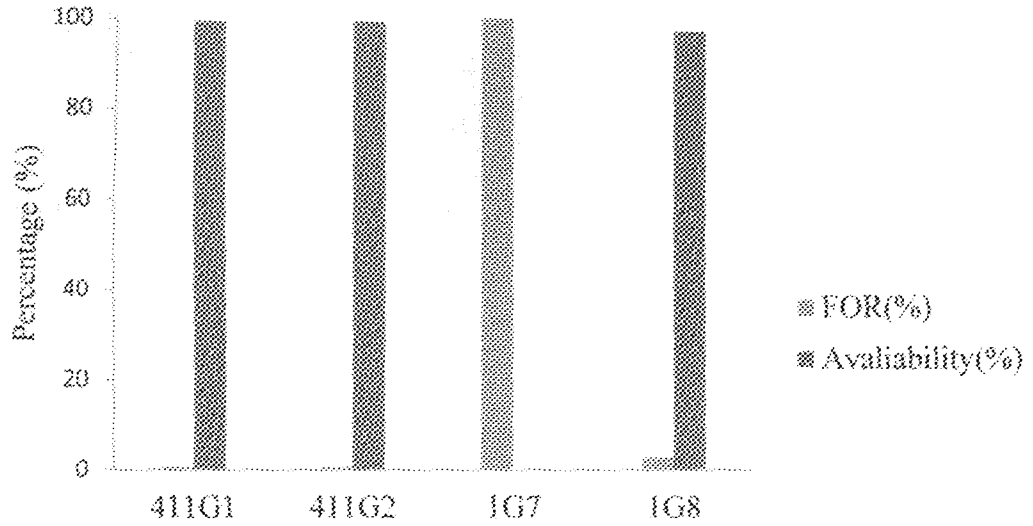

Fig. 4.7: Relationship between FOR and Availability of Shiroro & Kainji Units (2009)

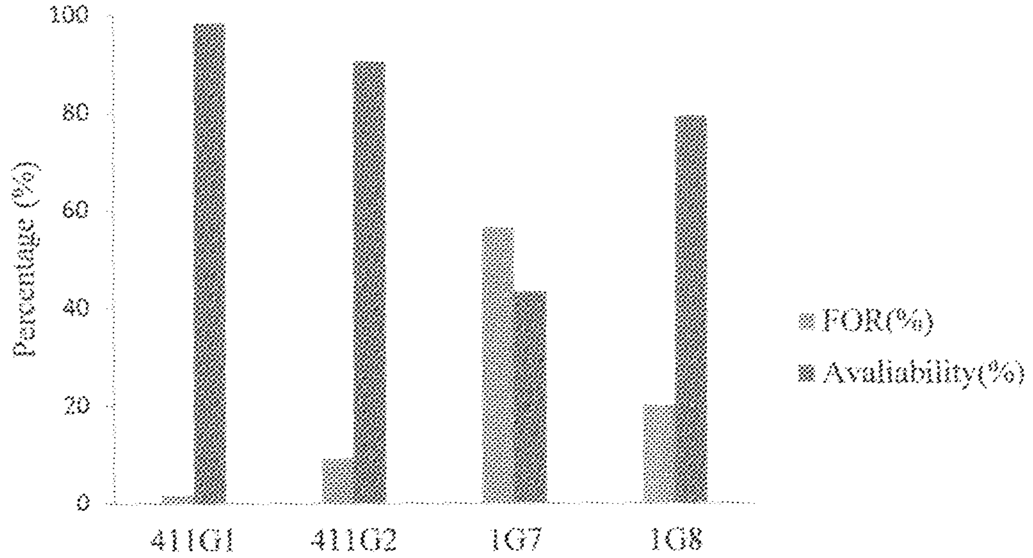

Fig. 4.8: Relationship between FOR and Availability of Shiroro & Kainji Units for Average Capacity Probability (2005-2009)

CHAPTER FIVE

5.0 DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

5.1 DISCUSSIONS OF RESULTS

Generally, typical values for Forced Outage Rates (FOR) tend to range between 0.3% and 29% which depends on factors such as unit type, size and age of the plant. Low values of force outage rates are expected for hydro units since they are supposed to be very reliable. The result obtained shows a good reliability performance of Shiroro unit 411G1 and 411G for the period of the study, this is evident from the graph of the following figures: Fig. 4.4, Fig. 4.5, Fig. 4.6 and Fig. 4.7. These graphs show the relationship between Availability and the Forced Outage Rate (FOR) of the units. It reveals that the lower the FOR of each unit, the higher the reliability of the unit. It is observed that only in year 2005 (see Fig. 4.3), unit 411G2 of Shiroro units experienced higher FOR, which makes the unit to be available for just 50 percent of the time in the year. Judging from the average reliability indices of Shiroro units (see Table 3.13) under period of study, it is obvious that unit 411G1 is more available than unit 411G2 because of its low Forced Outage Rate (FOR). Hence, the overall system availability for both units considered in Shiroro power station is 0.9860, while the system unavailability is 0.0140 (see Table 4.4) which results in frequency of system failure of 2.3786×10^{-3} and mean duration of system failure of 5.888hours. These results show that maintenance is properly done for the generating units at the Shiroro Hydro Electric Power Station.

Considering the Kainji units 1G7 and 1G8 for the period of study, In 2005 1G8 is more available than 1G7 because of its low FOR (see Fig.4.3), while the reversed is the case in

2006 (see Fig. 4.4). From year 2007 to 2009 (see Fig. 4.5, Fig. 4.6 and Fig. 4.7), it was observed that unit 1G8 has a better reliability performance than unit 1G7 due to lower Forced Outage Rate. In fact unit 1G7 is not available at all in 2009, because the unit is completely out of service on Stator Fault.

Judging from the average reliability indices of Kainji units (see Table 3.14) at the period of study, it could be observed that both units considered in the station performed below expectation due to high Forced Outage Rate which constantly occurred as a result of faults on the system. Hence the overall system availability for Kainji units is 0.4619, while the system unavailability is 0.5381 (see Table 4.7) which is more when compare with Shiroro units. The frequency of system failure and mean duration of failure for these units are 13.5×10^{-3} and 39.84 hours respectively. This is as a result of lack of proper maintenance. Maintenance is the 'backbone' of successful performance of generating units. It is quite obvious that there were prolong Forced Outage of Kainji Units which occurred from time to time, giving rise to very high unit force outage rates and this invariably implies unreliable performance of the units. Also from table 3.14, the MTTF for the Kainji units within the years considered is too low and this is obviously the cause of its unreliable performance. Low MTTF implies that there will be frequent outages and hence overall poor system performance. According to the tables presented in chapter three, year by year assessment shows that the performance of the Kainji units was best in 2007, but even then the performance was quite below expectation.

It can however be concluded that Kainji Hydro Electric Power Station perform below expectation than Shiroro Hydro Electric Power Station between year 2005 and 2009. Since the performance of the whole system is an integration of the performance of each unit, poor performance of individual units means poor performance of the entire system (station). There are several factors responsible for these poor performances. The major causes are the outages due to the surge and system swing. System swing refers to sudden drop followed by rise in frequency. Some outages are due to some external factors like load rejection from some other stations, thus, overloading the in-service units at the station, which could in-turn trip the whole units successively. Other existing outages are due to Fire outbreak, Breaker fault, Preventive checks, repairs and cleaning, Stator fault, Preventive replacement, Relay operation for unknown cause, Rotor fault, Intake gate fault, Governor fault, Metering system fault, Customer request, Head cover pump failure, System surge, Human accident, Power house roof leakage, Loose coupling, bolts and nuts, Automatic voltage regulator fault, Draft tube, Runner (blade, inspector door) fault, Generator/Station service transformers, Brake circuit, Pilot valve, Turbo vent Exciter, Thrust and upper guide bearing, Tail race discharge valve and low water level.

5.2 CONCLUSIONS

Reliability indices were obtained for the Shiroro and Kainji hydro electric power units 411G1, 411G2, 1G7 and 1G8. The frequency and duration approach to the reliability study was applied to the assessment of these units. These provided information on the knowledge of mean time of encountering certain available capacity states based on the probability and frequency of system failure. The frequent outages (forced and scheduled) greatly affected the reliability of the stations, particularly Kamji. The main result of our analysis here, when compared with the corresponding results in Shiroro units, indicates that Kainji units has so far performed below expectation.

There are some reasons behind this poor performance which are outlined in the following few paragraphs.

The trends of maintenance in both stations considered, clearly shows that standard maintenance practice is yet to be embraced. Routine maintenance during the study period is very few. The effect of these maintenance practices on the unit's forced outage rate is seen from the graph of Fig. 4.8 for Kainji unit. The pattern of the chart shows that the more the number of scheduled maintenance the lower the forced outage rate, that is, the failure rate drastically reduced as more maintenance is being carried out.

Of importance also is the proper scheduling of various unit maintenance periods without compromising overall system reliability. Scheduling maintenance means selecting the weeks in a year, usually during periods of low power demand or low inflow when each unit will be taken out of service and given necessary overhaul. At both stations, the idea of scheduling maintenance is generally lacking. Hence the following measures were recommended to improve the reliability of the stations.

1. Adequate maintenance of the units.
2. Adoption of preventive maintenance rather than break down maintenance.
3. Better control of system operations.
4. Equipment standardization/documentation
5. Provision of special maintenance tools
6. Ensure coordinated protection settings
7. Effective training of maintenance staff

5.3 RECOMMENDATIONS FOR FURTHER STUDY

The aim of this study is to provide a means to quantify and evaluate the reliability of major Hydro Electric Power Stations in Nigeria. Initially, three stations were earmarked for the study namely Kainji, Shiroro and Jebba Hydro electric Power Station. However, due to time constraint and limitation of data this intention was not materialized. Only two units each from Kainji and Shiroro Power Stations were considered and analyzed. The methodologies used in this study accelerate the realization of the objectives of this research, however, there are still rooms for improvement. The following are suggested ideas for further work in this study.

1. To develop reliability models for the other Electric power station in Nigeria, such as thermal power station, gas power station etc.
2. To extend the study to Transmission and Distribution subsystem of the Nigeria power system for effective operation or planning.

It should also be pointed out, however that the methods of collection and keeping of data on equipment by the supply authority should be improve. Apart from being a burden to researcher to compile, the available information and data are not elaborate enough to enhance a thorough reliability study. In fact, data banks should be developed to a point where information will be made available at all times (such as information about all types of equipment, failure mode, and various environmental factors and human errors).

Finally, it is hoped that findings from this study would be a useful addition to the resources regarding Nigeria electric power system reliability.

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APPENDICES

APPENDIX A

KAINJI HYDRO POWER STATION

GENERATING UNITS OUTAGE DATA

(2005-2009)

The outage types are:

F = Full forced outage

S = Scheduled outage

The duration is in hours and minutes.

The outage cause codes are:

01 Fire outbreak
02 Breaker fault
03 Preventive checks, repairs and cleaning
04 Stator fault
05 Preventive replacement
06 Relay operation for unknown cause
07 Rotor fault
08 Intake gate fault
09 Governor fault
10 Metering system fault
11 Customer request
12 Head cover pump failure
13 System surge
14 Human accident
15 Power house roof leakage
16 Loose coupling, bolts and nuts
17 Automatic voltage regulator fault
18 Draft tube
19 Runner (blade, inspector door) fault
20 Generator/Station service transformers
21 Brake circuit
22 Pilot valve
23 Turbo vent
24 Exciter
25 Thrust and upper guide bearing
26 Tail race discharge valve
27 Others.

2007 (1G8) Contd.

20	APR	11	F	0:45	27
21	APR	19	F	1:15	25
22	APR	27	S	5:11	3
23	JUN	1	F	1:05	27
24	JUN	6	F	0:56	6
25	JUN	26	S	185:28:00	5
26	AUG	25	F	7:39	27
27	SEP	7	F	2:15	27
28	SEP	11	S	5:03	3
29	SEP	29	F	1:26	12
30	SEP	30	F	1:55	27
31	OCT	1	F	0:57	13
32	OCT	6	F	1.55	27
33	OCT	21	F	16:20	13
34	NOV	3	F	2:52	27
35	NOV	14	S	6:23	3
36	DEC	11	S	15:58	5
37	DEC	14	S	30:58:00	3
38	DEC	27	F	0:42	6

2008 (1G7)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	APR	14	F	2629:33:00	4
2	AUG	31	F	3225:46:00	4
3	SEP	19	F	387:07:00	25
4	SEP	21	F	4:52	8
5	SEP	22	F	11:01	27

2008 (1G8)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	6	F	3:29	27
2	FEB	12	F	0:39	27
3	MAR	14	F	19:30	13
4	MAR	15	F	5:10	25
5	MAR	24	F	1:09	27
6	MAR	25	F	1:16	27
7	APR	3	F	3:21	25
8	APR	7	F	9:06	4
9	APR	12	F	7:13	13
10	APR	13	F	4:22	25
11	APR	19	F	0:44	4
12	APR	25	F	2:00	27
13	APR	28	F	1:32	27
14	MAY	2	F	26:38:00	27
15	MAY	11	F	18:48	4
16	MAY	15	F	2:38	27

2008(1G8) Contd.

17	MAY	16	F	3:35	27
18	MAY	19	F	5:40	27
19	MAY	28	F	2:08	27
20	JUN	5	F	1:05	9
21	JUN	13	F	2:20	27
22	JUN	16	F	2:07	6
23	JUN	17	F	6:34	27
24	JUN	28	F	1:16	6
25	JUN	21	F	3:42	27
26	JUN	22	F	2:23	13
27	JUN	23	F	2:37	6
28	JUN	25	F	8:46	13
29	JUN	26	F	0.09	13
30	JUN	27	F	2:46	6
31	JUN	28	F	2:41	27
32	JUN	30	F	2:28	27
33	JUL	1	F	2:57	25
34	JUL	3	F	3:34	27
35	JUL	4	F	1:06	27
36	JUL	15	F	14:01	27
37	JUL	27	F	1:24	13
38	JUL	28	F	0:13	13
39	JUL	30	S	9:06	3

2009 (1G7)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
0	0	0	0	0	0

2009 (1G8)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	16	F	3:03	13
2	JAN	22	F	0:10	13
3	JAN	23	F	3:13	25
4	JAN	31	F	0.31	13
5	FEB	6	F	4:03	13
6	FEB	7	F	0:26	13
7	FEB	13	F	1:30	27
8	FEB	20	F	0:15	13
9	FEB	23	F	1:15	27
10	FEB	24	F	2:26	27
11	FEB	25	F	2:39	27
12	MAR	2	F	0:12	13
13	MAR	7	F	1:29	13
14	MAR	8	F	0:30	25
15	MAR	13	F	0:46	25
16	MAR	16	F	0:48	6
17	MAR	17	F	1:04	2
18	APR	1	F	0:09	25
19	APR	7	F	1:14	27
20	APR	11	F	0:27	13
21	APR	16	F	5:01	9
22	APR	21	F	0:15	27
23	MAY	2	F	3:12	27
24	MAY	3	F	2:16	27
25	MAY	13	F	1:16	27
26	MAY	19	F	7:39	27
27	MAY	29	F	1:09	6
28	JUN	19	S	30:56:00	3
29	JUN	20	F	2:16	27
30	JUN	21	F	3:57	13
31	JUN	23	F	0:35	27
32	JUN	24	F	0:55	27
33	JUN	27	F	2:20	27
34	JUL	3	F	2:40	27
35	JUL	7	F	1:33	13
36	JUL	16	S	4.09	3
37	JUL	21	F	76:09:00	13
38	JUL	13	F	19:17	27

2009 (1G8) Contd.

39	JUL	14	F	0:32	25
40	JUL	30	F	16:00	13
41	AUG	14	F	1:50	13
42	AUG	17	F	1:21	27
43	AUG	19	F	3:38	13
44	AUG	20	F	0:14	13
45	AUG	24	F	0:58	27
46	AUG	26	F	2:44	27
47	SEP	8	F	2:53	27
48	SEP	9	F	1:33	27
49	OCT	8	F	0:08	13
50	OCT	11	F	2:26	6
51	OCT	12	F	2:55	25
52	OCT	13	F	1:19	25
53	OCT	15	S	9:41	3
54	OCT	16	F	15:32	13
55	OCT	22	F	20:07	20
56	NOV	5	F	2:56	13
57	DEC	8	F	6:17	13
58	DEC	9	F	1:22	25
59	DEC	24	F	2:08	6

APPENDIX B

SHIRORO HYDRO POWER STATION

GENERATION UNITS OUTAGE DATA

(2005-2009)

The outage types are:

F = Full forced outage

S = Scheduled outage

The duration is in hours and minutes.

The outage cause codes are:

01 Fire outbreak
02 Breaker fault
03 Preventive checks, repairs and cleaning
04 Stator fault
05 Preventive replacement
06 Relay operation for unknown cause
07 Rotor fault
08 Intake gate fault
09 Governor fault
10 Metering system fault
11 Customer request
12 Head cover pump failure
13 System surge
14 Human accident
15 Power house roof leakage
16 Loose coupling, bolts and nuts
17 Automatic voltage regulator fault
18 Draft tube
19 Runner (blade, inspector door) fault
20 Generator/Station service transformers
21 Brake circuit
22 Pilot valve
23 Turbo vent
24 Exciter
25 Thrust and upper guide bearing
26 Tail race discharge valve
27 Others

2005 (411G1)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	13	F	338:50:00	20
2	JAN	25	F	1:34	27
3	FEB	17	F	5:57	13
4	MAR	O2	F	0:52	2
5	APR	14	F	10:00	13
6	APR	24	F	3:04	27
7	MAY	14	F	1:29	27
8	JUN	21	F	9:40	6
9	JUL	2	F	1:34	19
10	JUL	6	F	4:10	18
11	JUL	10	F	1:32	9
12	JUL	11	F	9:03	27
13	JUL	12	F	0:17	24
14	JUL	13	F	2:48	19
15	AUG	4	F	2:00	2
16	AUG	20	F	2:12	6
17	SEP	2	F	0:20	27
18	SEP	18	F	1:25	19
19	SEP	21	F	0:14	19
20	NOV	10	F	2:14	27
21	DEC	27	F	3:05	18
22	DEC	29	F	2:20	24

2005 (411G2)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	MAR	27	F	3600:00:00	4
2	MAR	31	F	0:19	2
3	APR	14	F	9:50	18
4	APR	17	F	17:05	18
5	APR	18	F	1:05	27
6	JUN	17	F	33:00:00	8
7	JUN	20	F	1:15	6
8	JUN	22	F	1:54	24
9	JUN	23	F	3:16	10
10	JUL	5	F	8:41	13
11	AUG	1	F	1:15	19
12	AUG	6	F	2:07	24
13	SEP	12	F	2:00	28
14	SEP	12	F	0:20	24
15	SEP	19	F	1:07	26
16	SEP	22	F	34:13:00	27
17	SEP	29	F	1:35	25
18	NOV	10	F	1:00	24
19	DEC	7	F	2:39	27
20	DEC	12	F	2:13	2

2006 (411G1)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	6	F	1:45	24
2	FEB	18	F	3:24	27
3	APR	3	F	0:40	24
4	APR	17	F	0:52	20
5	MAY	27	F	27:20:00	8
6	MAY	30	F	0:43	25
7	JUN	8	F	0:59	5
8	SEP	13	F	2:46	24
9	SEP	20	F	0:31	5
10	SEP	20	F	4:17	26
11	OCT	4	F	0:49	25
12	OCT	31	F	7:22	13
13	NOV	7	F	1:17	24
14	NOV	30	F	1:27	5
15	DEC	1	F	2:35	27

2006 (411G2)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	7	F	1:46	27
2	JAN	16	F	5:24	27
3	JAN	18	F	2:12	24
4	JAN	18	F	1:19	27
5	JAN	22	F	2:03	6
6	JAN	29	F	0:52	6
7	FEB	13	F	1:10	3
8	FEB	21	F	0:52	3
9	MAR	2	F	4:42	27
10	MAR	3	F	5:02	27
11	MAR	3	F	5:45	6
12	MAR	29	F	1:22	2
13	APR	7	F	3:10	27
14	APR	26	F	0:30	27
15	MAY	16	F	1:56	3
16	MAY	19	F	4:27	9
17	JUL	21	F	2:53	27
18	AUG	4	F	0:33	24
19	AUG	13	F	1:15	24
20	AUG	14	F	0:39	25
21	AUG	17	F	1:02	6
22	AUG	24	F	2:15	9
23	AUG	25	F	0:53	9
24	AUG	29	F	5:31	27
25	SEP	1	F	1:00	9
26	SEP	7	F	1:36	24
27	SEP	8	F	5:21	9

2005 (1G7)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	9	F	1:04	27
2	JAN	10	F	2:17	13
3	JAN	11	F	0:43	27
4	JAN	12	S	2:10	5
5	JAN	22	F	0:12	17
6	FEB	23	S	1:26	5
7	FEB	9	S	11:04	3
8	FEB	18	F	18:25	2
9	FEB	19	F	14:25	27
10	FEB	22	F	6:31	27
11	FEB	25	F	1:32	13
12	FEB	26	F	2:44	13
13	FEB	27	F	1:20	27
14	FEB	28	S	5:19	3
15	MAR	9	F	2:16	27
16	MAR	13	F	0:13	27
17	MAR	14	F	26:43:00	2
18	APR	4	F	2:11	27
19	APR	5	F	10:56	13
20	APR	8	F	6:37	27
21	APR	9	F	3:05	27
22	APR	13	F	3:31	27
23	APR	18	F	4:02	27
24	APR	18	S	5:50	3
25	MAY	3	S	9:39	3
26	JUN	24	F	1:22	9
27	JUN	7	F	0:38	13
28	JUL	30	F	0:24	25
29	AUG	2	F	3:38	27
30	AUG	20	F	3:53	6
31	AUG	29	F	0:45	9
32	AUG	30	S	13:36	3
33	SEP	12	F	10:25	27
34	SEP	19	F	22:27	13
35	SEP	19	S	7:38	5
36	SEP	29	F	3:59	13
37	SEP	30	F	0:32	13
38	OCT	11	S	6:01	3
39	NOV	7	F	1:07	9
40	NOV	24	F	4:15	13
41	DEC	11	F	4:35	13
42	DEC	13	F	0:29	25
43	DEC	15	S	10:13	3
44	DEC	16	F	13:04	8
45	DEC	29	F	0:34	27

2005 (1G8)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	9	F	1:04	27
2	JAN	10	F	0:23	13
3	JAN	12	F	46:56:00	13
4	JAN	13	F	0:12	27
5	JUN	8	F	3522:03:00	27
6	JUN	14	F	0:56	3
7	JUN	29	F	0:14	27
8	JUL	4	S	3:03	3
9	JUL	5	F	12:17	13
10	JUL	8	F	0:40	24
11	JUL	9	F	35:11:00	24
12	SEP	22	F	3:05	25
13	SEP	22	F	2950:42:00	9

2006 (1G7)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	2	F	11:42	27
2	JAN	3	F	5:55	25
3	JAN	17	S	7:03	3
4	JAN	27	F	1:55	13
5	JAN	30	F	33:36:00	25
6	JAN	31	F	31:41:00	25
7	FEB	3	F	11:50	12
8	FEB	4	F	4:00	12
9	FEB	9	F	16:19	27
10	FEB	17	F	1:10	9
11	FEB	20	F	1:53	27
12	MAR	5	F	12:48	27
13	MAR	8	F	2.45	13
14	MAR	16	F	2:26	13
15	MAR	20	F	0:54	27
16	MAR	29	F	3:31	27
17	APR	6	F	1.33	25
18	APR	7	F	1.11	25
19	APR	8	F	6:25	25
20	APR	9	F	0:25	25

2005 (1G8)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	9	F	1:04	27
2	JAN	10	F	0:23	13
3	JAN	12	F	46:56:00	13
4	JAN	13	F	0:12	27
5	JUN	6	F	3522:03:00	27
6	JUN	14	F	0:56	3
7	JUN	29	F	0:14	27
8	JUL	4	S	3:03	3
9	JUL	5	F	12.17	13
10	JUL	8	F	0:40	24
11	JUL	9	F	35:11:00	24
12	SEP	22	F	3:05	25
13	SEP	22	F	2950:42:00	9

2006 (1G7)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	2	F	11.42	27
2	JAN	3	F	5:55	25
3	JAN	17	S	7.03	3
4	JAN	27	F	1:55	13
5	JAN	30	F	33:36:00	25
6	JAN	31	F	31:41:00	25
7	FEB	3	F	11:50	12
8	FEB	4	F	4:00	12
9	FEB	9	F	16:19	27
10	FEB	17	F	1:10	9
11	FEB	20	F	1:53	27
12	MAR	5	F	12:48	27
13	MAR	6	F	2:45	13
14	MAR	16	F	2:26	13
15	MAR	20	F	0:54	27
16	MAR	29	F	3:31	27
17	APR	6	F	1:33	25
18	APR	7	F	1:11	25
19	APR	8	F	6:25	25
20	APR	9	F	0:25	25

2007(1G7) Contd.

21	APR	14	F	3:06	25
22	APR	15	F	2:49	25
23	APR	21	F	0:33	9
24	APR	22	S	14:17	3
25	APR	27	F	3:14	25
26	APR	28	F	10:37	25
27	MAY	3	F	10:02	25
28	MAY	4	F	1:14	13
29	MAY	5	F	2:02	25
30	MAY	6	F	3:09	27
31	MAY	8	F	0:11	9
33	MAY	9	F	0:20	27
34	MAY	10	F	0:17	27
35	MAY	14	F	1:20	27
36	MAY	18	F	2:39	9
37	MAY	20	F	2:42	27
38	MAY	22	F	5:01	9
39	MAY	24	S	36:37:00	3
40	MAY	25	F	1:53	27
41	JUN	1	F	3:23	2
42	JUN	9	F	2:10	27
43	JUN	25	F	6:28	9
44	JUN	30	F	4:58	13
45	AUG	11	F	900:19:00	27
46	AUG	13	F	0:57	27
47	AUG	17	F	11:38	27
48	AUG	18	F	1:06	27
49	AUG	19	F	6:13	12
50	SEP	3	F	15:46	27
51	SEP	6	F	0:42	27
52	SEP	18	F	10:04	27
53	SEP	19	S	25:39:00	12
54	SEP	26	F	5:06	20
55	SEP	29	F	3:54	20
56	OCT	1	F	4:42	9
57	OCT	31	F	0:24	13
58	NOV	9	F	1:48	9
59	NOV	18	F	5:53	27
60	NOV	21	F	0:15	27
61	DEC	2	F	1:39	2
62	DEC	4	F	2:35	2
63	DEC	5	F	8:25	2
64	DEC	18	F	11:06	6
65	DEC	26	F	1:20	27
66	DEC	27	F	0:43	27

2006 (1G8)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	23	F	2950:42:00	25
2	JAN	28	F	20:20	13
3	FEB	2	S	14:08	16
4	SEP	5	F	5168:41:00	25
5	SEP	6	S	20:02	5
6	SEP	9	F	1:25	5
7	SEP	18	F	1:38	27
8	SEP	19	F	1:07	25
9	OCT	8	S	317:30:00	27
10	OCT	9	F	0:16	6
11	OCT	10	F	1:03	6
12	OCT	11	F	0:06	6
13	OCT	15	F	27:39:00	5
14	OCT	31	F	1:04	13
15	NOV	3	F	5:05	27
16	NOV	4	F	11:41	25
17	NOV	15	S	263:33.00	25
18	NOV	18	F	4:07	27
19	NOV	21	F	1:07	13
20	NOV	28	F	7:51	27
21	NOV	29	F	7:54	25
22	DEC	2	F	2:29	2
23	DEC	4	F	2:55	2
24	DEC	5	F	1:13	27
25	DEC	6	F	14:09	6
26	DEC	18	F	12:21	6
27	DEC	26	F	1:42	27
28	DEC	27	F	0:12	27

2007 (1G7)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	27	F	4:29	2
2	FEB	2	F	7:48	13
3	FEB	7	F	1:19	27
4	FEB	10	S	7:37	3
5	FEB	15	S	3:07	3
6	FEB	16	S	7:13	5
7	FEB	29	S	9:06	13
8	MAR	3	F	12:03	27
9	MAR	4	F	8:06	5
10	MAR	14	S	11:37	27
11	MAR	15	F	1:53	27
12	MAR	16	F	1:19	27

2007 (1G7) Contd.

13	MAR	18	F	1:51	8
14	MAR	19	F	3:37	27
15	MAR	27	F	1:53	27
16	MAR	28	F	1:32	27
17	MAR	31	F	1.48	27
18	APR	1	F	1:53	27
19	APR	3	F	1:48	27
20	APR	7	F	5:37	2
21	APR	7	F	1:31	8
22	APR	11	F	0:39	27
23	JUN	1	F	0:54	27
24	JUN	5	S	8:39	3
25	JUN	21	S	4:21	5
26	JUL	9	S	2:25	9
27	JUL	12	F	5:09	17
28	JUL	20	F	6:15	12
29	JUL	25	F	3:08	9
30	AUG	21	F	7:29	4
31	AUG	22	F	2.06	27
32	SEP	6	F	1:16	9
33	SEP	7	F	2:06	27
34	SEP	30	F	3:55	27
35	DEC	7	F	1853:20:00	4

2007 (1G8)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	19	F	4:37	12
2	JAN	27	F	1:41	2
3	FEB	2	F	0:22	13
4	FEB	7	F	1:10	27
5	FEB	13	F	1:32	27
6	MAR	2	F	2:27	27
7	MAR	4	F	4:17	27
8	MAR	14	S	11:01	3
9	MAR	15	F	6:28	27
10	MAR	16	F	0:57	27
11	MAR	17	F	1:24	25
12	MAR	18	F	0:46	27
13	MAR	27	F	1:53	27
14	MAR	28	F	1:32	27
15	MAR	31	F	0:44	27
16	APR	1	F	0:57	27
17	APR	3	F	1:18	27
18	APR	7	F	1:09	6
19	APR	7	F	1:04	27

2006 (411G2) Contd.

28	SEP	8	F	18:56	9
29	SEP	11	F	28:02:00	9
30	NOV	9	F	2:45	9
31	NOV	10	F	3:24	9
32	NOV	20	F	1:32	9

2007 (411G1)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	4	F	2:46	27
2	JAN	18	F	2:42	24
3	JAN	22	F	79:10:00	20
4	JAN	25	F	7:26	16
5	JAN	25	F	0:22	24
6	JAN	27	F	1:14	27
7	FEB	2	F	2:38	16
8	FEB	11	F	0:55	24
9	FEB	12	F	0:43	24
10	FEB	19	F	0:51	24
11	MAR	4	F	0:52	24
12	MAR	21	F	7:15	3
13	MAR	25	F	1:37	24
14	APR	13	F	0:09	27
15	APR	19	F	2:06	8
16	APR	21	F	3:49	8
17	APR	30	F	1:00	24
18	JUN	24	F	0:52	25
19	JUN	29	F	0:38	24
20	JUN	30	F	2:33	24
21	JUL	1	F	3:21	24
22	JUL	2	F	2:51	24
23	JUL	5	F	2:20	6
24	JUL	10	F	2:49	6
25	AUG	6	F	0:43	10
26	SEP	7	F	1:10	25
27	SEP	11	F	0:39	25

2007 (411G2)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	25	F	0:30	6
2	FEB	26	F	1:38	9
3	MAR	25	F	1:54	9
4	APR	1	F	5:36	27
5	MAY	14	F	55:37:00	9
6	MAY	18	F	1:15	9
7	MAY	27	F	6:04	3
8	AUG	22	F	0:39	9

2007 (411G2) Contd.

9	AUG	31	F	0:34	9
10	SEP	6	F	0:39	20
11	SEP	24	F	4:19	9
12	SEP	24	F	0:26	25
13	SEP	29	F	3:20	13
14	OCT	23	F	3:16	13
15	NOV	1	S	2:23	3
16	NOV	8	F	1:39	9
17	NOV	9	F	6:04	9
18	NOV	11	F	2:23	27
19	DEC	12	F	1:41	9
20	DEC	16	F	4:09	6

2008 (411G1)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	3	F	3:06	6
2	JAN	4	F	7:48	6
3	JAN	29	S	145:18:00	5
4	JAN	30	F	3:04	9
5	JAN	31	F	1:29	9
6	FEB	1	F	6:25	9
7	FEB	2	F	1:57	27
8	FEB	4	F	6:26	9
9	FEB	5	F	0:26	27
10	FEB	12	F	5:02	9
11	FEB	22	F	2:59	16
12	JUN	20	F	0:25	9
13	JUN	24	F	0:42	13
14	JUL	14	F	2:44	20
15	AUG	20	F	0:34	6
16	SEP	1	F	0:40	9
17	SEP	24	F	0:11	6
18	OCT	3	F	0:34	25
19	OCT	29	F	2:10	20
20	NOV	6	F	19:13	20
21	NOV	18	F	3:04	27
22	NOV	21	F	0:22	27
23	DEC	10	F	0:13	27

2008 (411G2)

S/NO.	MONTH	DAY	OUTAGE TYPE	DURATION	CAUSE CODE
1	JAN	2	F	0:15	20
2	JAN	30	F	0:45	21
3	FEB	1	F	1:22	6
4	MAR	25	F	2:32	9

APPENDIX D

Failure Event Record

UNIT ____________ REPORT DATE ____________

		EVENT DATES								OPERATIONAL INFORMATION			PARTIAL OUTAGE DATA	
		START				END								
EVENT CAUSE CODE	EVENT TYPE	MONTH	DAY	HOUR	MINUTE	MONTH	DAY	HOUR	MINUTE	HOURS WAITING	MAN HOURS WORKED ON PRIMARY CAUSE	MAN HOURS WORKED ON MAJOR EQUIPMENT	AVAILABLE CAPACITY BEFORE OUTAGE	REDUCTION FROM MAVAILABLE CAPACITY
14 15 16	17	18 19	20 21	22 23 24	25	26 27	28 29	30 31	32 33	34 35 36 37	38 39 40 41 42	43 44 45 46 47	48 49 50 51	52 53 54 55

MENT

LEM

Catastrophic		Degraded		Incipient	

RE MODE

Seizure		Erratic output		Wont release		severe vibration	
Short-to-ground		Rupture		Spurious operation			

ER OF DETECTION

Alarm		Testing		Prevention Maint.	
Inspection		Abnormal Indication			

RE APPEARANCE

RE MECHANISM

Pitting		Electrical treeing		Corrosion		Wearing	
Oveaheating		Erosion		Fatigue			

EDIATE ACTIVITY PHASE

(a) Unit States			(b) System Repairs	
Normal Operation			Repair	
Start-up			Replacement	
On-line			Inspection	
Shut-down			Surveillance	
Off-line			Betterment	
			Preventive Repairs	
			Preventive Replace	
			Preventive Insp.	

EPITATING FACTOR(S)

NTRIBUTING ACTIVITY PHASE(S)

(a) Units States			(b) System Phases	
System Operation			Repairs	
Plant Operation			Replacement	
Start-up			Installation	
On-line			Betterment	
Shutdown			Surveillance Test	
			Investigation	
			Engineering	
			Manufacturing	
			Training	
			Admin and Policy	
			Inspection	

NTRIBUTING FACTOR(S)

Normal Aging		Random Failure		Systematic		Human Factor	

FFECT(S)

DISPOSITION

APPENDIX C

MATLAB CODE

```
format short g
SOH1 = [0,0,0,145.18,257.49];
SOH2 = [0,0,8.27,0,737.41];
FOH1 = [402.67,56.78,126.38,69.66,59.35];
FOH2 = [3695.63,121.60,95.15,66.40,62.43];
NFO1 = [22,15,27,22,19];
NFO2 = [20,32,19,15,7];
H = 8760;
numOfYears = 5;
disp('SHIRORO UNIT RESULTS')
disp(' ')
for num = 1:numOfYears
  SH1(num) = H - ( FOH1(num) + SOH1(num) ) ;
  SH2(num) = H - ( FOH2(num) + SOH2(num) ) ;


 SOR1(num) = (SOH1(num) / H) * 100;
 SOR2(num) = (SOH2(num) / H) * 100;


 FOR1(num) = (FOH1(num) / H) * 100;
 FOR2(num) = (FOH2(num) / H) * 100;


 MTTR1(num) = FOH1(num) / NFO1(num);
 MTTR2(num) = FOH2(num) / NFO2(num);


 MTTF1(num) = SH1(num) / NFO1(num);
 MTTF2(num) = SH2(num) / NFO2(num);


 MTBF1(num) = MTTF1(num) + MTTR1(num);
 MTBF2(num) = MTTF2(num) + MTTR2(num);
```

```
LH1(num) = 1 / MTTF1(num);

LH2(num) = 1 / MTTF2(num);


mH1(num) = 1 / MTTR1(num);

mH2(num) = 1 / MTTR2(num);


A1(num) = mH1(num) / ( mH1(num) + LH1(num) );

A2(num) = mH2(num) / ( mH2(num) + LH2(num) );


U1(num) = 1 - A1(num);

U2(num) = 1 - A2(num);


  if (num == 1)

  disp('Results for 2005 4HG1')

  disp('SOH   FOH      SH        NFO      SOR%  FOR%      MTTR     MTTF      MTBF  LH       mH        A      U')

  result11 =
[SOH1(num),FOH1(num),SH1(num),NFO1(num),SOR1(num),FOR1(num),MTTR1(num),MTTF1(num),MTBF1(num),LH1(num),mH1(num),A
1(num),U1(num)];

  disp(num2str(result11,'%11.4g'))



  disp('Results for 2005 4HG2')

  disp('SOH   FOH      SH        NFO      SOR%  FOR%      MTTR     MTTF      MTBF  LH       mH        A      U')

  result12 =
[SOH2(num),FOH2(num),SH2(num),NFO2(num),SOR2(num),FOR2(num),MTTR2(num),MTTF2(num),MTBF2(num),LH2(num),mH2(num),A
2(num),U2(num)];

  disp(num2str(result12,'%11.4g'))

  disp(' ')

  end


  if (num == 2)

  disp('Results for 2006 4HG1')

  disp('SOH   FOH      SH        NFO      SOR%  FOR%      MTTR     MTTF      MTBF  LH       mH        A      U')
```

```
    result21 =
[SOH1(num),FOH1(num),SH1(num),NFO1(num),SOR1(num),FOR1(num),MTTR1(num),MTTF1(num),MTBF1(num),LH1(num),mH1(num),A
1(num),U1(num)];

    disp(num2str(result21,'%11.4g'))



    disp('Results for 2006 4HG2')

    disp('SOH   FOH      SH       NFO      SOR%  FOR%     MTTR     MTTF     MTBF  LH      mH       A     U')

    result22 =
[SOH2(num),FOH2(num),SH2(num),NFO2(num),SOR2(num),FOR2(num),MTTR2(num),MTTF2(num),MTBF2(num),LH2(num),mH2(num),A
2(num),U2(num)];

    disp(num2str(result22,'%11.4g'))

    disp(' ')

    end



    if (num == 3)

    disp('Results for 2007 4HG1')

    disp('SOH   FOH      SH       NFO      SOR%  FOR%     MTTR     MTTF     MTBF  LH      mH       A     U')

    result31 =
[SOH1(num),FOH1(num),SH1(num),NFO1(num),SOR1(num),FOR1(num),MTTR1(num),MTTF1(num),MTBF1(num),LH1(num),mH1(num),A
1(num),U1(num)];

    disp(num2str(result31,'%11.4g'))



    disp('Results for 2007 4HG2')

    disp('SOH   FOH      SH       NFO      SOR%  FOR%     MTTR     MTTF     MTBF  LH      mH       A     U')

    result32 =
[SOH2(num),FOH2(num),SH2(num),NFO2(num),SOR2(num),FOR2(num),MTTR2(num),MTTF2(num),MTBF2(num),LH2(num),mH2(num),A
2(num),U2(num)];

    disp(num2str(result32,'%11.4g'))

    disp(' ')

    end



    if (num == 4)

    disp('Results for 2008 4HG1')

    disp('SOH   FOH      SH       NFO      SOR%  FOR%     MTTR     MTTF     MTBF  LH      mH       A     U')
```

```
    result41 =
[SOH1(num),FOH1(num),SH1(num),NFO1(num),SOR1(num),FOR1(num),MTTR1(num),MTTF1(num),MTBF1(num),LH1(num),mH1(num),A
1(num),U1(num)];

     disp(num2str(result41,'%11.4g'));



     disp('Results for 2008 4(KT2)')

     disp('SOH   FOH      SH       NFO      SOR%  FOR%     MTTR     MTTF     MTBF  LH      mH       A      U')

     result42 =
[SOH2(num),FOH2(num),SH2(num),NFO2(num),SOR2(num),FOR2(num),MTTR2(num),MTTF2(num),MTBF2(num),LH2(num),mH2(num),A
2(num),U2(num)];

     disp(num2str(result42,'%11.4g'))

     disp(' ')

     end

  if (num == 5)

      disp('Results for 2009 4(KT1)')

      disp('SOH   FOH      SH       NFO      SOR%  FOR%     MTTR     MTTF     MTBF  LH      mH       A      U')

      result51 =
[SOH1(num),FOH1(num),SH1(num),NFO1(num),SOR1(num),FOR1(num),MTTR1(num),MTTF1(num),MTBF1(num),LH1(num),mH1(num),A
1(num), U1(num)];

       disp(num2str(result51,'%11.4g'))



       disp('Results for 2009 4(KT2)')

       disp('SOH   FOH      SH       NFO      SOR%  FOR%     MTTR     MTTF     MTBF  LH      mH       A      U')

       result52 =
[SOH2(num),FOH2(num),SH2(num),NFO2(num),SOR2(num),FOR2(num),MTTR2(num),MTTF2(num),MTBF2(num),LH2(num),mH2(num),A
2(num),U2(num)];

        disp(num2str(result52,'%11.4g'))

        disp(' ')

        end

   end
```