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Evaluating the Reliability and Availability of Kaligandaki "A" Hydropower Station (144MW) using a Markov-Based Approach.

by

Binod Prashad Pandey

A THESIS

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Binod Prashad Pandey

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ABSTRACT

The Kaligandaki "A" Hydropower Station plays a vital role in meeting the growing energy demands of Western Nepal. As hydropower stations are critical infrastructure assets, ensuring their reliability and availability is of utmost importance. This thesis presents a comprehensive evaluation of the reliability and availability of the Kaligandaki "A" Hydropower Station using a Markov model which is conducted by collecting the daily operational and maintenance data for the period of FY 2016/17 to FY 2022/23. The primary indicators of reliability indices such as failure rate (λ), repair rate (μ), MTTR, MTBF, and MTTF were obtained by collecting and analysing data. Operational data for each unit on an annual basis were obtained from the hydropower station. Once all the data had been organized, the different types of failures for each unit were categorized, considering the various sub-units and systems involved. Based on this classification, Markov states are established. The failure rate and repair rate for each state are determined using the categorized data. Finally, availability and reliability are calculated based on their respective definitions. The reliability scores of the units ranged from 0.952622 to 0.999762, while the availability scores ranged from 0.568571 to 0.894388. The data analysis conducted from fiscal year 2016/17 to fiscal year 2022/23 indicates that the station exhibits a high level of reliability, with a majority of instances exceeding 99%. Additionally, the station demonstrates a strong availability rate, surpassing 98% during the same period.

Keywords: Reliability, Availability, Repair Rate, Failure Rate, Markov model

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LIST OF ABBREVIATIONS

MW	: Mega Watt
KM	: Kilo Meter
GoN	: Government of Nepal
MoEWRI	: Ministry of Energy, Water Resources and Irrigation
NEA	: Nepal Electricity Authority
GD	: Generation Directorate
KGAHPS	: Kaligandaki "A" Hydropower Station
WECS	: Water and Energy Commission Secretariat
kWh	: Kilo Watt hour
MWh	: Mega Watt hour
GWh	: Giga Watt hour
IPP	: Independent Power Producer
INPS	: Integrated Nepal Power System
IOE	: Institute of Engineering.
NEA	: Nepal Electricity Authority
kW	: Kilo Watt
μ	: Repair rate
λ	: Failure rate
A	: Availability
U	: Unavailability
R	: Reliability
Q	: Unreliability
MTTR	: Mean Time to Repair
MTTF	: Mean Time to Failure
MTBF	: Mean Time between Failures

FOH	: Forced Outage Hours
SH	: Service Hours
TuOH	: Turbine and Auxiliaries Outage Hours
GvOH	: Governor System Outage Hours.
GOH	: Generator and Auxiliaries Outage Hours
CBOH	: Unit Circuit Breaker Outage Hours
EOH	: Excitation System Outage Hours
GIS	: Gas Insulated Switchgear
SwOH	: GIS and Switchyard Outage Hours.
EfOH	: External Factor Outage Hours
LDC	: Load Dispatch Centre
FTA	: Fault Tree Analysis

CHAPTER ONE: INTRODUCTION

1.1 Background

The Kaligandaki "A" Hydropower Station (144MW), a second largest hydropower station currently in operation of Nepal, is a significant infrastructure asset in Nepal, contributing to the country's energy production and socio-economic development. Located on the Kaligandaki River in western Nepal, the hydropower station harnesses the potential energy of water to generate electricity.

Nepal, a landlocked country with abundant water resources, heavily relies on hydropower as a primary source of energy. Hydropower stations like Kaligandaki "A" play a vital role in meeting the increasing energy demands of the country's growing population and expanding industries. The reliable and continuous operation of such hydropower systems is crucial to ensure a stable power supply and support economic growth.

Reliability and availability are key aspects of hydropower systems. Reliability refers to the ability of the system to perform its intended function without failures, while availability refers to the readiness of the system to operate when needed. Evaluating the reliability and availability of hydropower stations is essential for understanding their performance characteristics, identifying potential failure points, and formulating effective maintenance strategies.

Markov models provide a powerful analytical framework for studying the reliability and availability of complex systems. Markov models analyze the system's state transitions over time, considering factors such as component failures, repairs, and maintenance activities. By applying a Markov model to the Kaligandaki "A" Hydropower Station, it becomes possible to quantify the system's reliability and availability, assess the impact of different maintenance strategies, and optimize the overall system performance.

Understanding the reliability and availability of the Kaligandaki "A" Hydropower Station through a Markov model analysis can provide valuable insights for hydropower operators, maintenance engineers, and policymakers. It enables informed decision-making regarding maintenance planning, resource allocation, and risk management, leading to enhanced operational efficiency, reduced downtime, and improved performance of the hydropower station.

This thesis aims to conduct a comprehensive evaluation of the reliability and availability of the Kaligandaki "A" Hydropower Station using a Markov model. By studying the system's state transitions, analysing relevant data, and considering various maintenance strategies, this research seeks to contribute to the understanding and optimization of hydropower system reliability and availability assessment.

1.2 Statement of Problem

Kaligandaki 'A' Hydropower Station, located at Beltari, Syangja is the second largest hydropower station operating in Nepal with installed capacity of 144 MW with 3 units each having capacity of 48 MW. It is a six-hour peaking run-of-river type hydropower station having annual design generation of 842 GWh and was commissioned in 2002. When compared to the central & western region, the mid-western part of Nepal has a no any large-scale hydropower stations (more than 30 MW), which makes it difficult for the Nepal Electricity Authority (NEA) to cope with up with the growing load demand there. It is essential to ensure the availability of the Kaligandaki Hydropower station as much as achievable in order to fulfil the increasing need for electricity in this region, as well as to properly balance the voltage level and ensure the stability of the grid.

The Nepal Electricity Authority has begun trading electricity on the competitive markets in India and Bangladesh. In this context, evaluating the availability and reliability of major hydropower stations becomes crucial. Such evaluations serve an important role in assessing the performance, ability, and weaknesses of each unit. This analysis facilitates planning and determining the appropriate schedules for periodic maintenance, minimal replacement, or repairs in the event of failure, thus avoiding penalties, if any.

1.3 Objective of Study

1.3.1 Main Objective

The main objective of this study is to conduct Reliability and Availability Analysis of Kaligandaki “A” Hydropower Station.

1.3.2 Specific Objectives

i. To evaluate essential parameters, including repair rate, failure rate, MTTR, MTTF, and MTBF, in order to determine each unit's availability and reliability.
ii. To estimate the loss of sales of electricity due to the unplanned breakdown of units.
iii. To develop a fault tree structure of unit failure in the station.

1.4 Scope and Limitations of Study

The scope of this thesis on the Evaluating the Reliability and Availability of Kaligandaki "A" Hydropower Station (144MW) using a Markov-Based Approach is defined as follows:

i. The thesis employs a Markov model as the analytical framework for assessing reliability and availability.
ii. It covers data collection for parameter estimation and model validation. The daily operational data and other relevant data associated with the Kaligandaki "A" Hydropower Station for the last 7 Fiscal Years.
iii. The evaluation explores the Kaligandaki "A" Hydropower Station's components, subsystems, and interconnections. Assessment of reliability and availability for the main components and their impact on system performance.
iv. It covers the fault tree analysis for a failure of unit in the station based on historical operational data.

Despite the comprehensive approach taken in this thesis, there are certain limitations that should be acknowledged as below:

i. The availability of accurate and comprehensive data for parameter estimation and validation may pose a challenge. The thesis relies on the availability and quality of data provided by the Kaligandaki "A" Hydropower Station management and other relevant sources.
ii. The Markov model used in this thesis assumes certain simplifying assumptions to make the analysis feasible. These assumptions may not fully capture the complex dynamics of the hydropower system and its real-world operation.
iii. This study's outcomes and recommendations apply mainly to the Kaligandaki "A" Hydropower Station. Each hydropower station's unique characteristics, operational conditions, and data availability must be addressed for reliable applicability.
iv. The thesis focuses on hydropower station internal reliability and availability. This research does not address external issues like natural disasters, regulatory changes, or grid instability that may affect reliability and availability.

1.5 Organization of Study

This thesis consists of five chapters, which are illustrated, in following order.

Chapter One includes introduction topic with Background, Statement of Problem, Objectives of Study and Scope and Limitations of Study.

Chapter Two provides a brief summary of the various literatures consulted in the course of this thesis work, including but not limited to a review of the literature on maintenance practises in hydropower stations, evaluations of reliability and availability using analytical methods, and a fault tree analysis of hydropower stations.

Chapter Three explains about the methodology taken to carry out the thesis work.

Chapter Four provides an overview of the findings and the reasoning behind them alongside tables and figures.

Chapter Five provides the study's final findings and any necessary recommendations to the relevant authority.

The abstract and list of acknowledgements can be found at the beginning, while the references and appendices can be found at the end of the thesis.

CHAPTER TWO: LITERATURE REVIEW

2.1 Current Energy Scenario of Nepal

Nepal, a sovereign country located in South Asia, is geographically landlocked and has an estimated population of approximately 30 million people. The country possesses an abundance of natural resources, including water, forests, and minerals. However, it has encountered challenges in fulfilling the energy demands of its growing population. At present, traditional biomass holds a dominant position in Nepal's energy mix; however, this source is known to be environmentally harmful and inefficient. However, substantial efforts have been made in recent years to develop modern, sustainable energy sources. In recent years, notable endeavours have been undertaken to enhance the energy sector of the nation and enhance the availability of contemporary and sustainable energy sources (WECS, 2022).

Nepal's energy sector is confronted with a significant obstacle in the form of its geographical landscape. The nation holds some of the planet's loftiest peaks and most challenging landscapes, rendering the conveyance of energy resources arduous and costly. Furthermore, a significant portion of Nepal's population resides in geographically isolated rural regions, which pose challenges in terms of accessibility and infrastructure development.

At present, the primary source of electricity generation in Nepal is hydropower. The nation possesses a substantial quantity of rivers and waterfalls, thereby presenting ample prospects for the advancement of hydropower. As per the doctoral research conducted by Dr. Hari Man Shrestha, Nepal exhibits a considerable capacity to produce hydropower of up to 83,000 megawatts. However, the current state of development of this potential remains significantly inadequate. As of July 2023, the aggregate installed capacity of hydropower in Nepal was approximately 2533 MW. Apart from hydropower, Nepal possesses substantial prospects for alternative renewable energy sources, including solar and wind. Nepal's geography is highly conducive to the utilisation of solar energy owing to its ample exposure to sunlight throughout the year. The present installed capacity of solar power projects is approximately 83.52 megawatts (Nepal Electricity Authority).

Although there have been advancements in the development of Nepal's energy sector, there are still noteworthy obstacles that need to be addressed. The exorbitant expenses associated with energy infrastructure development, particularly in remote regions, constitute a major obstacle to the expansion of modern energy sources. Furthermore, there is a notable dependence on conventional biomass for the purposes of cooking and heating, thereby resulting in deforestation and indoor air pollution.

According to the fiscal year 2023/24 budget speech, Nepal's installed capacity will reach 3600 MW by year's end. The aforementioned objective will be realised by means of executing hydropower projects owned by NEA's subsidiary companies as well as the integration of solar and hydropower plants developed by Independent Power Producers (IPP) (Ministry of Finance Government of Nepal, 2023).

In conclusion, hydropower and solar energy development in Nepal are progressing swiftly. Despite major hurdles, the government's ambitious plans and commitment to expanding the utilisation of modern energy sources give reason for confidence about the country's energy future.

2.2 Reliability and Availability Analysis

Reliability and availability analysis plays a crucial role in assessing the performance and effectiveness of complex systems, such as hydropower stations. By evaluating the reliability and availability of a system, engineers and operators can identify potential failure points, optimize maintenance strategies, and improve overall system performance. In the context of the Kaligandaki "A" Hydropower Station, reliability and availability analysis using a Markov model provides a quantitative approach to assess these important system characteristics.

2.2.1 Terminology

i. **Reliability:** "the probability that a device or system will perform its intended function adequately for the intended period of time under the intended operating conditions" (Majeed & Sadiq, 2006).

ii. **Availability:** "the proportion of time that is in or available for service over the long term" (Majeed & Sadiq, 2006).

iii. **Energy not generated:** "the quantity of energy lost as a result of a malfunction."

iv. **Forced outage:** "An outage is caused by emergency conditions that are directly linked to a component or unit, necessitating the immediate removal of the unit from service, either automatically or as soon as switching operations can be carried out" (Majeed & Sadiq, 2006).

v. **Scheduled outage:** "A scheduled outage is a deliberate removal of a unit from service at a predetermined time, typically for the purposes of construction, preventive maintenance, repair, or reserve" (Majeed & Sadiq, 2006).

vi. **Failure:** The term "failure" refers to the event in which an asset is unable to perform its intended function adequately under specified conditions (Smith, 2017).

vii. **Failure Rate:** It refers to the number of times a failure event occurs within a certain time frame. The time frame might be a day, a month, a year, or millions of hours (Smith, 2017).

viii. **Mean Time to Failure (MTTF):** It describes the amount of time the system lasts after installation under certain circumstances before experiencing its first breakdown (Smith, 2017).

ix. **Mean Time to Repair (MTTR):** It is the amount of time needed to put the system back online after it has had a failure (Smith, 2017).

x. **Mean Time between Failures (MTBF):** It is the amount of time, on average, that passes between occurrences of a failure in the system. In terms of mathematics, this represents the addition of MTTF and MTTR (Smith, 2017).

2.2.2 Reliability Analysis:

Reliability analysis focuses on the ability of a system to perform its intended function without failures over a specified period. It involves analysing the behaviour of individual components and their impact on the overall system reliability. Key metrics used in reliability analysis include:

i. **System Reliability:** The probability that the system will perform its intended function without failure over a specified time period.

ii. **Component Reliability:** The probability that a specific component will perform its intended function without failure over a specified time period.

iii. **Mean Time to Failure (MTTF):** The average time between failures for a component or the entire system.

Reliability analysis involves estimating the failure rates of components, which can be determined from historical data, manufacturer specifications, or expert judgment. These failure rates are used to calculate the reliability metrics and assess the reliability performance of the system.

2.2.3 Availability Analysis:

Availability analysis focuses on the readiness of a system to operate when needed. It considers not only the occurrence of failures but also the time required to restore the system to a fully functional state after a failure. Key metrics used in availability analysis include:

i. **System Availability:** The probability that the system is available and ready to perform its intended function at any given time.

ii. **Component Availability:** The probability that a specific component is available and ready to perform its intended function at any given time.
iii. **Mean Time between Failures (MTBF):** The average time between consecutive failures for a component or the entire system.

Availability analysis takes into account not only the failure rates of components but also the repair times and maintenance activities. These factors are considered in the Markov model to calculate availability metrics and evaluate the availability performance of the system.

2.3 Markov Models in Reliability Analysis

Markov models are widely used in reliability analysis to assess the performance and behaviour of complex systems over time. They provide a powerful mathematical framework for studying the state transitions of a system, incorporating factors such as component failures, repairs, and maintenance activities. In the context of reliability analysis, Markov models are particularly useful for quantifying the reliability and availability of systems, including hydropower stations like the Kaligandaki "A" Hydropower Station.

Here are key aspects of using Markov models in reliability analysis:

i. **State Representation:** In a Markov model, the system's states represent the different conditions or states the system can be in. For reliability analysis, typical states can include "working," "failed," "under repair," or "under maintenance." These states capture the system's behaviour and provide a basis for analysing its reliability and availability.
ii. **State Transitions:** Markov models capture the transitions between different states based on certain probabilities. The transitions represent the movement of the system from one state to another. For example, a working component may transition to a failed state due to a failure event, and a failed component may transition to a repaired state after maintenance or repair activities. The probabilities of these transitions are influenced by factors such as failure rates, repair rates, and maintenance schedules.
iii. **Transition Probabilities:** Transition probabilities determine the likelihood of moving from one state to another. In reliability analysis, these probabilities are often estimated based on component failure rates, repair rates, and maintenance activities. The reliability and availability of the system depend on accurately estimating these transition probabilities.
iv. **Markov Chain:** The sequence of state transitions forms a Markov chain, which is a mathematical representation of the system's behaviour. Markov chains have the property of memorylessness, meaning that the future behaviour of the system depends only on its current state and not on its past history. This property simplifies the analysis and calculations involved in the Markov model.

v. **Model Equations and Analysis:** The Markov model is defined by a set of equations that describe the probabilities of transitioning between states. These equations can be formulated as a set of linear equations or differential equations, depending on the specific characteristics of the system. Solving these equations allows for the determination of steady-state probabilities, which represent the long-term behaviour of the system.

vi. **Reliability and Availability Measures:** By analysing the steady-state probabilities derived from the Markov model, various reliability and availability measures can be calculated. These measures include system reliability, component reliability, mean time to failure (MTTF), system availability, component availability, mean time between failures (MTBF), and other relevant metrics. These measures provide quantitative assessments of the system's reliability and availability performance.

Markov models in reliability analysis offer a systematic and quantitative approach to assess the reliability and availability of complex systems like hydropower stations. By applying these models to the Kaligandaki "A" Hydropower Station, the research aims to gain insights into the system's behaviour, identify critical components, and recommend the potential enhancement in operation of plant.

2.3.1 Hydro Unit Model

To create a model of a hydroelectric unit based on its typical operational mode. The phenomenon under consideration may be categorised into two distinct states, namely the up-state and the down-state. The diagram representing the state-space is presented below (Majeed & Sadiq, 2006).

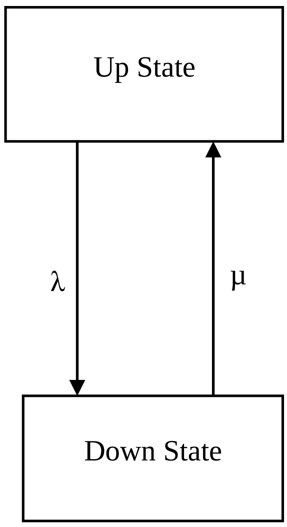


Figure 2.1: Two-State Markov Model *(Majeed & Sadiq, 2006)*

It is said that a unit is in the "up-state" when it is either actively serving its purpose or is prepared to do so. It moves from the "up-state" to the "down-state" as a result of forced or scheduled outages. A forced outage is the unplanned closure of a generating unit as a result of emergency circumstances or an unexpected malfunction, which makes the generating unit unavailable for load. This kind of outage is also known as an unplanned outage. On the other hand, the intended shutdown of a unit that generates electricity for the purpose of inspection or maintenance in accordance with a predefined timetable is what is meant by the term "scheduled outage" (Dash & Das, 2014). Figure 2.1 shows the two state Markov model defining Upstate and Down State only.

Due to either forced or scheduled outages, the hydro-unit transit from upstate to downstate. We make the following assumptions in order to derive the Markov model of a Hydro-unit (Majeed & Sadiq, 2006):

i. The rates of failure and repair follow an exponential distribution.
ii. There is no transition between scheduled and forced outages. The unit is immediately returning to upstate following repair.

The Markov model that has been developed, referred to as the three-state Markov model, is depicted in Figure 2.2. This model is an extension of the two-state model, as it integrates distinct scheduled and forced outages, and defines the down state as a separate state within the system (Majeed & Sadiq, 2006).

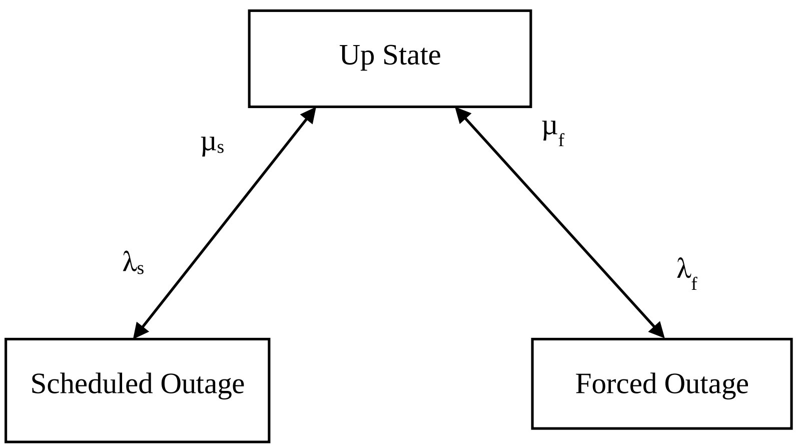


Figure 2.2: Three State Markov Model *(Majeed & Sadiq, 2006)*

This three state Markov model has been widely utilized by various researchers, as evident in studies such as (Sahu & Barve, 2013) on the reliability and availability evaluation of PATHRI & CHILLA Hydro Power Station in India, (Sapkota, Bajracharya, & Luintel, 2014) for reliability and availability evaluation of Sunkoshi Hydropower Station, (Majeed & Sadiq, 2006) for the availability and reliability evaluation of Dokan Hydro Power Station, (Dash & Das, 2014) for the availability assessment of generating units of Balimela Hydro Electric Power Station (510 MW), and (Minaye & Hailu, 2016) for the reliability, availability, and performance evaluation of Gilgel Gibe I and Gilgel Gibe II Hydro Power Stations. These studies have successfully employed the model to identify major faults that impact the reliability indices of each unit.

According to (Sahu & Barve, 2013) research, the reliability and availability of PHPS were measured at 0.942681 and 0.97012, respectively. On the other hand, the same was found for CHPS, and it was found to be 0.951120 and 0.960530. According to the findings of this study, the components responsible for Pathri Hydropower Station's low levels of reliability and availability were the Main unit transformer and the Turbine for Unit No. 2, and the Turbine and Governor system for Unit No. 3, whereas the problems at the Chilla hydropower station were due to issues with the turbine system.

Similar research was conducted for Sunkoshi Hydropower Station (Sapkota, Bajracharya, & Luintel, 2014). Where they have discovered over 99% reliability for each unit and availability ranging from 72% to 99%. Lack of water and Trashrack cleaning appeared to be the most common scheduled disruptions.

(Majeed & Sadiq, 2006) Carried out a study for the Dokan Hydropower Station, and their findings indicated that the system's reliability and availability were, respectively, 0.926358 and 0.991977. They identified the key unit flaws as an overheating thrust bearing in Unit no. 2, a defective left-hand servomotor and an operational ring in Turbine unit no. 1, and an overheating turbine bearing in Turbine unit no. 4.

(Dash & Das, 2014) Conducted research that was very similar for the Balimela Hydro Electric Power Station, which has 510 MW of capacity. They discovered that the units' availability ranged from 21% to above 99%, while the reliability of the units ranged from 31% to above 99%. The overheating of the thrust bearing as well as a few minor problems with the excitation system and the governing system were the causes of the low reliability and availability of the units.

Researchers, including (Minaye & Hailu, 2016), have conducted reliability analyses using both analytical methods and Monte Carlo simulation. They compared the results obtained from these approaches and concluded that both methods are applicable in the reliability analysis of hydraulic units. It is worth noting that these studies have utilized various modelling approaches, but the common terms employed throughout their analyses are failure rate, repair rate, Forced outage rate, MTTR, MTTF, MTBF.

2.4 Network modeling and reliability evaluation

A system is usually depicted as a network, in which the various components of the system are linked to one another in either series, parallel, or a meshed configuration, or in any combination of these (Billinton & Allan , 1992).

2.4.1 Series system

From the perspective of reliability, a collection of components is considered to exist in series if just one of them must fail for the system to fail or all of them must function for the system to succeed. Take into account a system that consists of two independent components A and B linked in series, each of which has a reliability of R_A and R_B, respectively. Thus, reliability of system success R_S=R_A*R_B.

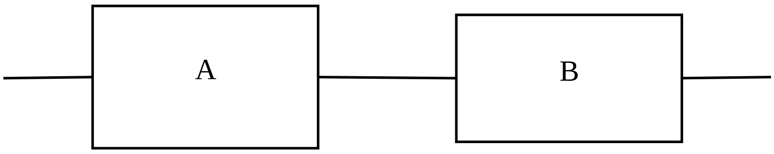


Figure 2.3: Two Component Series System (Billinton & Allan , 1992)

2.4.2 Parallel system

From the point of view of reliability, a group of components is said to be in parallel if only one must function for the system to succeed or all must fail for the system to fail. As illustrated in Figure 2.5, the system consists of two independent components A and B that are linked in parallel. The probabilities of success (or reliability) of each component are R_A and R_B, whereas the probabilities of failure are Q_A and Q_B. Then probability of system failure, Q_s, unreliability, is thus,

Q_S=Q_A*Q_B and reliability of system R_S=1-Q_S.

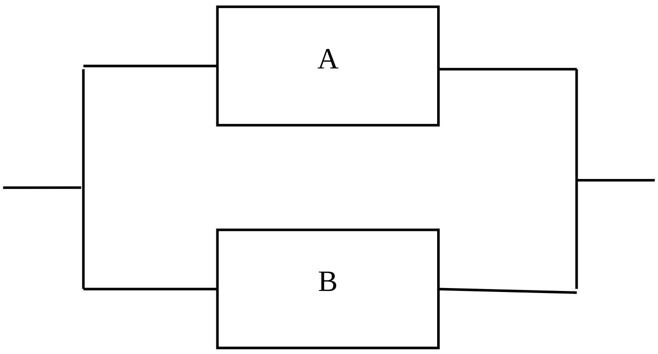


Figure 2.4: Two Component Parallel System *(Billinton & Allan , 1992)*

2.4.3 Series parallel system

If a complex system has both series and parallel systems, then it is a series and parallel system. By merging the proper parallel and series branches of the reliability model, the complex configuration is successively reduced until only one equivalent element is left. Thus, the reliability (or unreliability) of the initial setup is represented by this comparable element. A (network) reduction method is the term used to describe the approach used to solve such complex systems.

2.4.4 Partially redundant system

There may be some partly redundant components in a system, therefore the extreme scenarios of a series system (non-redundant) and a parallel system (fully redundant) may not be relevant. Series and parallel system approaches cannot be employed directly in a partly redundant system. However, any sequence with partial redundancy may be assessed using the notions of binomial distribution.

2.4.5 Standby redundant system

One or more branches of the redundant components might not be constantly operational, but instead remain in a dormant mode under normal operating conditions; that is, they are only activated when a routinely operating component fails. In Figure 2.6, A is in normal operation and B is only activated when A cannot operate for whatever reason. As the function of switch, S, there are two conceptions for the standby component: flawless switching and defective switching. In faultless switching, the normal operating position to standby position transition of switch S is flawless. When A fails, however, the switch S has a chance of failing to transition from the branch containing component A to the branch containing component B.

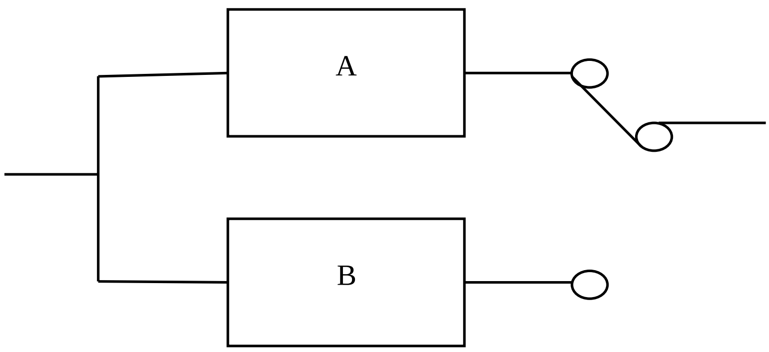


Figure 2.5: Standby Redundant System *(Billinton & Allan , 1992)*

2.5 Fault Tree Analysis

Fault Tree Analysis, often known as FTA, is a method that is both systematic and graphical, and it is used to investigate and evaluate the possible reasons why a system fails. It gives an organised way to discover and understand the combinations of events or situations that might lead to a certain undesirable event or system failure. This can be very helpful in preventing or mitigating these types of problems. Evaluation of the reliability and security of complex systems is a common application for FTA, which is used extensively in many different sectors, including engineering, safety, and risk assessment. The following is an outline of the most important aspects and procedures involved in Fault Tree Analysis.

2.5.1 Basic Concepts

i. **Top Event:** The undesired event or system failure that is the focus of the analysis.
ii. **Primary Events:** Basic events or conditions that contribute to the occurrence of the top event.
iii. **Gates:** Logical operators (AND, OR) used to combine events and represent the relationships between them.
iv. **Intermediate Events:** Events that result from the combination of primary events or other intermediate events.
v. **Cut Sets:** Sets of events that, when occurring together, lead to the occurrence of the top event.

2.5.2 Constructing the Fault Tree

i. **Identify the top event:** Define the specific failure or undesired event to be analysed.
ii. **Identify the primary events:** Determine the contributing events or conditions that can lead to the top event.
iii. **Define the logical relationships:** Use gates (AND, OR) to represent the relationships between events.
iv. **Construct the fault tree diagram:** Visualize the relationships and hierarchy of events using graphical symbols.

2.5.3 Interpretation and Mitigation

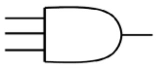
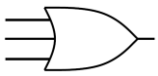
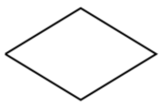
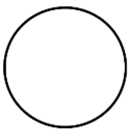
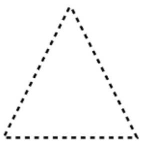
i. **Interpret the results:** Analyze the fault tree analysis results to understand the critical events, weak points, and potential failure paths within the system.
ii. **Identify vulnerabilities:** Identify the events or combinations of events that contribute most significantly to the top event probability. These events represent the critical vulnerabilities within the system.

iii. **Develop mitigation strategies:** Based on the identified vulnerabilities, develop and prioritize strategies to mitigate the risks, enhance system reliability, and prevent the occurrence of the top event.

Fault Tree Analysis provides a systematic and structured approach to assess the causes and probabilities of system failures. It helps engineers and analysts identify critical failure paths, prioritize risk mitigation efforts, and make informed decisions to enhance system reliability and safety. FTA is often used in conjunction with other reliability analysis techniques to provide a comprehensive assessment of system performance.

2.5.4 Symbols Used in FTA

Table 2.1: Common Symbols used in Fault Tree Analysis *(Cavallaro, 1992)*

Symbol	Function
AND Gate 	All inputs necessary to generate the output event.
OR Gate 	Any single input event that can trigger an output event.
Rectangle 	A malfunction that is the outcome of a collection of fault events that have occurred via the logic gates.
Diamond 	A fault occurrence for which the reasons are unknown.
Circle 	A basic fault events. This consists of component defects for which the frequency and mode of failure are known.
Triangle 	A suppressed tree. The tree is detailed in another figure.

CHAPTER THREE: METHODOLOGY

The methodology of this thesis on the Evaluating the Reliability and Availability of Kaligandaki "A" Hydropower Station (144MW) using a Markov-Based Approach involves the following key steps:

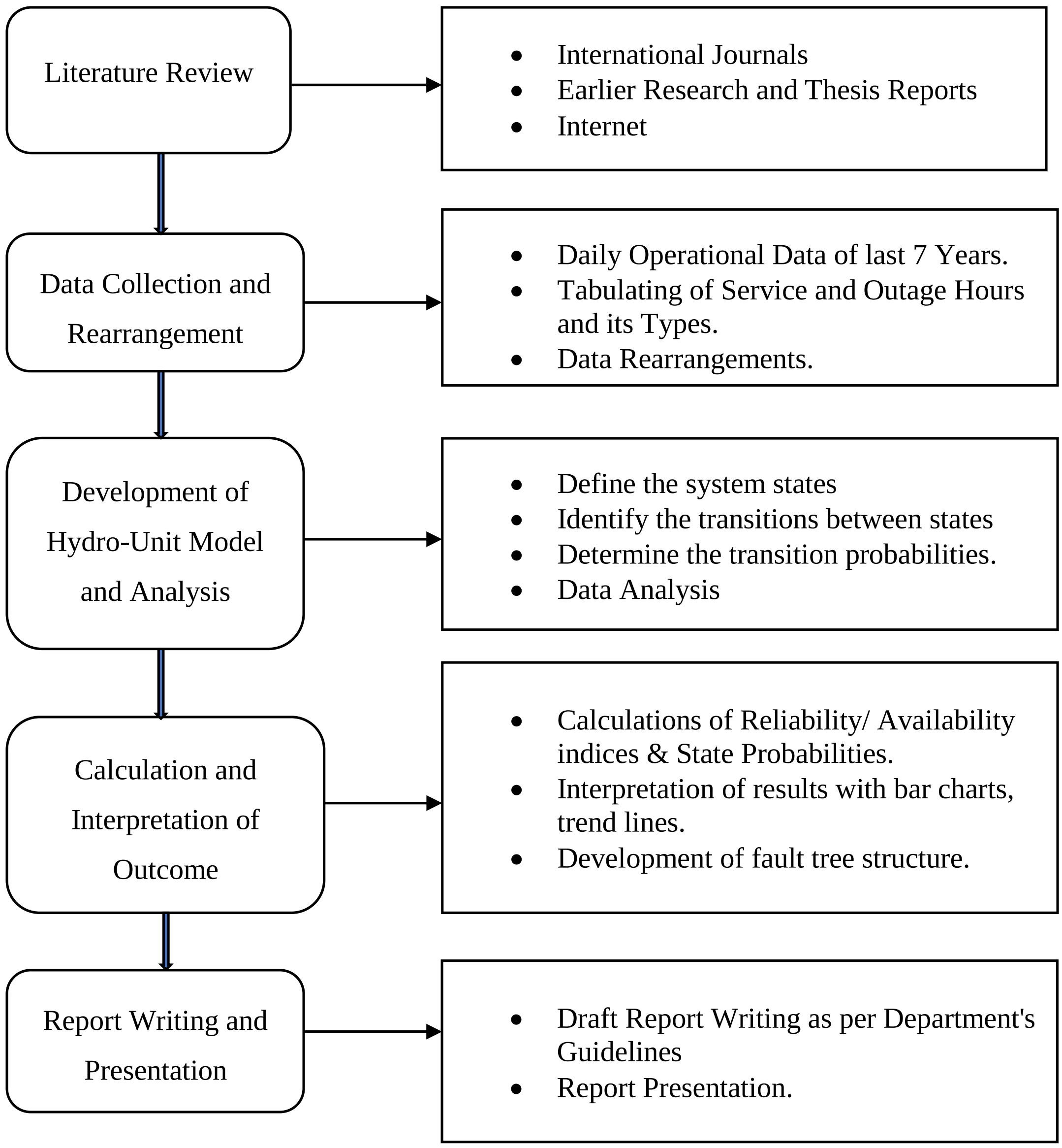


Figure 3.1: Research Methodology Chart

3.1 Literature Review

An exhaustive assessment of the relevant literature, research papers, and technical reports on the reliability and availability evaluation of hydropower systems, Markov models, and maintenance techniques was the first stage in the process of carrying out this research work.

This review was the first step. This assisted in both the establishment of a robust theoretical framework and the identification of current knowledge gaps in the area.

3.2 Data Collection

The next phase was to collect relevant data for the Kaligandaki "A" Hydropower Station. This included gathering historical operation and maintenance records, data on failures and repairs, data on maintenance schedules, and any other information that was important. This data serves as the basis for parameter estimation, model development, and validation.

3.3 Development of Hydro-Unit Model and Analysis

In the three state Markov Model these Hydro-unit forced outages and their down states, as discussed in literature review, are further classified into the following categories:

i. **Scheduled outage** (Desander Flushing, Intake Backwash, High Flooding, Lack of Water, Unit Overhauling, Plant Shutdown for Tunnel inspection, System Outage, LDC Instruction/Reserved)
ii. **Turbine and Auxiliaries** (Main Inlet Valve, Balancing pipe, Draft tube, Bottom Ring, Head Cover, Guide Bearing, Guide Vane, Runner, Guide vane shear pin, shaft seal)
iii. **Governor System** (Proportionate Valve, Hydraulic Oil Lines, Oil Pumping Unit)
iv. **Generator and Auxiliaries** (Rotor, Stator, Stator Cooling system)
v. **Unit Circuit Breaker** (Main unit circuit breaker & protection panel)
vi. **Excitation System** (AVR, Carbon Brush/Slip Ring)
vii. **GIS and Switchyard** (Gas Insulated switchgear, Unit Power Transformer, Transmission Line (132kV Circuit Breakers)).
viii. **External Factors.** (Unknown causes)

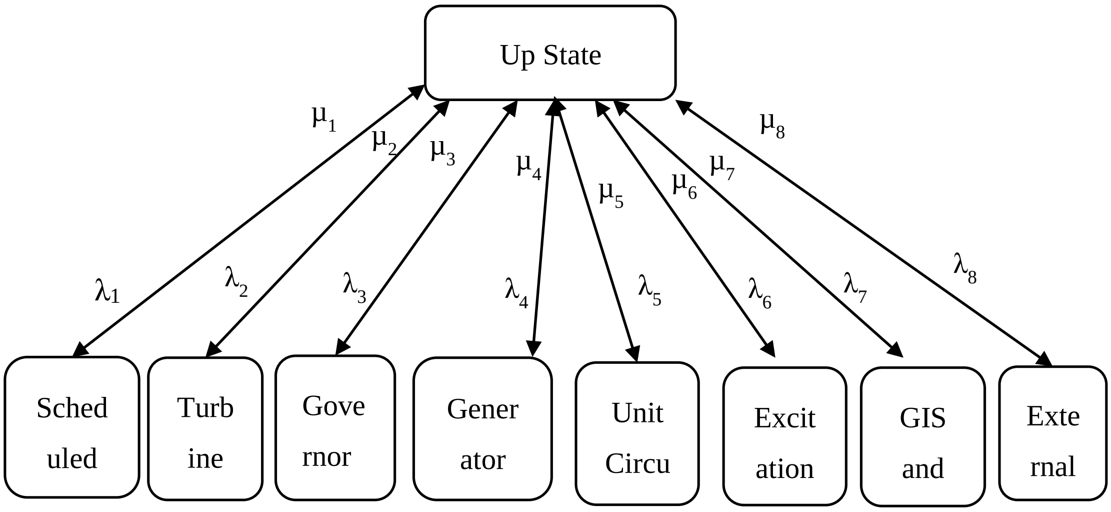


Figure 3.2: Developed Hydro-Unit Model (Dash & Das, 2014)

3.4 Calculation and Interpretation of Outcome:

From the developed Hydro-Unit model, the state probability of their components can be computed as follows:

Table 3.1 State Probability Value *(Dash & Das, 2014)*

State Number	**State Probability**	
0	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_0/D
1	$\lambda_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_1/D
2	$\mu_1\lambda_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_2/D
3	$\mu_1\mu_2\lambda_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_3/D
4	$\mu_1\mu_2\mu_3\lambda_4\mu_5\mu_6\mu_7\mu_8/D$	d_4/D
5	$\mu_1\mu_2\mu_3\mu_4\lambda_5\mu_6\mu_7\mu_8/D$	d_5/D
6	$\mu_1\mu_2\mu_3\mu_4\mu_5\lambda_6\mu_7\mu_8/D$	d_6/D
7	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\lambda_7\mu_8/D$	d_7/D
8	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\lambda_8/D$	d_8/D
Where, $D = d_0+d_1+d_2+d_3+d_4+d_5+d_6+d_7+d_8$		

Thus, reliability & availability indices can be calculated by adopting the approach by (Dash & Das, 2014) as follows.

- Mean time to repair, $MTTR = \frac{FOH}{N}$
- Mean time to failure, $MTTF = \frac{SH}{N}$
- Mean time between failures, $MTBF = MTTR + MTTF$
- Repair Rate, $\mu = \frac{1}{MTTR}$

- Failure Rate, $\lambda = \frac{1}{MTTF}$

Here,

- ✓ N represents the count of type of outages experienced by a unit.
- ✓ Forced outage hours (FOH) refer to the duration in hours for which a unit or significant equipment remained inoperable owing to an unexpected outage.
- ✓ SH stands for "service hours" or "running hours" which refers to the total number of hours that the unit was in fact operating with the breakers closed.

As per the definition of reliability, it can be defined as the probability of a unit to function without any failure. The two possible states that are considered to be without failure are denoted as 0 and 1. The availability of a unit refers to the probability that it is in state 0.

Thus, Reliability**,** $\mathbf{R = P_0 + P_1}$ and **Availability,** $\mathbf{A = P_0}$

After computing the unit and component wise reliability and availability of all studied fiscal years, the outcomes are interpreted and represented by relevant bar graphs, trend lines.

To determine the loss of electricity sales incurred by a utility as a result of forced outages in a particular unit, we collected data on the total number of forced outages experienced by the unit during each fiscal year. The system loss of the Integrated Nepal Power System (INPS) for the corresponding fiscal year was derived from the annual reports disseminated by the Nepal Electricity Authority (NEA). Likewise, the mean sales rate per unit was derived from the aforementioned report pertaining to the specified year. Ultimately, the quantification of sales decline was determined through the utilisation of the aforementioned data.

3.5 Report Writing and Presentation:

The final stage is report writing and presentation of the results of the evaluations of reliability and availability. Providing insights into the Kaligandaki "A" Hydropower Station's performance characteristics, critical components, and potential areas for improvement. Propose recommendations for maintenance strategies, decision-making processes, and optimisation approaches based on the findings of the research.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 State Probability Determination

Through the examination of operational data spanning seven years, from FY 2016/17 to FY 2022/23, the probabilities of various states within the Markov Model have been determined. These probabilities have been tabulated for each unit and year, alongside corresponding values for Mean Time to Repair (MTTR), Mean Time between Failures (MTBF), Mean Time to Failure (MTTF), Repair Rate, and Failure Rate.

Table 4.1: Determination of State Probability of Unit No. 2 FY 2017/18

State No.	Basic Event	No. of Occur	Total Repair Hrs	MTTR	MTTF	MTBF	Repair Rate	Failure Rate	State Prob
0	Up State								0.817262
1	Scheduled Outage (SOH)	109	1558.25	14.30	65.86	80.16	0.069950	0.015184	0.177396
2	Turbine (TuOH)	3	8.60	2.87	2392.94	2395.81	0.348837	0.000418	0.000979
4	Generator (GOH)	5	37.57	7.51	1435.77	1443.28	0.133097	0.000696	0.004277
7	GIS & Switchyard (SwOH)	1	0.75	0.75	7178.83	7179.58	1.333333	0.000139	0.000085

Table 4.1 represents the state probabilities of the different components of the unit no. 2 of a hydropower station in FY 2017/18.

The scheduled outage is seen predominant among all of the outage events particularly lack of water during dry season, LDC instruction during low demand on grid and unit overhauling time period.

The major forced outage events for down state of unit no. 2 in FY 2017/18 are Generator and Turbine related outages consisting 37.57 hours and 8.60 hours of repair time respectively other than scheduled outages.

The individual state probability of each component’s unit wise for all of the seven fiscal years has been computed accordingly.

4.2 Evaluation of Reliability and Availability of individual units.

As described in Methodology chapter, reliability is defined as the probability of a unit to function without failure. The two possible states that are considered to be without failure are denoted as 0 & 1. The availability of a unit refers to the probability that it is in state 0.

Thus, **Reliability, R = $P_0 + P_1$**

And **Availability, A = P_0**

Hence, reliability and availability of the unit no. 2 in FY 2017/18 are evaluated as,

Reliability of Unit No. 2 for FY 2017/18,

$R_2 = P_0 + P_1 = 0.817262 + 0.177396 = 0.994658$

Availability of Unit No. 2 for FY 2017/18,

$A_2 = P_0 = 0.817262$

Similarly, unit wise evaluation of reliability and availability of all three units and station is done for all seven years duration of the studied data which is illustrated as below.

Table 4.2: Service and Outage Hours Details FY 2016/17

	Unit No. 1	Unit No. 2	Unit No. 3	Total of Station
Service Hours	5943.85	7741.22	6570.08	20255.15
Scheduled Outage Hours	2720.00	1016.70	2185.73	5922.43
Forced Outage Hours	96.15	2.08	4.18	102.42
Total Observed Hours	8760.00	8760.00	8760.00	26280.00

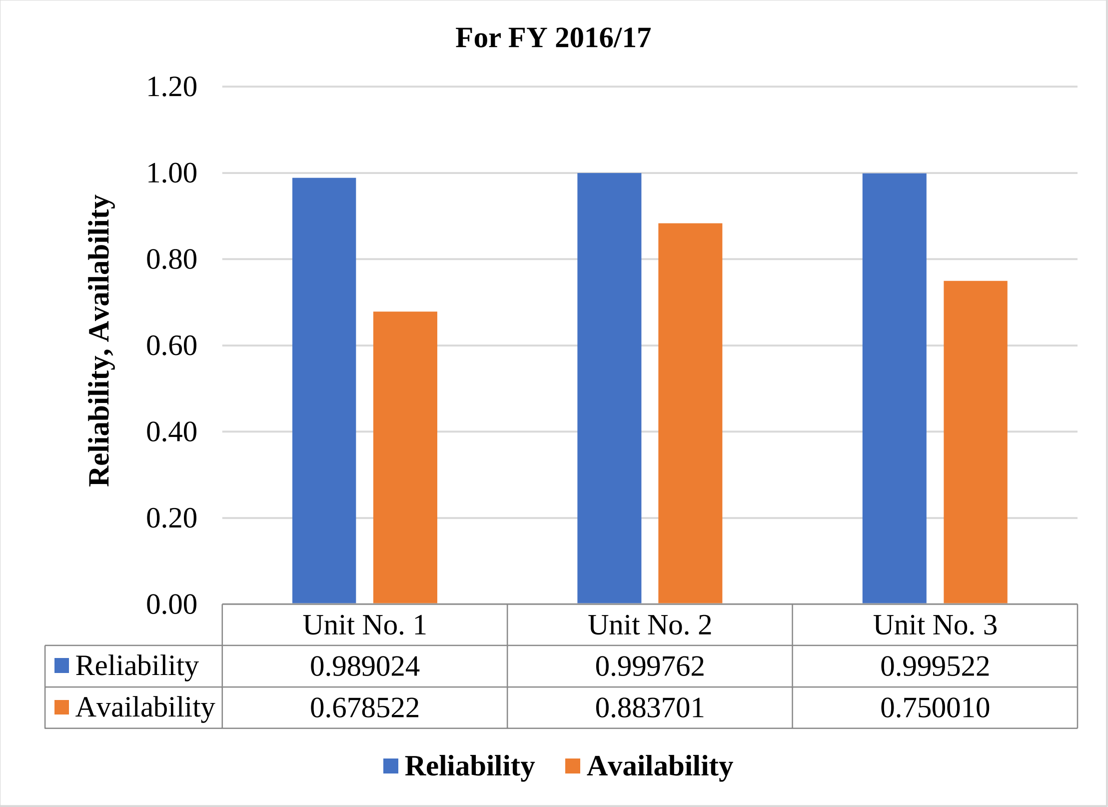
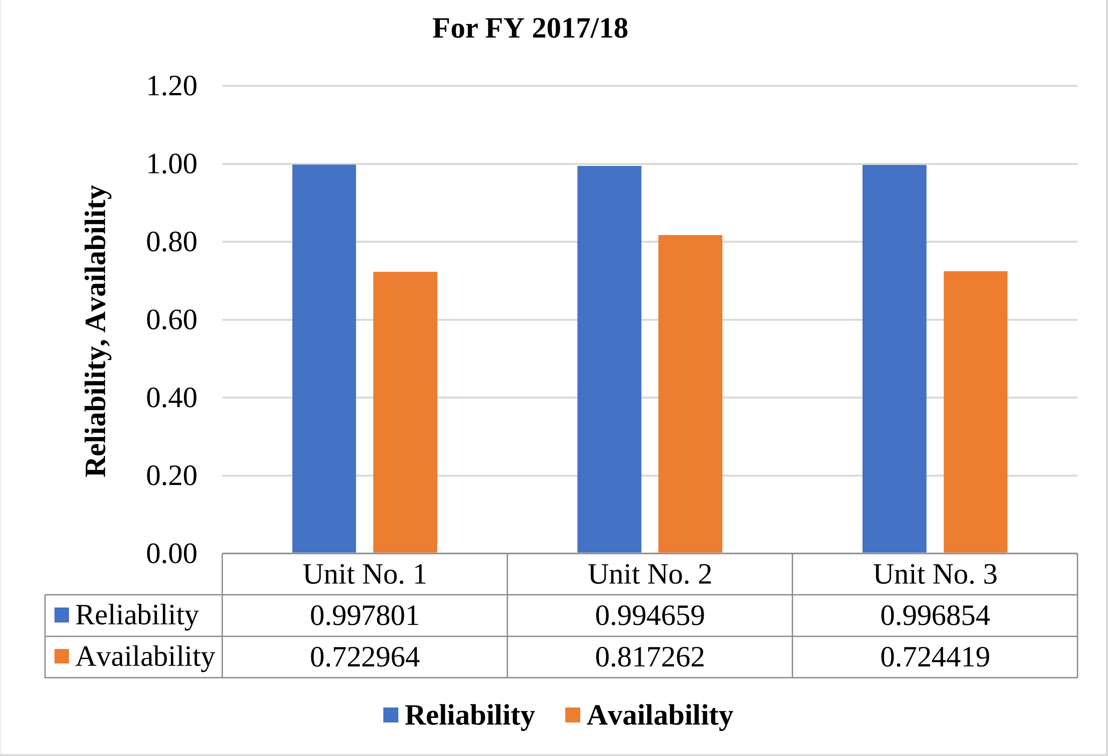


Figure 4.1: Unit wise Reliability and Availability for FY 2016/17

Table 4.2 and Figure 4.1 shows the details of running and outage hours and corresponding reliability and availability calculations for the FY 2016/17. Unit No. 1 had a reliability of 98.90% and an availability of 67.85%, indicating a high chance of operating without failure but with lower availability. Unit No. 2 demonstrated exceptional reliability at 99.98% and a good availability of 88.37%. Unit No. 3 showed a reliability of 99.95% but had a slightly lower availability of 75%.

Table 4.3: Service and Outage Hours Details FY 2017/18

	Unit No. 1	Unit No. 2	Unit No. 3	Total of Station
Service Hours	6350.52	7178.83	6363.30	19892.65
Scheduled Outage Hours	2414.17	1558.25	2393.07	6365.48
Forced Outage Hours	19.32	46.92	27.63	93.87
Total Observed Hours	8784.00	8784.00	8784.00	26352.00



	Unit No. 1	Unit No. 2	Unit No. 3
Reliability	0.997801	0.994659	0.996854
Availability	0.722964	0.817262	0.724419

Figure 4.2: Unit wise Reliability and Availability for FY 2017/18

In the fiscal year 2017/18, three units (Unit No. 1, Unit No. 2, and Unit No. 3) in a station were monitored for their operational performance. Unit No. 1 exhibited a high reliability of 99.78% but had a slightly lower availability of 72.30%. Unit No. 2 demonstrated a reliability of 99.47% and an availability of 81.73%. Unit No. 3 showcased a reliability of 99.69% with a similar availability of 72.44%.

Table 4.4: Service and Outage Hours Details FY 2018/19

	Unit No. 1	Unit No. 2	Unit No. 3	Total of Station
Service Hours	6499.90	6875.07	6664.45	20039.42
Scheduled Outage Hours	2235.82	1870.05	2083.58	6189.45
Forced Outage Hours	24.28	14.88	11.96	51.13
Total Observed Hours	8760.00	8760.00	8760.00	26280.00

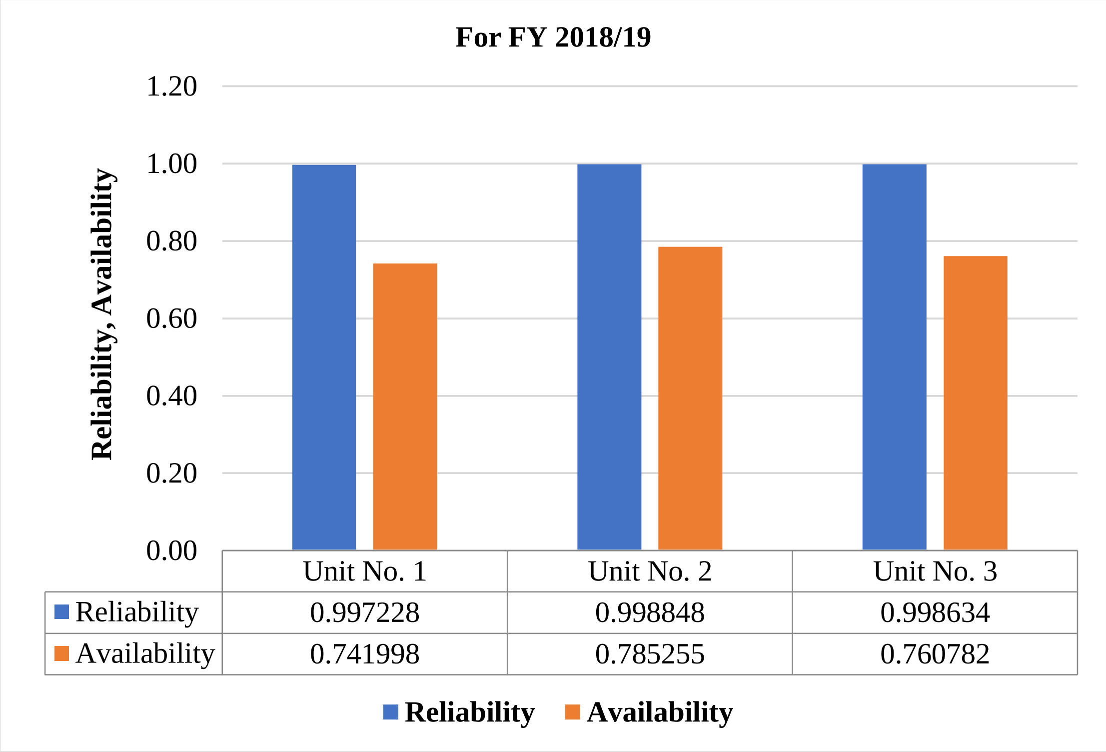


Figure 4.3: Unit wise Reliability and Availability for FY 2018/19

With reference to the data presented in Table 4.4 and Figure 4.3 for the fiscal year 2018/19, it can be observed that Unit No. 1 exhibited a reliability of 99.72% and an availability of 74.20%. These figures suggest that the unit is highly dependable and has a low probability of failure, albeit with a slightly reduced availability. The results of Unit No. 2's performance evaluation indicate a high level of reliability at 99.88% and good availability at 78.53%. Unit 3 exhibited a reliability rate of 99.86% along with an availability rate of 76.08% that is comparable.

Table 4.5: Service and Outage Hours Details FY 2019/20

	Unit No. 1	Unit No. 2	Unit No. 3	Total of Station
Service Hours	6539.93	7094.37	6492.62	20126.92
Scheduled Outage Hours	2199.60	1645.42	2247.85	6092.87
Forced Outage Hours	20.47	20.22	19.53	60.22
Total Observed Hours	8760.00	8760.00	8760.00	26280.00

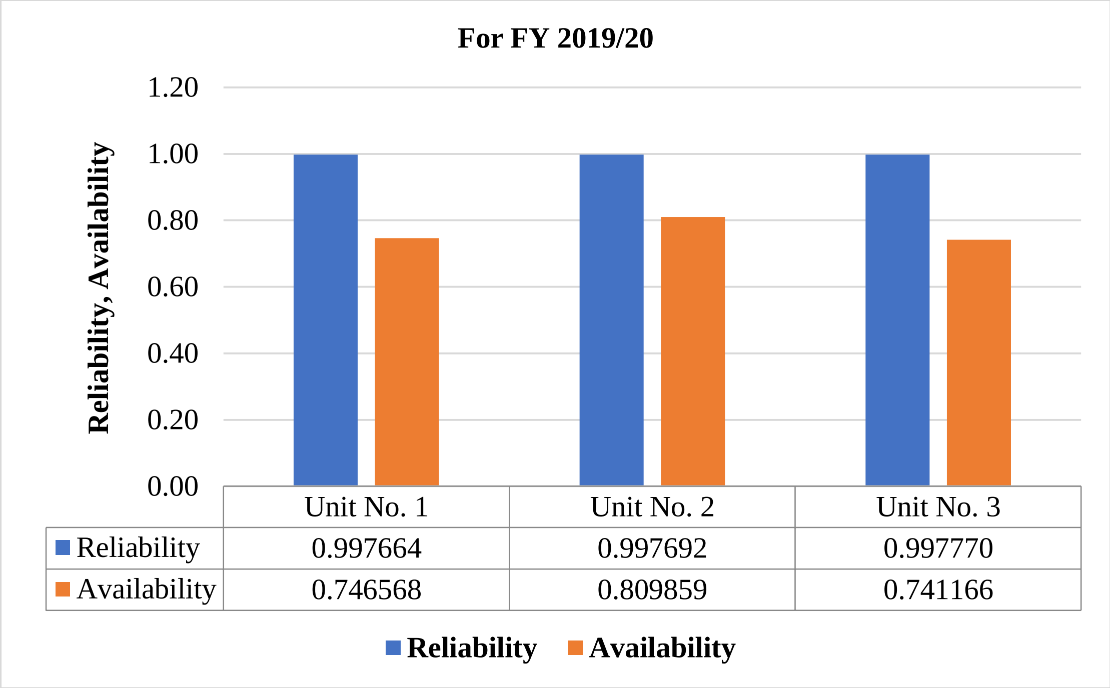


Figure 4.4: Unit wise Reliability and Availability for FY 2019/20

During fiscal year 2019/20, the operational success of three units (Unit No. 1, Unit No. 2, and Unit No. 3) in a station was tracked. Unit No. 1 had a reliability of 99.77% and an availability of 74.67%, which means it was very likely to work without any problems. Unit No. 2 had a reliability of 99.77% and an availability of 80.99%, which shows that it was very reliable and was available well. Unit No. 3 had a 99.78% reliability and a similar 74.12% availability.

Table 4.6: Service and Outage Hours Details FY 2020/21

	Unit No. 1	**Unit No. 2**	**Unit No. 3**	**Total of Station**
Service Hours	7036.28	4980.68	6872.82	18889.78
Scheduled Outage Hours	1706.10	3740.95	1854.87	7301.92
Forced Outage Hours	17.62	38.37	32.32	88.30
Total Observed Hours	8760.00	8760.00	8760.00	26280.00

Table 4.6 and Figure 4.5 show that Unit No. 1 had a reliability of 99.80% and an availability of 80.32% in the fiscal year 2020–21. This means that it was likely to work without problems and that it was available most of the time. Unit No. 2 had a reliability of 99.56%, but its availability was only 56.86%. Unit No. 3 had a reliability of 99.63% and an availability of 78.46%.

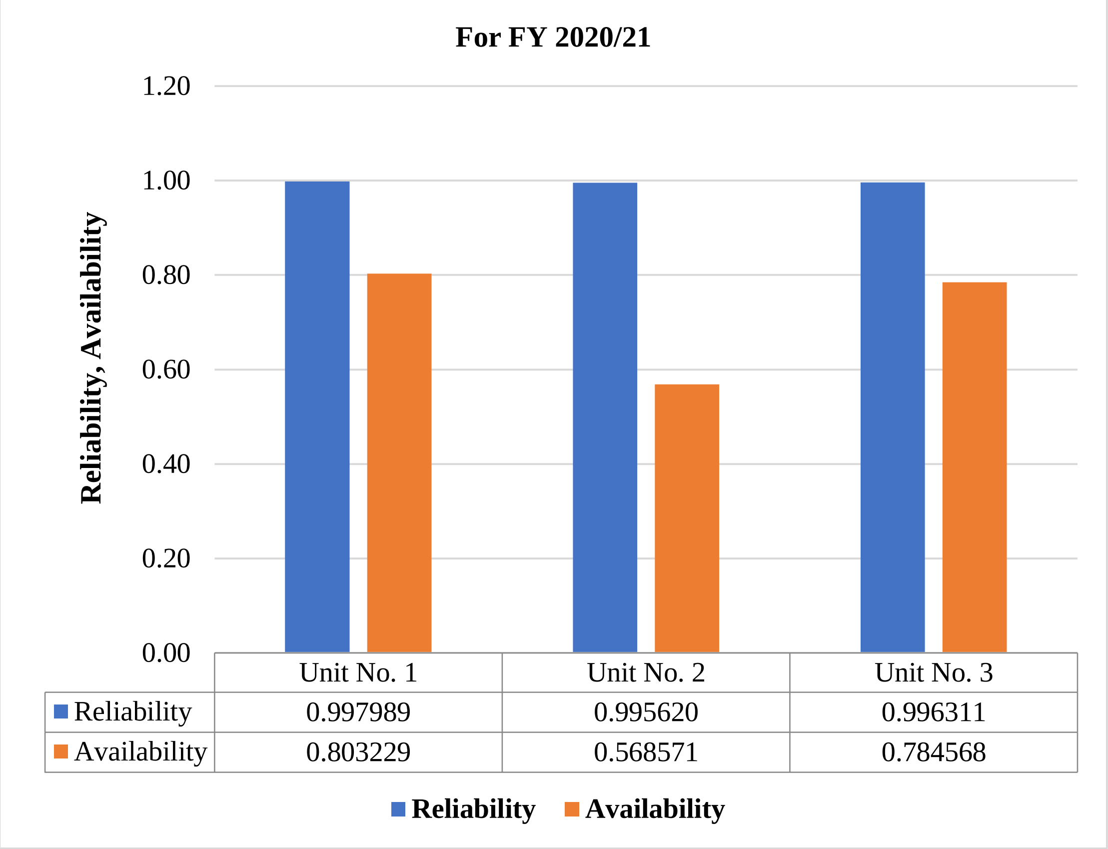


Figure 4.5: Unit wise Reliability and Availability for FY 2020/21

Table 4.7: Service and Outage Hours Details FY 2021/22

	Unit No. 1	**Unit No. 2**	**Unit No. 3**	**Total of Station**
Service Hours	7629.22	7856.30	6767.23	22252.75
Scheduled Outage Hours	1119.40	918.18	2013.35	4050.93
Forced Outage Hours	35.38	9.52	3.42	48.32
Total Observed Hours	8784.00	8784.00	8784.00	26352.00

Referring to table 4.7 and figure 4.6 for fiscal year 2021/22, Unit No. 1 exhibited a reliability of 99.60 percent and an availability of 86.85 percent, indicating a high likelihood of operating without failure and a relatively good availability. The reliability of Unit No. 2 was 99.89% and its availability was 89.44%. The reliability of Unit No. 3 was 99.96%, but its availability was only 77.04 percent.

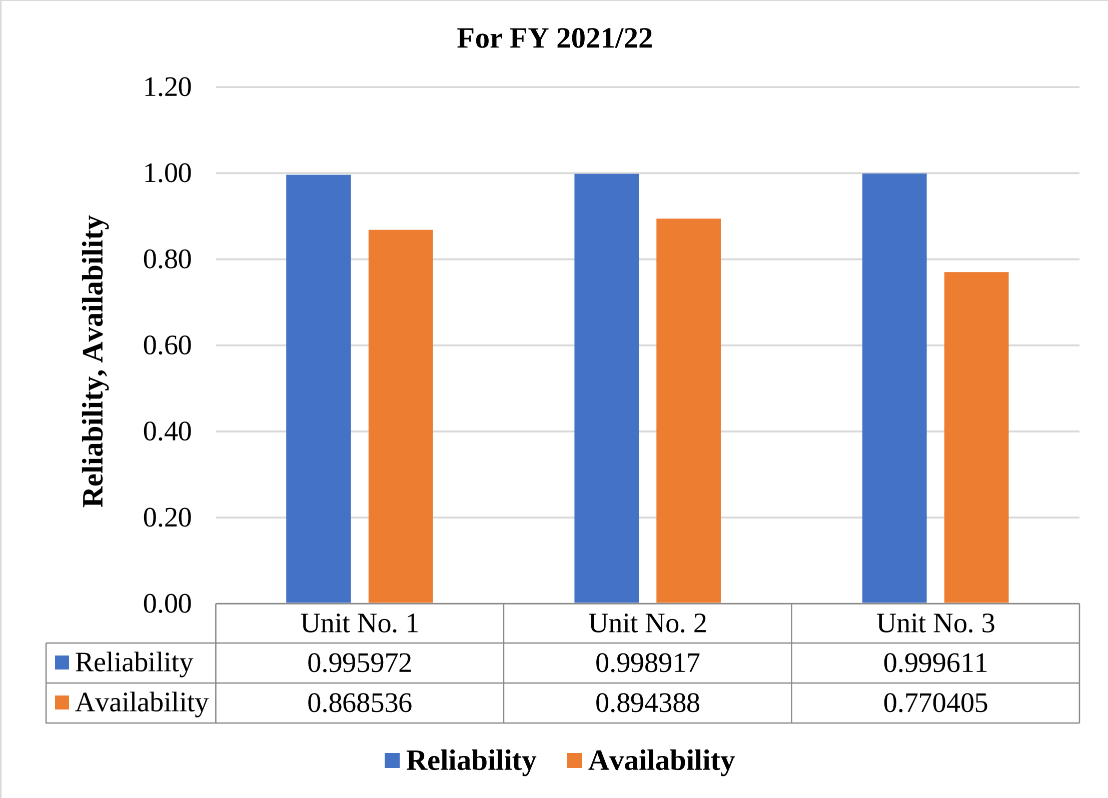


Figure 4.6: Unit wise Reliability and Availability for FY 2021/22

Table 4.8: Service and Outage Hours Details FY 2022/23

	Unit No. 1	**Unit No. 2**	**Unit No. 3**	**Total of Station**
Service Hours	6326.37	6973.92	6112.03	19412.32
Scheduled Outage Hours	2018.60	1721.40	2599.53	6339.53
Forced Outage Hours	415.03	64.68	48.43	528.15
Total Observed Hours	8760.00	8760.00	8760.00	26280.00

During fiscal year 2022/23, the operating performance of three units (Unit No. 1, Unit No. 2, and Unit No. 3) of a station was monitored. With a rate of 99.94%, Unit No. 3 demonstrated outstanding reliability, suggesting a very low likelihood of failure throughout the defined time period. Its availability was 69.77%, implying that it was operational for roughly 69.77% of the hours recorded. Unit No. 2 demonstrated 99.27% reliability and 79.62% availability, indicating a relatively high possibility of reliable operation with a high availability rate. Unit No. 1 had a low score of 95.26% reliability as it has been put into forced breakdown due to the problem in Stator Coils of generator. It was available in this FY for 72.21% of time.

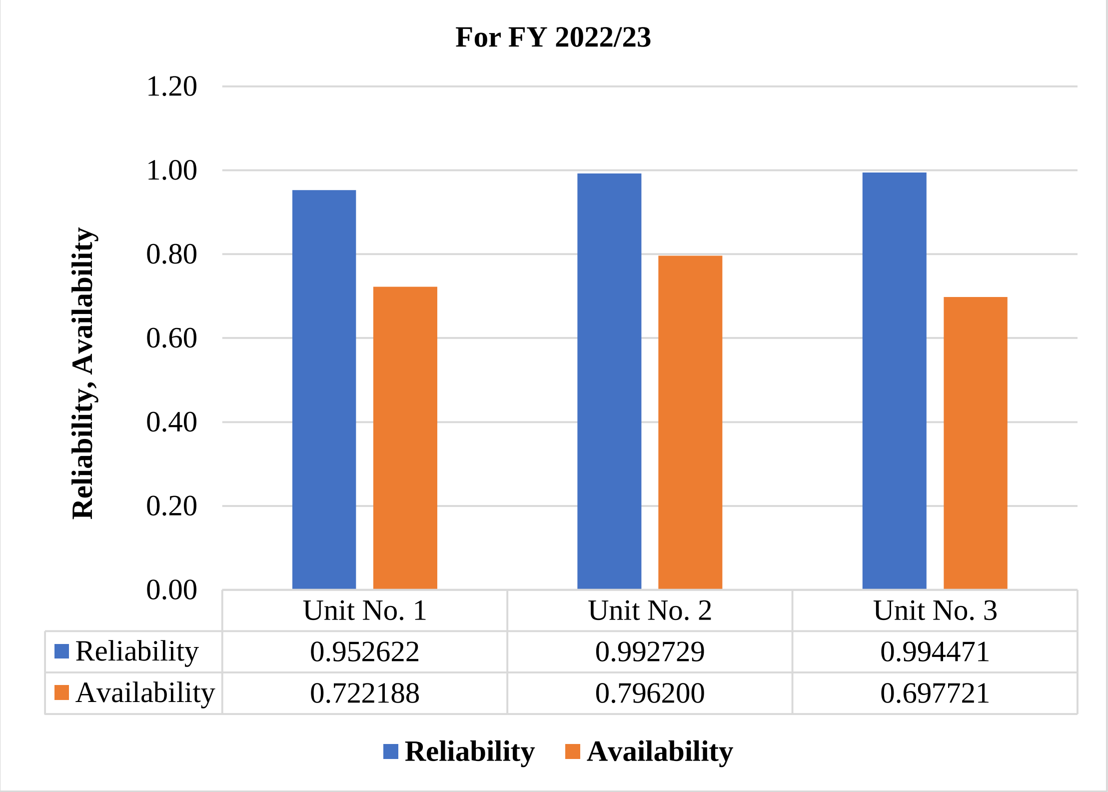


Figure 4-7: Unit wise Reliability and Availability for FY 2022/23

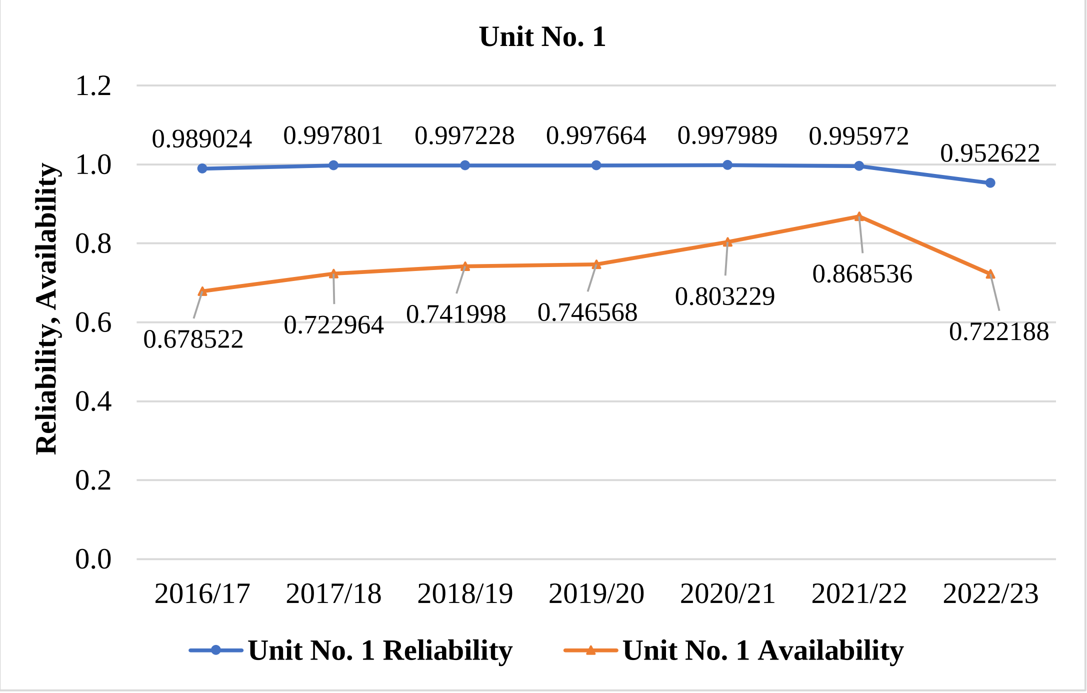


Figure 4.8: Trend line of Reliability and Availability for Unit No. 1 for 7 FY's

The graphical representation in Figure 4.8 illustrates the Trend Line model showcasing the Reliability and Availability of Unit No. 1. The data reveals that the Unit exhibited a reliability rate of 98.90% during the fiscal year 2016/17. This rate experienced an upward trend, reaching 99.7% in the fiscal year 2019/20. However, it experienced a decline in the fiscal year 2022/23, recording a reliability rate of 95.26%, which was the lowest observed during the specified period. The decrease in reliability score can be attributed to the significant occurrence of breakdown outages experienced by the unit. The unit's availability fluctuated between 67.85% in the fiscal year 2016/17 and 86.85% in the fiscal year 2021/22.

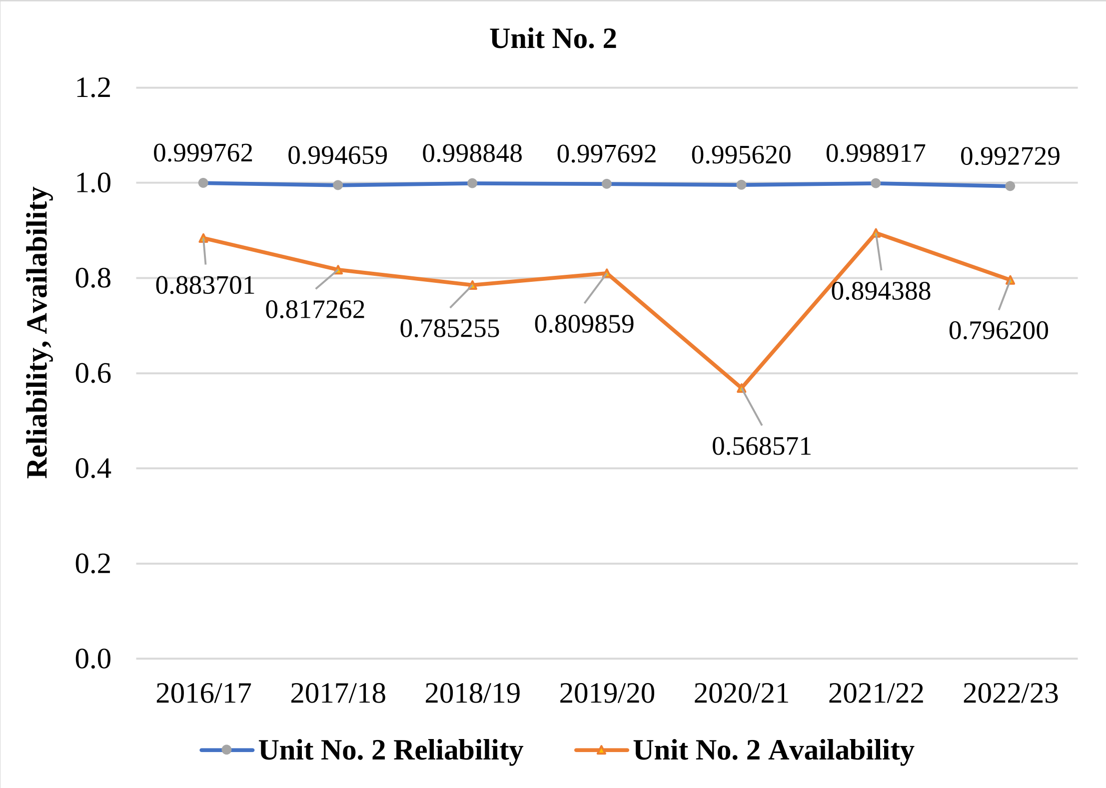


Figure 4.9: Trend line of Reliability and Availability for Unit No. 2 for 7 FY's

The trend line representation of the availability and reliability of Unit No. 2 is displayed in Figure 4.9. The reliability of the unit was found to be greater than 99% over the entirety of the research. On the other hand, it was observed that its availability was 56.85% in FY 2020/21 and 89.43% in FY 2021/22. This has occurred because the unit has been allocated maximum number of scheduled outage hours in that fiscal year.

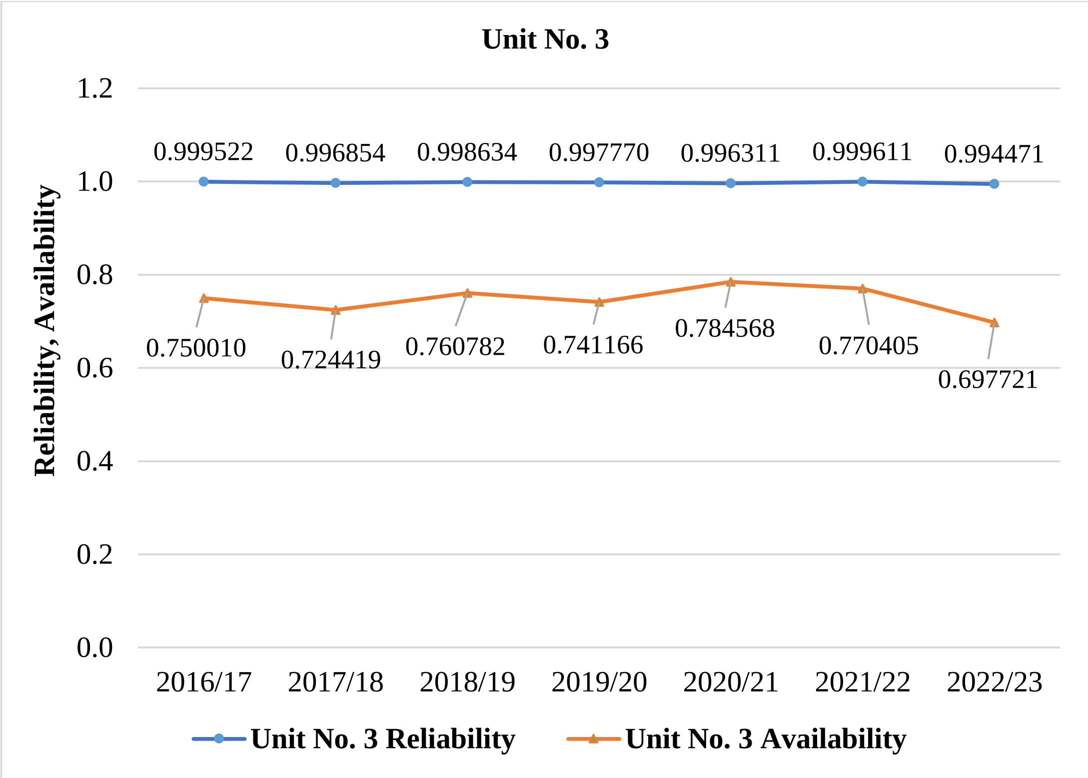


Figure 4.10: Trend line of Reliability and Availability for Unit No. 3 for 7 FY's

Figure 4.10 illustrates the Trend Line representation of Unit No. 3's Reliability and Availability. Throughout the duration of the study, the unit's reliability was shown to be greater than 99%. However, its availability was found to be 69.77% in fiscal year 2022/23 and 78.45% in fiscal year 2020/21.

Table 4.9: Summary of Unit wise Reliability and Availability for 7 FY's

FY	Unit No. 1		Unit No. 2		Unit No. 3	
	Reliability	Availability	Reliability	Availability	Reliability	Availability
2016/17	0.989024	0.678522	0.999762	0.883701	0.999522	0.750010
2017/18	0.997801	0.722964	0.994659	0.817262	0.996854	0.724419
2018/19	0.997228	0.741998	0.998848	0.785255	0.998634	0.760782
2019/20	0.997664	0.746568	0.997692	0.809859	0.997770	0.741166
2020/21	0.997989	0.803229	0.995620	0.568571	0.996311	0.784568
2021/22	0.995972	0.868536	0.998917	0.894388	0.999611	0.770405
2022/23	0.952622	0.722188	0.992729	0.796200	0.994471	0.697721

Table 4.9 illustrates the yearly reliability and availability of all units throughout the designated study period. The study revealed that unit number 2 exhibited the highest levels of reliability and availability.

4.3 Reliability and Availability of the Kaligandaki 'A" Hydropower Station

4.3.1 Calculation of the Station Reliability

(Billinton & Allan , 1992) States the reliability of a system consisting two independent components A and B that are linked in parallel. The probabilities of success (or reliability) of each component are R_A and R_B, whereas the probabilities of failure are Q_A and Q_B. Then probability of system failure, Q_s, unreliability, is thus,

$Q_S = Q_A * Q_B$ and reliability of system $R_S = 1 - Q_S$.

Since all of the three units of KGAHPS are connected in parallel with grid and are independent of each other, we can apply the above formula to calculate the reliability of station from FY 2016/17 to FY 2022/23 as below.

Reliability of Unit no. 1 = Average of Reliability of Unit 1 during 7 FY's = 0.989757

Reliability of Unit no. 2 = Average of Reliability of Unit 2 during 7 FY's = 0.996890

Reliability of Unit no. 3 = Average of Reliability of Unit 3 during 7 FY's = 0.997596

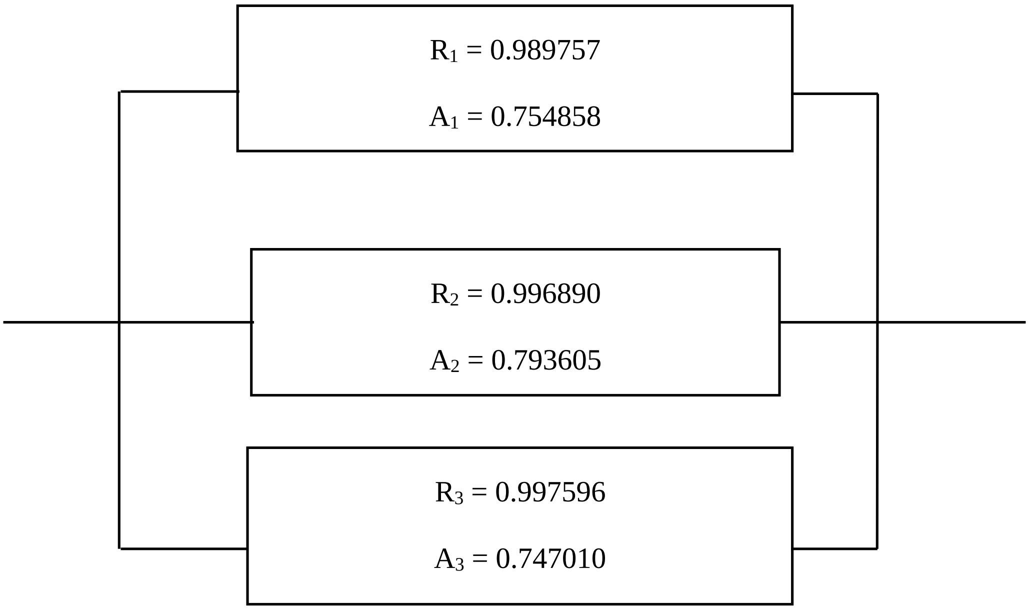


Figure 4.11: Three Units Connected in Parallel with Grid

Unreliability of Unit No. 1, $Q_1 = 1 - R_1 = 0.010243$

Unreliability of Unit No. 2, $Q_2 = 1 - R_2 = 0.003110$

Unreliability of Unit No. 3, $Q_3 = 1 - R_3 = 0.002404$

Unreliability of Station, $Q_s = Q_1 x Q_2 x Q_3 = 7.66 \text{ x}10^{-8}$

Hence, Reliability of Station = 1 - Q_s = 0.999999923

From the above analysis, the hydropower station demonstrated a high degree of reliability index 0.999999923 during the studied data of last seven fiscal years.

4.3.2 Calculation of the Station Availability

Considering same above scenario for availability calculation during study period of 7 FY's at least one unit is in operation is taken as station available. For this again the all of the three units of KGAHPS are connected in parallel with grid and are independent of each other, we can apply the above formula to calculate the availability of station. (Hoda & Kamali Roosta, 2014)

Availability of Unit no. 1 = Average of Availability of Unit 1 during 7 FY's = 0.754858

Availability of Unit no. 2 = Average of Availability of Unit 2 during 7 FY's = 0.793605

Availability of Unit no. 3 = Average of Availability of Unit 3 during 7 FY's = 0.747010

Unavailability of Unit No. 1, $U_1 = 1-A_1$ = 0.245142

Unavailability of Unit No. 2, $U_2 = 1-A_2$ = 0.206395

Unavailability of Unit No. 3, $U_3 = 1-A_3$ = 0.252990

Unavailability of Station, $U_s = U_1 x U_2 x U_3$ = 0.012800305

Hence, Availability of Station = 1 - U_s = 0.987199695

Thus, station is available with at least of its one unit is in operation is 0.987199695 during the study period of 7 years.

4.4 Expected Energy Not Supplied and Loss of Sales

When a unit experiences a forced outage, it means that it is unable to generate electricity due to unexpected failures or malfunctions. Although there are scheduled outages for preventive as well as overhaul maintenance of the units, sudden and unexpected breakdown of the machines occurs which results in the unreliable supply of electricity and lack of electricity generation from the affected unit that reduces the overall revenue generated by the station. For the calculation of loss of sales of electricity overall NEA system loss and average sale price of electricity for corresponding fiscal year are taken into consideration as below tabulated for unit no. 1. Since overall NEA system loss and average sales rate of electricity for FY 2022/23 are not disclosed yet, it has been taken equal to that of previous year. (Nepal Electricity Authority, 2022)

Table 4.10: Loss of Sales of Electricity due to Forced Outages of Unit No. 1

FY	Per Unit Capacity (MW)	NEA System Loss %	Unit Rate (NRs. /kWh)	Unit No. 1		
				Forced Outage Hrs	**Energy Expected Not Supplied (MWh)**	**Loss of Sales of Electricity (NRs.)**
2016/17	48	22.90	10.00	96.15	3,558.32	35,583,192.00
2017/18	48	20.45	10.10	19.32	737.59	7,449,647.62
2018/19	48	15.32	10.65	24.28	987.06	10,512,158.94
2019/20	48	15.27	10.92	20.47	832.38	9,089,642.11
2020/21	48	17.18	9.68	17.62	700.33	6,779,167.73
2021/22	48	15.38	9.30	35.38	1,437.19	13,365,855.73
2022/23	48	15.38	9.30	415.03	16,857.66	156,776,206.06

Similarly, loss of electricity sales for all three units for all seven fiscal years were calculated and are tabulated below.

Table 4.11: Loss of Electricity Sales of Station due to Forced Outages

FY	Unit 1 (NRs.)	Unit 2 (NRs.)	Unit 3 (NRs.)	Station (NRs.)
2016/17	35,583,192.00	770,987.66	1,548,155.66	37,902,335.33
2017/18	7,449,647.62	18,093,819.46	10,657,014.26	36,200,481.34
2018/19	10,512,158.94	6,442,614.95	5,178,593.21	22,133,367.10
2019/20	9,089,642.11	8,978,656.33	8,675,144.20	26,743,442.64
2020/21	6,779,167.73	14,764,048.89	12,435,946.00	33,979,162.62
2021/22	13,365,855.73	3,594,873.28	1,290,599.06	18,251,328.06
2022/23	156,776,206.06	24,433,707.78	18,295,372.98	199,505,286.82

Despite the hydropower station demonstrated a high degree of reliability in comparison to the internationally accepted benchmark (ERC, 2019), there is a significant revenue loss due to the sudden breakdown of units showing minimum of NRs. 18 million in FY 2021/22 and maximum of 199 million in FY 2022/23. Unit number 1 has incurred a revenue loss exceeding 156 million as a result of a total of 412 hours of downtime caused by the insulation rupture in the stator coils of the generator.

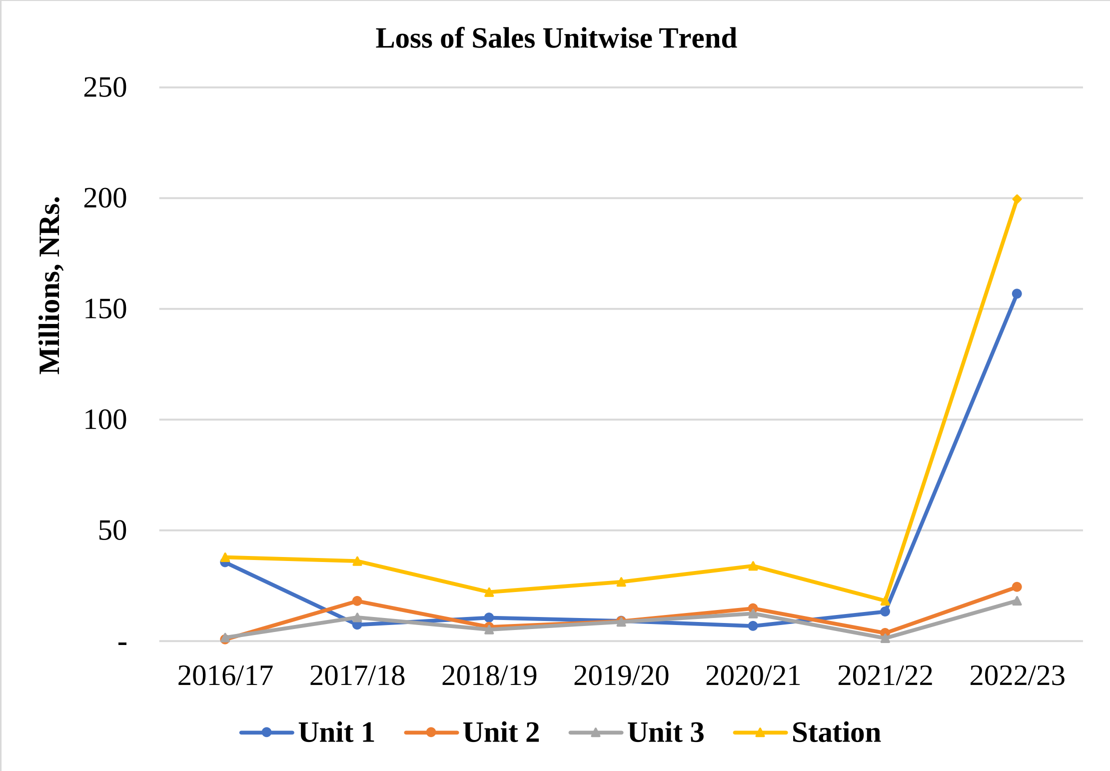


Figure 4.12: Loss of Electricity Sales Trend

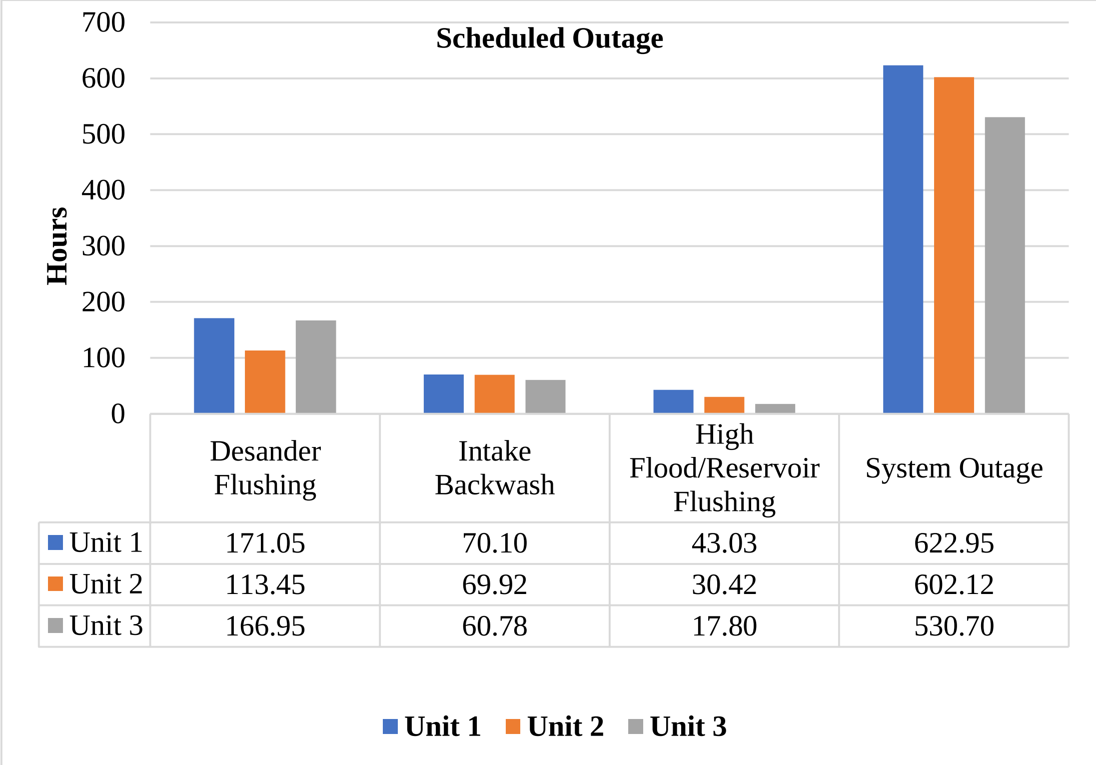
4.5 Outage Hours Details during 7 FY's

Table 4.12: Service and Outage Hours details of 7 FY's

	Unit 1	Unit 2	Unit 3	Total
Scheduled Outage Hours	14,413.68	12,470.95	15,377.98	42,262.62
Forced Outage Hours	628.25	196.67	147.48	972.40
Service Hours	46,326.07	48,700.38	39,075.30	140,868.99
Total Observed Hours	61,368.00	61,368.00	61,368.00	184,104.00

Table 4.13: Major Scheduled Outages during 7 FY's

Major Events	Unit 1 (hrs.)	Unit 2 (hrs.)	Unit 3 (hrs.)	Total (hrs.)
Desander Flushing	171.05	113.45	166.95	451.45
Intake Backwash	70.10	69.92	60.78	200.80
Lack of Water	10257.83	8820.65	10072.83	29151.32
LDC Instruction	1422.15	827.78	1948.65	4198.58
High Flood/Reservoir Flushing	43.03	30.42	17.80	91.25
System Outage	622.95	602.12	530.70	1755.77
Unit Overhauling/Plant Shutdown	1826.57	2006.62	2580.27	6413.45



	Desander Flushing	Intake Backwash	High Flood/Reservoir Flushing	System Outage
Unit 1	171.05	70.10	43.03	622.95
Unit 2	113.45	69.92	30.42	602.12
Unit 3	166.95	60.78	17.80	530.70

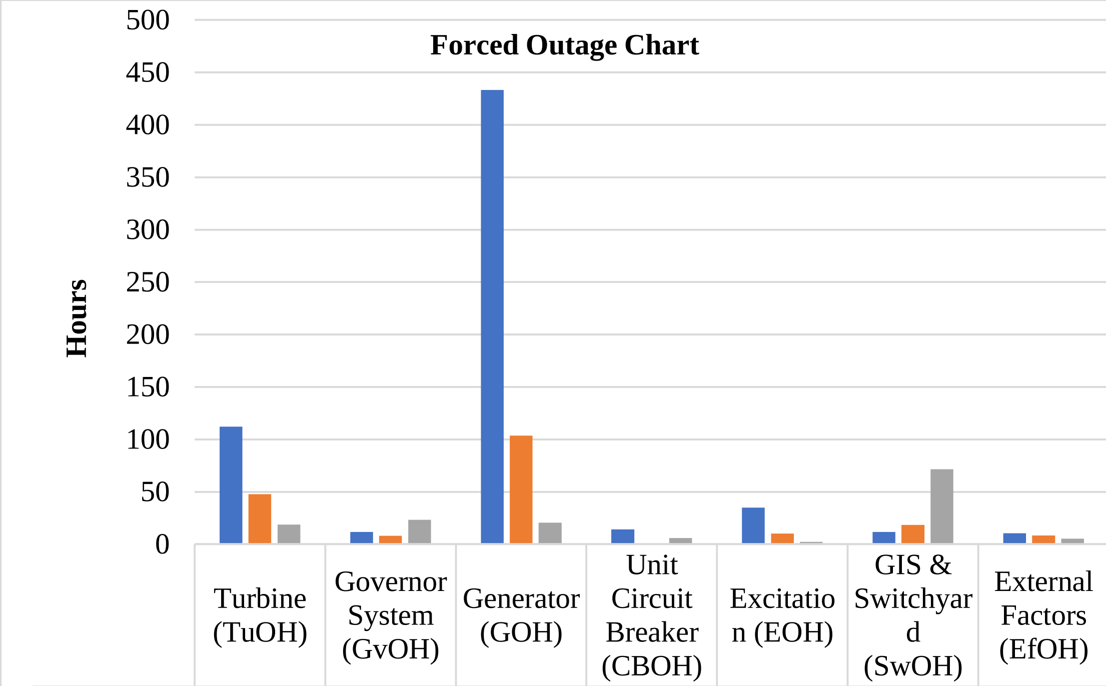
Figure 4.13: Major Scheduled Outages that should be minimized

The scheduled or planned outages that took place throughout the time period covered by the study are illustrated in Tables 4.13 and Figure 4.12. The primary reasons for the halting of units were a lack of water, LDC instruction, unit overhauling or plant shutdown, and system outages. These factors were responsible for a total of 29151.32 hours, 4198.58 hours, 6413.45 hours, and 1755.77 hours of downtime, respectively. Outages, other than of those caused by a lack of water and unit overhauling or plant shutdown, can be reduced to a minimum by ensuring a reliable grid supply. Other scheduled outages such as desander flushing, intake backwashing, and heavy flood/reservoir flushing have also consumed a large amount of outage hours. These outages have taken 451.45 hours, 200.80 hours, and 91.25 hours, respectively. These power interruptions take place during the rainy season, when the enormous sediment load brought by the Kaligandaki River causes the sediment bed level to rise dramatically, sometimes all the way up to 4 meters within 3-4 days, making it necessary to flush the desander once a week. Due to the fact that the desander at the station is of the open channel gravity flow type and continuous flushing cannot be achieved, the station must be shut down. In a similar manner, the development of roads at the bank of the Kaligandaki River on both sides and the mixing of garbage on the river in the upstream portion of the river have produced regular chocking of trash racks, which limits the water flow and causes machines to be forced to shut down. Even though there are two numbers of trash rack cleaning machines functioning 24 hours a day, the necessity of intake backwash is caused by the accumulation of debris in the trash racks during flood times. The use of dredger machines for continuous desilting in the reservoir and the application of any other techniques that can control the sedimentation and debris chocking concerns are both effective ways to reduce the frequency and length of these sorts of outages.

Table 4.14: Component wise Forced Outage of 7 FY's

	Unit No. 1 (hrs.)	**Unit No. 2 (hrs.)**	**Unit No. 3 (hrs.)**	**Total (hrs.)**
Turbine (TuOH)	112.03	47.87	18.80	178.70
Governor System (GvOH)	11.60	8.05	23.33	42.98
Generator (GOH)	433.35	103.67	20.48	557.50
Unit Circuit Breaker (CBOH)	14.27	0.00	5.77	20.03
Excitation (EOH)	34.88	10.20	2.30	47.38
GIS & Switchyard (SwOH)	11.55	18.47	71.51	101.53
External Factors (EfOH)	10.57	8.42	5.28	24.27

Among the forced outages that happened over the 7-year study period, the repair hours for the turbine system, generator system, and GIS/Switchyard components were 178.70 hours, 557.50 hours, and 101.53 hours, respectively. Regular turbine overhauling is performed after every three years for each unit, but generator overhauling has not been performed since the time of commissioning, which should be considered to avoid any catastrophic malfunction. The governor system, excitation system, and an unknown fault all contributed to the unit's breakdown, resulting in repair times of 42.98 hours, 47.38 hours, and 24.27 hours, respectively. These forced outages could be reduced by complete replacing of malfunctioning components during overhauling and utilising people efficiently during breakdowns to reduce net downtime.



	Turbine (TuOH)	Governor System (GvOH)	Generator (GOH)	Unit Circuit Breaker (CBOH)	Excitation (EOH)	GIS & Switchyard (SwOH)	External Factors (EfOH)
Unit No. 1	112.03	11.60	433.35	14.27	34.88	11.55	10.57
Unit No. 2	47.87	8.05	103.67	0.00	10.20	18.47	8.42
Unit No. 3	18.80	23.33	20.48	5.77	2.30	71.51	5.28

Figure 4.14: Major Component wise Forced Outages occurred during 7 FY's

4.6 Fault Tree Development for a unit failure

The fault tree structure for a unit failure at KGAHPS has been developed using historical operational data from the past seven fiscal years. The Top Event of the fault tree is referred to as the unit failure of the KGAHPS. The fault initiation events were classified into two categories: forced outages and scheduled outages. Scheduled outages can be categorised into three distinct types: Unit Kept Idle, Preventive Maintenance, and System Reserve. The occurrences of forced outages were categorised into seven distinct types: Turbine and auxiliary, Governor System, Generator and auxiliary, Unit circuit breaker, Excitation System, GIS and Switchyard, and External Factors. In this way, the basic events of the unit failure are analysed and discussed.

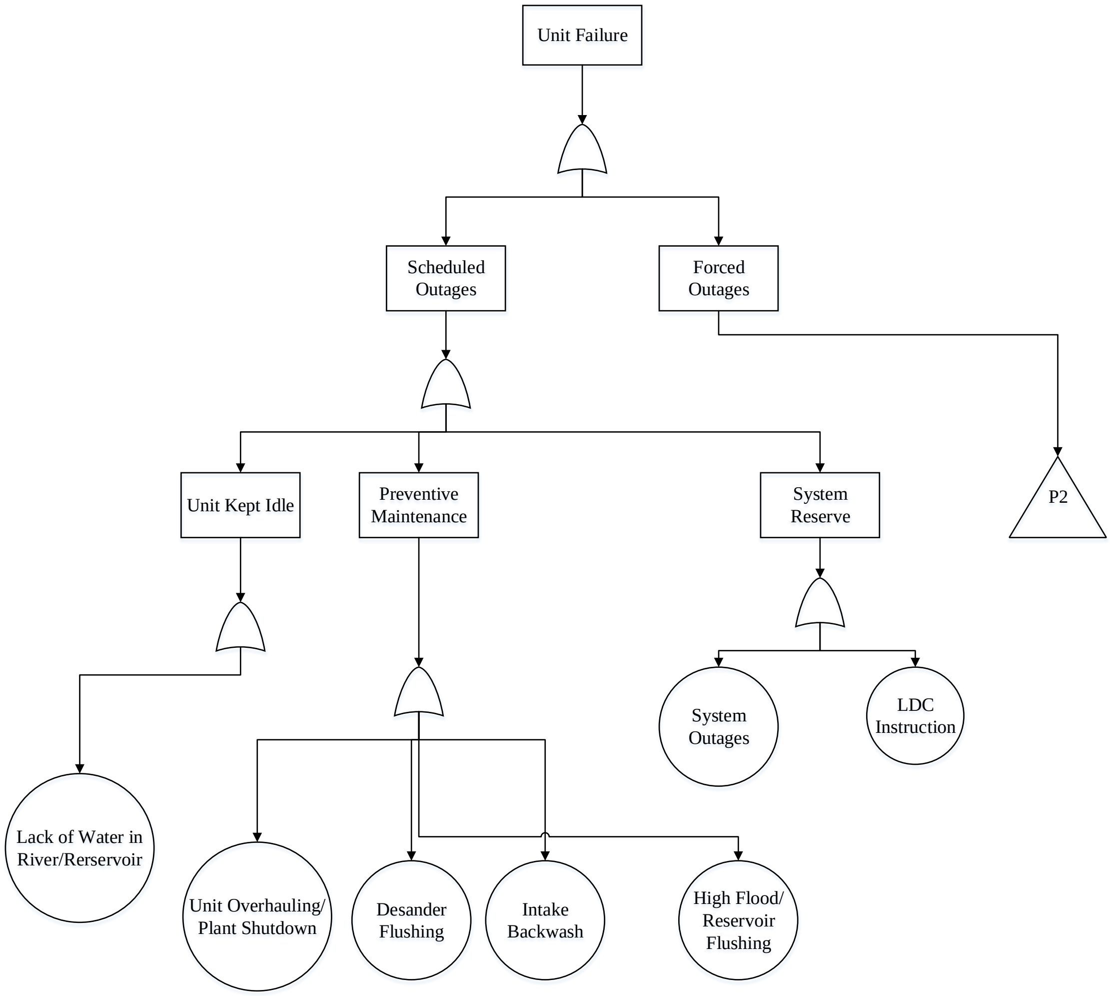


Figure 4.15: Fault Tree Structure of Typical Unit Failure in KGAHPS

Upon careful examination of the operational data gathered from seven fiscal years, scheduled outages have been observed as the primary cause for the unavailability of units. The unit must be kept idle due to inadequate flow in the river or reservoir during the dry season. The power station's designed discharge is 147 m^3/s, while the highest observed flood in the river is approximately 4500 m^3/s, and the recorded minimum flow is around 40 m^3/s, as stated in the dam operation manual of the plant. Thus, the power station can only run two units at partial load continuously during the dry season. During the monsoon season, a significant issue arises with the accumulation of debris in the trash racks and the deposition of silt in the desander basin. As a result, it becomes necessary to perform frequent intake backwash and desander flushing procedures. Likewise, the occurrence of a significant flood along the river necessitated the temporary cessation of operations for the dam and associated equipment in order to ensure safety. The values taken during design for the maximum flood discharge for a 20-year, 100-year, and 1000-year return period are 3740 m^3/s, 4770 m^3/s, and 6400 m^3/s, respectively.

According to the dam operation manual provided by the station, it is advised to refrain from operating the power plant if the river's discharge exceeds a threshold of 2000 m^3/s. Another contributing factor to the shutdown of the plant is the abrupt increase in river discharge during the wet season.

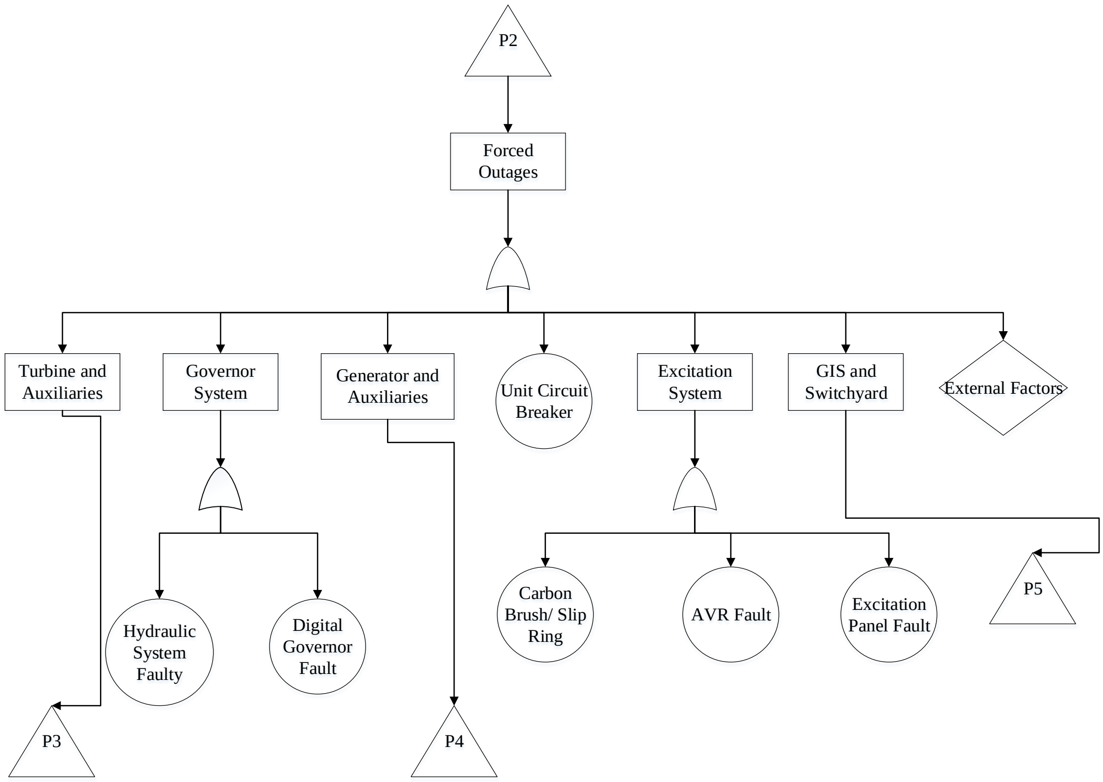


Figure 4.16: Fault Tree Structure of Unit Failure due to Forced Outages

In addition to planned outages, the KGAHPS units experience shutdowns due to a range of breakdown events, as previously mentioned. The primary occurrences of forced outages in the analysed data were observed in turbine and auxiliary systems. The erosion of hydromechanical components, such as the spiral case, bottom ring, draft tube, and pressure distribution pipelines, is caused by the presence of high levels of silt and quartz particles in the sediment-laden water. This erosion leads to the forced shutdown of units for control of water leakage, specifically during the rainy season. In the turbine and auxiliary systems, other problems have been found, such as a broken shear pin in the guide vane operating mechanism and problems with the lubricating oil and shaft seal cooling water system. The occurrence of outage events in the governor system can be likened to malfunctions in the hydraulic system, such as insufficient pressure within the system, inadequate oil levels in the oil pumping units, and the entrapment of air within the hydraulic pipelines. Another issue observed is the occurrence of outages, which can be attributed to a problem with the proportionate valve. Specifically, the valve exhibits a sluggish response when there is a sudden increase or decrease in the load within the system.

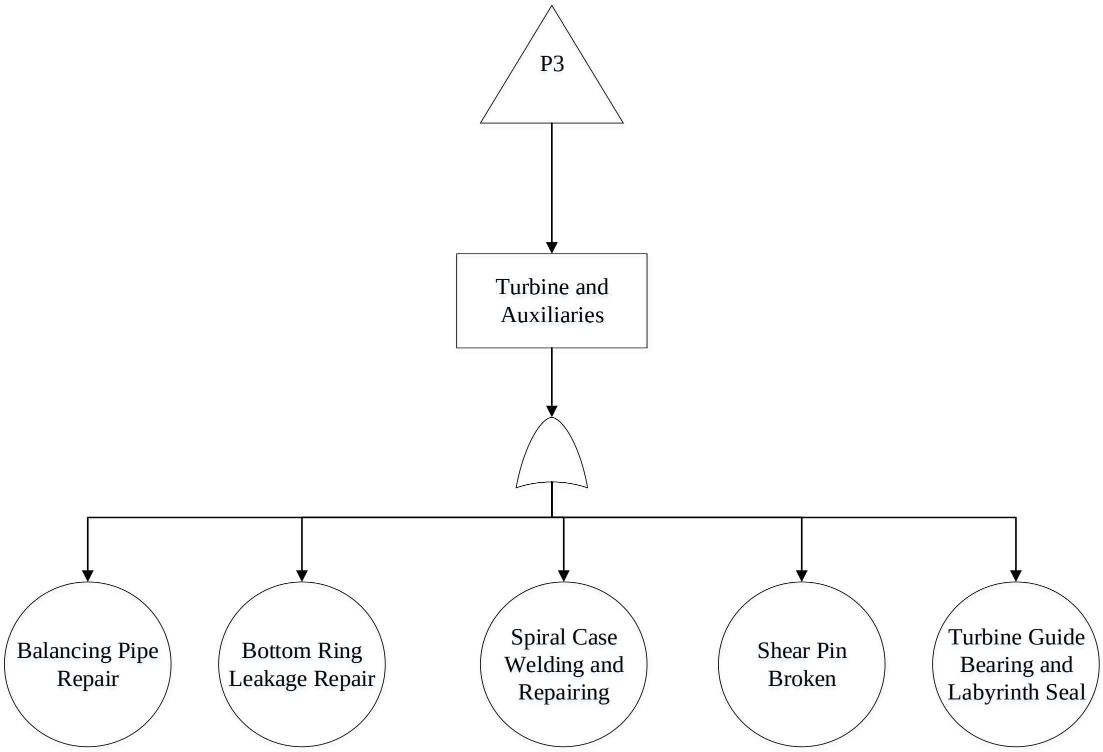


Figure 4.17: Fault Tree Structure of Unit Failure due to Turbine and Auxiliaries

Following the occurrence of a breakdown in the turbine and auxiliary systems, another significant malfunction was subsequently observed in the generator and auxiliary components. The power station uses a stator cooling water system that draws water directly from the tailrace, which is known to contain a significant amount of sediment suspended in the water flow. Despite the presence of a desander in the cooling water system, it is unable to effectively remove all silt particles. Consequently, the heat exchanger tubes in the cooling water system become clogged, necessitating frequent cleaning. This leads to the forced shutdown of a unit. Similarly, the station has provision for an intermediate shaft between the turbine main shaft and rotor shaft. Therefore, during the process of overhauling, a comprehensive inspection and maintenance of the turbine components are conducted. However, due to the rotor not being disassembled, the maintenance of the generator components is not carried out adequately. In recent years, there has been a growing concern regarding issues encountered in the rotor and stator components. During the fiscal year 2022/23, unit number 2 experienced a total breakdown duration of 63.68 hours as a result of damage to the conductor connecting link in the rotor. The station has been observed to provide a high reactive load exceeding 30 MVAR per unit, which surpasses the allowable limit. Consequently, this leads to an elevation in the temperature of the stator and rotor windings, as well as other components. The abrupt fluctuations in temperature induce alterations in the material characteristics, leading to the formation of cracks in the metallic components and compromising the insulation integrity of the coils. Unit number 3 experienced a mandatory shutdown lasting 412.37 hours as a result of an insulation rupture in the stator coils of the generator. Given that the generator has not undergone any overhauling since its initial operation, it is imperative for the authorities to include the generator's overhaul in their routine turbine maintenance plan.

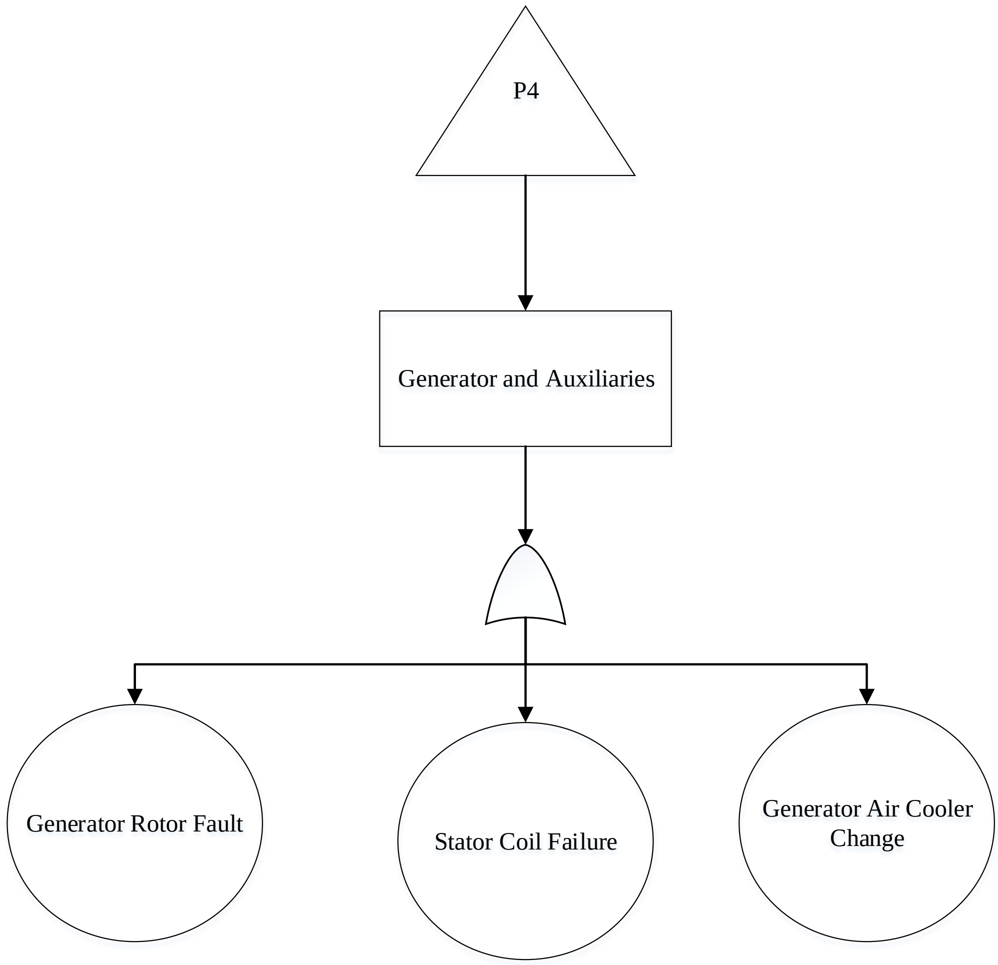


Figure 4.18: Fault Tree Structure of Unit Failure due to Generator and Auxiliaries

The station employs a static excitation system. The utilisation of the rotating rectifier is absent in the static excitation system, as the provision of power to the rotor field is achieved through stationary brushes. In this particular system, the alternating current (AC) power is derived from the generator terminal. It is subsequently reduced in voltage through a step-down process and converted into direct current (DC) using fully controlled thyristor bridges. The resulting DC power is then supplied directly to the field of the primary generator via slip rings, thereby enabling the regulation of the generator's voltage output. The stator and rectifier of the alternator remain in a fixed position. The issue encountered with the excitation system was identified as a recurring requirement for carbon brush replacement and slip ring cleaning. Furthermore, certain occurrences were observed where minor issues were identified in the excitation control panels and automatic voltage regulator (AVR) protection system. The unit circuit breaker has also experienced some instances of breakdown, which involve issues with the protection panel relays, CTs, and PTs.

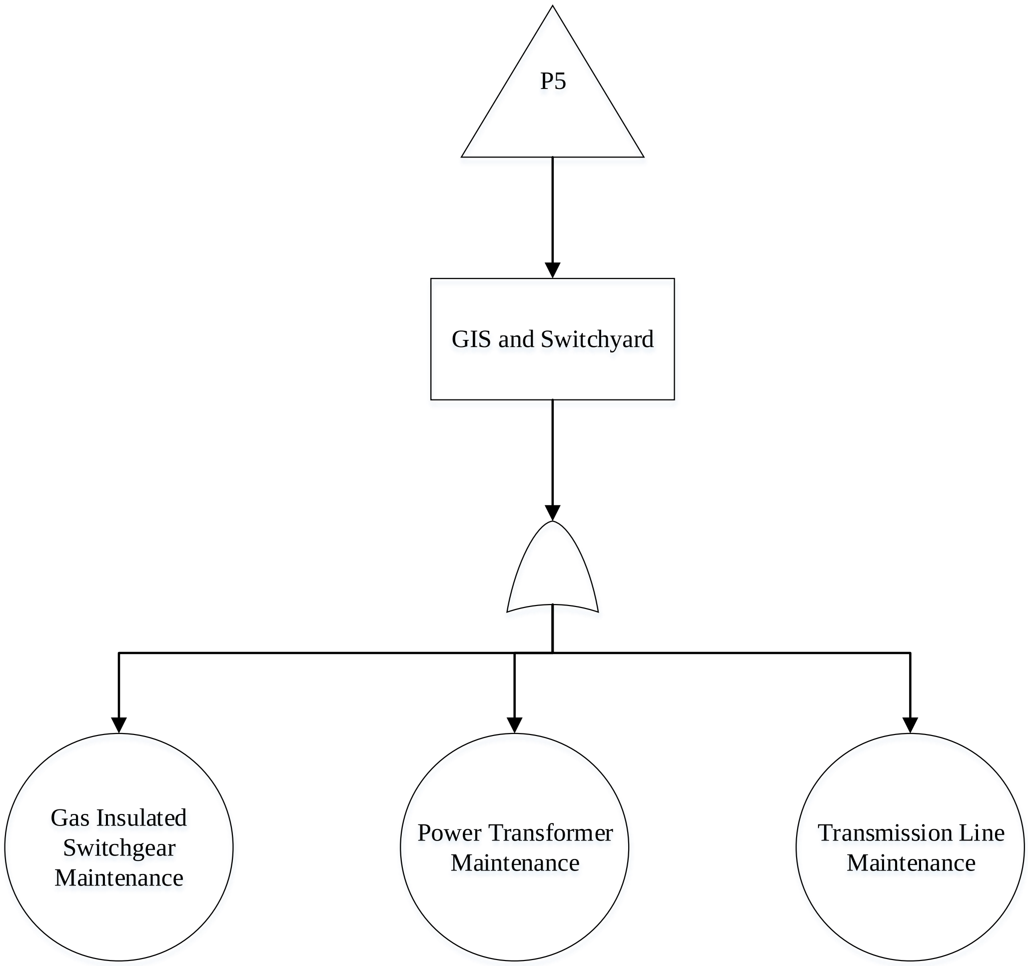


Figure 4.19: Fault Tree Structure of Unit Failure due to GIS and Switchyard

The generating voltage of the station is 13.8 kV, which is subsequently stepped up to 132 kV for the purpose of transmission. The station utilises a 13.8 kV/132 kV, 56.5 MVA power transformer, and gas-insulated switchgear. The observed breakdown events in this system are mainly issues encountered in the current transformers (CTs), voltage transformers (VTs), and transformer bushings. The switchyard of a station may encounter various issues pertaining to transmission lines, such as the occurrence of sparking in the isolator switches and the puncture of the discs and pins.

4.7 Comparison of Outcomes to Similar Studies

The present study reveals that the reliability of the Kaligandaki “A” Hydropower Station exceeds 99.99%, a finding that may be compared to a comparable investigation conducted on the Sunkoshi small hydropower station, which similarly reported a reliability level of 0.9999. This study presents a comparison of unitwise reliability, revealing a range of reliability percentages between 95.26% and 99.98%. Notably, all units of the Sunkoshi Hydropower Station had a reliability rate exceeding 99%. This can be mostly attributed to a reduced frequency of forced outage incidents encountered by the units in that location. The operational duration of the units at the Sunkoshi hydropower station during a period of seven years is determined to be 46606.76 hours for Unit No. 3, 51075.15 hours for Unit No. 2, and 55269.61 hours for Unit No. 1. Upon comparing the uptime durations of Sunkoshi hydropower with that of Kaligandaki 'A' Hydropower Station, it becomes evident that Sunkoshi hydropower exhibits a greater uptime. Thus availability of the units of the Sunkoshi Hydropower Station is higher compared to the Kaligandaki “A” Hydropower Station, with a range of 76.03% to 90.10%. Likewise, a study conducted on the Bijaypur-I Small Hydropower Plant has demonstrated a reliability rate of 98.19% and an availability rate of 99.25%, indicating a notable resemblance to the findings of the current research.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on an analysis of operational data spanning from fiscal year 2016/17 to fiscal year 2022/23, it is evident that the hydropower station exhibited a noteworthy degree of reliability, as indicated by a reliability index of 0.999999923. During the research period, it was determined that the station had an availability rate of 0.987199695, with at least one of its individual units was operational. The findings of this research study are summarised as:

For the whole seven-year study period, the component-level reliability and availability of each unit of station were assessed. Unit No. 1 was found to have a reliability that ranged from 95.26% in FY 2022/23 to 99.79% in FY 2020/21, and an availability that ranged from 67.85% in FY 2016/17 to 86.85% in FY 2021/22, showing a decreased failure probability and more operational accessibility. Unit No. 2 exhibits a notable reliability range of 99.27% in the fiscal year 2022/23 and an even higher reliability range of 99.98% in the fiscal year 2016/17, thereby indicating its propensity for consistent and dependable operation. During the fiscal year 2020/21, Unit No. 2 experienced significant planned outages, resulting in an availability range of 56.86%. However, in the subsequent fiscal year 2021/22, the availability of Unit No. 2 improved to 89.44%. Unit No. 3 demonstrates commendable reliability, as evidenced by a reliability range of 99.45% in FY 2022/23 to 99.96% in FY 2021/22. This indicates a high level of dependability and a low likelihood of failures. The availability of the unit varied from 69.77% in FY 2022/23 to 78.46% in FY 2020/21. This indicates that there were significant scheduled outages assigned to the unit, resulting in a slightly lower than normal availability.

These indicators provide essential information on each unit's performance and dependability, allowing for an assessment of its operating efficiency and potential impact on the system as a whole. The resource's decreased availability can be ascribed to a variety of issues, including insufficient river flow during the dry season, the necessity for frequent desander and reservoir flushing due to higher floods, and the Kaligandaki River's significant silt burden and need of shutdown for Intake Backwash due to debris clogging at Trash Racks. During a dry season, the hydropower station's ability to create a constant supply of energy is hampered by a shortage of water in the river. Furthermore, due to the higher flood levels and significant sediment load in the river, regular maintenance actions such as desander and reservoir flushing are required, which might result in temporary shutdowns and reduced operational capacity. A complete assessment of a hydropower plant's reliability necessitates an investigation of the aforementioned characteristics as well as the development of methods to address them. To offset the negative effects on the hydropower station's operation and improve its operational preparedness, viable methods include optimizing the design of desander units and implementing real-time monitoring of sedimentation, enhancing the performance of trash rack cleaning machines by installing larger or more efficient trash racks, implementing automated cleaning systems, Sediment removal and dredging and Optimising water management during the dry season may reduce outage events and increase hydropower plant availability.

The operational performance of the station has demonstrated a high level of efficiency, with a reliability exceeding 99%. However, the availability of the individual unit has varied between 56.86% (Unit 2, fiscal year 2020/21) and 89.44% (Unit 2, fiscal year 2021/22). In addition to the prevalence of scheduled outages, a significant number of forced outages are also observed, contributing to reduced availability. The analysis of electricity sales reveals a significant monetary loss ranging from NRs. 18 million to 199 million per year as a result of forced outages is being faced by the station. This financial impact could be substantially mitigated by replacing malfunctioning components during overhauling processes and optimising human resources during breakdowns, thereby reducing overall downtime.

The Fault Tree was developed based on the 25 numbers of basic events analysed from the collected data of the last seven fiscal years. It was observed that during the seven years of operation scheduled outages are the major causes of unit unavailability. Insufficient river flow has alone caused about 29000 hrs. of unit shutdown. Similarly the Forced outage events were mostly predominated by Generator and Auxiliaries with 557 hrs. and Turbine & Auxiliaries with 178 hrs. of forced shutdown of units.

5.2 Recommendations

i. It is necessary to install sufficient capacitor banks in the grid substations because supplying reactive power through the generating station in excess of its designated capacity causes the generator's temperature to rise, resulting in unneeded equipment shutdowns and a shorter lifespan.

ii. Major turbine and generator components are experiencing forced outages at the site. The generator hasn't been overhauled since it was first put into service, but the turbine is regularly serviced, thus the responsible authorities should think about scheduling an overhaul of the generator.

iii. It is important to conduct bathymetric surveys of the reservoir so that one can determine the level of sedimentation that has occurred within the reservoir, as well as to conduct other civil studies that will help reduce the outages time due to sedimentation and debris clogging.

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ANNEXES

KGAHPS SALIENT FEATURES

Installed capacity	144 MW
Type	Run of the river peaks (6 hours per day)
Location	Rural Municipality of Kaligandaki, Syangja
Average annual generation	842 GWh
Live storage volume	3.1 million m^3
Catchment area	The Kaligandaki River covers 7618 km^2 and the Aandhikhola River 476 km^2.
Total length of waterways	5905-meter headrace tunnel and 183-meter power conduit
Maximum net head/gross head	115m / 130m
Penstock	1 No., 243m long, Ø 5.25m, steel lined, inclined
Turbine	
OEM	Toshiba, Japan
Number/Type	3 Francis
Output	48MW each
Flow (Rated)	47 m^3/s per unit
Speed (Rated)	300rpm
Generator	
OEM	Toshiba, Japan
Output (Rated)	56.5MVA
Voltage (Rated)	13.8kV
Frequency (Rated)	50Hz
Power factor (Rated)	0.85
Excitation	Static
OEM Power transformer	Koncar, Croatia
Power transformer	13.8/132 kV, 3 phases, 56.5 MVA, 3 nos.
Transmission line	132 kV, 104.6 km, single circuit to Pokhara sub-station of 65.5 km, and double circuit to Butwal sub-station of 39.1 km.
Project Cost	US$ 354.8 Million

Source: (Nepal Electricity Authority, 2022)

PRIMARY OPERATIONAL DATA

Data Collected for FY 2016/17 (in hh:mm)

S.N.	Events	Unit 1		Unit 2		Unit 3		Total Repair Hours	Total Nos.
		Repair Hours	Nos.	Repair Hours	Nos.	Repair Hours	Nos.		
1	Desander Flushing	20:47	6	3:06	3	1:59	3	25:52	12
2	Intake Backwash	10:10	5	12:12	6	6:30	5	28:52	16
3	Balancing Pipe Repair	8:40	2	0:00	0	2:17	1	10:57	3
4	Guide Bearing and Labyrinth Seal	73:41	2	0:00	0	0:00	0	73:41	2
5	Shear Pin Broken	1:55	1	0:00	0	0:00	0	1:55	1
6	Governor Fault	0:00	0	2:05	3	0:00	0	2:05	3
7	Lack of Water	1921:30	5	653:28	6	1519:34	6	4094:32	17
8	LDC Instruction	162:58	4	67:11	2	100:29	1	330:38	7
9	High Flood/Reservoir Flushing	18:45	3	17:52	3	4:37	2	41:14	8
10	System Outage	80:07	78	75:18	80	54:15	78	209:40	236
11	Generator Rotor Fault	1:21	1	0:00	0	0:00	0	1:21	1
12	Carbon Brush change/Slip Ring cleaning	4:51	2	0:00	0	0:00	0	4:51	2
13	Excitation Failure	0:41	1	0:00	0	1:07	2	1:48	3
14	Generator Circuit Breaker	1:00	1	0:00	0	0:47	1	1:47	2
15	Generator air cooler change	4:00	2	0:00	0	0:00	0	4:00	2
16	Gas Insulated Switchgear Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
17	Power Transformer Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
18	Transmission Line Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
19	Unit Overhauling/Plant Shutdown	505:43	2	187:35	1	498:20	0	1191:38	3
20	External Factors	0:00	0	0:00	0	0:00	0	0:00	0
21	Service Hours	5943:51	0	7741:13	0	6570:05	0	20255:09	0
	Total Observed Hours	8760:00	0	8760:00	0	8760:00	0	26280:00	0

Data Collected for FY 2017/18 (in hh:mm)

S.N.	Events	Unit 1		Unit 2		Unit 3		Total Repair Hours	Total Nos.
		Repair Hours	Nos.	Repair Hours	Nos.	Repair Hours	Nos.		
1	Desander Flushing	9:40	2	14:02	4	17:59	6	41:41	12
2	Intake Backwash	8:49	5	9:44	6	5:07	5	23:40	16
3	Balancing Pipe Repair	0:00	0	1:18	1	2:34	1	3:52	2
4	Bottom Ring Leakage Repair	2:40	1	0:00	0	3:56	1	6:36	2
5	Guide Bearing and Labyrinth Seal	0:00	0	7:18	2	3:58	1	11:16	3
6	Governor Fault	11:36	1	0:00	0	7:11	3	18:47	4
7	Lack of Water	2024:23	5	1390:45	5	1391:38	5	4806:46	15
8	LDC Instruction	296:37	2	61:25	3	445:27	3	803:29	8
9	High Flood/Reservoir Flushing	5:55	1	6:40	1	8:28	1	21:03	3
10	System Outage	68:46	68	75:39	90	59:31	79	203:56	237
11	Generator Rotor Fault	1:50	1	0:00	0	0:00	0	1:50	1
12	Carbon Brush change/Slip Ring cleaning	0:00	0	0:00	0	0:00	0	0:00	0
13	Excitation Failure	0:00	0	0:00	0	0:00	0	0:00	0
14	Trapezoidal Seal Replacement Generator	0:00	0	27:34	1	0:00	0	27:34	1
15	Generator air cooler change	3:13	1	10:00	4	9:59	4	23:12	9
16	Gas Insulated Switchgear Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
17	Power Transformer Maintenance	0:00	0	0:45	1	0:00	0	0:45	1
18	Transmission Line Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
19	Unit Overhauling/Plant Shutdown	0:00	0	0:00	0	464:54	3	464:54	3
20	External Factors	0:00	0	0:00	0	0:00	0	0:00	0
21	Service Hours	6350:31	0	7178:50	0	6363:18	0	19892:39	0
	Total Observed Hours	8784:00	0	8784:00	0	8784:00	0	26352:00	0

Data Collected for FY 2018/19 (in hh:mm)

S.N.	Events	Unit 1		Unit 2		Unit 3		Total Repair Hours	Total Nos.
		Repair Hours	Nos.	Repair Hours	Nos.	Repair Hours	Nos.		
1	Desander Flushing	14:24	4	3:15	2	34:49	11	52:28	17
2	Intake Backwash	8:20	2	7:42	2	5:42	3	21:44	7
3	Balancing Pipe Repair	0:00	0	7:02	1	0:00	0	7:02	1
4	Bottom Ring Leakage Repair	5:10	1	0:00	0	0:00	0	5:10	1
5	Shear Pin Broken	5:30	1	0:00	0	0:00	0	5:30	1
6	Hydraulic Oil Change	0:00	0	0:00	0	3:39	1	3:39	1
7	Lack of Water	1697:09	5	975:06	5	1227:52	5	3900:07	15
8	LDC Instruction	207:20	3	33:35	3	507:21	2	748:16	8
9	High Flood/Reservoir Flushing	18:22	1	5:53	1	4:43	1	28:58	3
10	System Outage	69:47	71	71:21	90	85:23	113	226:31	274
11	Generator Rotor Fault	0:00	0	0:00	0	0:00	0	0:00	0
12	Carbon Brush change/Slip Ring cleaning	0:00	0	4:48	2	0:00	0	4:48	2
13	Excitation Failure	0:00	0	0:00	0	0:00	0	0:00	0
14	Generator Circuit Breaker	0:00	0	0:00	0	0:00	0	0:00	0
15	Generator air cooler change	0:00	0	0:00	0	0:00	0	0:00	0
16	Gas Insulated Switchgear Maintenance	3:03	1	3:03	1	3:03	1	9:09	3
17	Power Transformer Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
18	Transmission Line Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
19	Unit Overhauling/Plant Shutdown	220:27	2	773:11	2	217:45	2	1211:23	6
20	External Factors	10:34	1	0:00	0	5:17	1	15:51	2
21	Service Hours	6499:54	0	6875:04	0	6664:26	0	20039:24	0
Total Observed Hours		8760:00	0	8760:00	0	8760:00	0	26280:00	0

Data Collected for FY 2019/20 (in hh:mm)

S.N.	Events	Unit 1		Unit 2		Unit 3		Total Repair Hours	Total Nos.
		Repair Hours	Nos.	Repair Hours	Nos.	Repair Hours	Nos.		
1	Desander Flushing	48:55	13	11:30	4	22:06	7	82:31	24
2	Intake Backwash	10:39	9	11:45	10	10:49	9	33:13	28
3	Balancing Pipe Repair	0:00	0	7:45	1	0:00	0	7:45	1
4	Bottom Ring Leakage Repair	9:11	2	0:00	0	0:00	0	9:11	2
5	Shear Pin Broken	3:30	1	0:00	0	0:00	0	3:30	1
6	Governor Fault	0:00	0	1:38	1	6:07	1	7:45	2
7	Lack of Water	1143:58	7	979:39	7	1237:08	7	3360:45	21
8	LDC Instruction	232:20	3	243:23	3	101:47	4	577:30	10
9	High Flood/Reservoir Flushing	0:00	0	0:00	0	0:00	0	0:00	0
10	System Outage	110:20	93	96:58	92	91:41	118	298:59	303
11	Generator Rotor Fault	0:00	0	0:00	0	0:00	0	0:00	0
12	Carbon Brush change/Slip Ring cleaning	2:25	1	0:00	0	0:00	0	2:25	1
13	Excitation Failure	5:22	3	0:00	0	0:00	0	5:22	3
14	Generator Circuit Breaker	0:00	0	0:00	0	3:20	1	3:20	1
15	Generator air cooler change	0:00	0	2:25	1	3:35	1	6:00	2
16	Gas Insulated Switchgear Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
17	Power Transformer Maintenance	0:00	0	0:00	0	6:30	1	6:30	1
18	Transmission Line Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
19	Unit Overhauling/Plant Shutdown	653:24	3	302:10	2	784:20	4	1739:54	9
20	External Factors	0:00	0	8:25	1	0:00	0	8:25	1
21	Service Hours	6539:56	0	7094:22	0	6492:37	0	20126:55	0
	Total Observed Hours	8760:00	0	8760:00	0	8760:00	0	26280:00	0

Data Collected for FY 2020/21 (in hh:mm)

S.N.	Events	Unit 1		Unit 2		Unit 3		Total Repair Hours	Total Nos.
		Repair Hours	Nos.	Repair Hours	Nos.	Repair Hours	Nos.		
1	Desander Flushing	51:22	6	62:52	9	57:41	11	171:55	26
2	Intake Backwash	18:14	10	13:16	8	17:54	9	49:24	27
3	Balancing Pipe Repair	1:45	1	24:00	1	0:00	0	25:45	2
4	Bottom Ring Leakage Repair	0:00	0	0:00	0	0:00	0	0:00	0
5	Shear Pin Broken	0:00	0	0:00	0	0:00	0	0:00	0
6	Governor Fault	0:00	0	4:20	1	5:30	1	9:50	2
7	Lack of Water	1158:30	5	2687:11	5	1330:29	5	5176:10	15
8	LDC Instruction	385:35	5	317:10	5	367:48	5	1070:33	15
9	High Flood/Reservoir Flushing	0:00	0	0:00	0	0:00	0	0:00	0
10	System Outage	92:25	144	60:00	101	81:00	145	233:25	390
11	Generator Rotor Fault	3:28	1	0:00	0	0:45	1	4:13	2
12	Carbon Brush change/Slip Ring cleaning	0:00	0	0:00	0	0:00	0	0:00	0
13	Excitation Failure	3:54	1	2:02	2	0:18	1	6:14	4
14	Generator Circuit Breaker	0:00	0	0:00	0	0:00	0	0:00	0
15	Generator air cooler change	0:00	0	0:00	0	6:10	2	6:10	2
16	Gas Insulated Switchgear Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
17	Power Transformer Maintenance	0:00	0	4:30	1	16:21	1	20:51	2
18	Transmission Line Maintenance	8:30	1	3:30	1	3:15	1	15:15	3
19	Unit Overhauling/Plant Shutdown	0:00	0	600:28	1	0:00	0	600:28	1
20	External Factors	0:00	0	0:00	0	0:00	0	0:00	0
21	Service Hours	7036:17	0	4980:41	0	6872:49	0	18889:47	0
	Total Observed Hours	8760:00	0	8760:00	0	8760:00	0	26280:00	0

Data Collected for FY 2021/22 (in hh:mm)

S.N.	Events	Unit 1		Unit 2		Unit 3		Total Repair Hours	Total Nos.
		Repair Hours	Nos.	Repair Hours	Nos.	Repair Hours	Nos.		
1	Desander Flushing	21:08	4	10:10	2	19:46	6	51:04	12
2	Intake Backwash	6:53	6	8:02	6	8:39	6	23:34	18
3	Balancing Pipe Repair	0:00	0	0:00	0	0:00	0	0:00	0
4	Bottom Ring Leakage Repair	0:00	0	0:00	0	0:00	0	0:00	0
5	Shear Pin Broken	0:00	0	0:29	1	0:00	0	0:29	1
6	Governor Fault	0:00	0	0:00	0	0:53	1	0:53	1
7	Lack of Water	894:56	6	694:10	5	1534:18	6	3123:24	17
8	LDC Instruction	83:58	5	92:37	3	368:35	4	545:10	12
9	High Flood/Reservoir Flushing	0:00	0	0:00	0	0:00	0	0:00	0
10	System Outage	112:29	164	113:12	173	82:03	175	307:44	512
11	Generator Rotor Fault	0:16	1	0:00	0	0:00	0	0:16	1
12	Carbon Brush change/Slip Ring cleaning	0:00	0	0:00	0	0:00	0	0:00	0
13	Excitation Failure	16:37	18	2:22	1	0:53	1	19:52	20
14	Generator Circuit Breaker	13:16	1	0:00	0	1:39	1	14:55	2
15	Generator air cooler change	5:14	1	0:00	0	0:00	0	5:14	1
16	Gas Insulated Switchgear Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
17	Power Transformer Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
18	Transmission Line Maintenance	0:00	0	6:40	1	0:00	0	6:40	1
19	Unit Overhauling/Plant Shutdown	0:00	0	0:00	0	0:00	0	0:00	0
20	External Factors	0:00	0	0:00	0	0:00	0	0:00	0
21	Service Hours	7629:13	0	7856:18	0	6767:14	0	22252:45	0
	Total Observed Hours	8784:00	0	8784:00	0	8784:00	0	26352:00	0

Data Collected for FY 2022/23 (in hh:mm)

S.N.	Events	Unit 1		Unit 2		Unit 3		Total Repair Hours	Total Nos.
		Repair Hours	Nos.	Repair Hours	Nos.	Repair Hours	Nos.		
1	Desander Flushing	4:47	2	8:32	3	12:37	4	25:56	9
2	Intake Backwash	7:01	6	7:14	8	6:06	7	20:21	21
3	Balancing Pipe Repair	0:00	0	0:00	0	0:00	0	0:00	0
4	Bottom Ring Leakage Repair	0:00	0	0:00	0	0:00	0	0:00	0
5	Spiral Case Welding & Repairing	0:00	0	0:00	0	6:03	1	6:03	1
6	Governor Fault	0:00	0	0:00	0	0:00	0	0:00	0
7	Lack of Water	1417:24	6	1440:20	7	1831:51	7	4689:35	20
8	LDC Instruction	53:21	12	12:26	6	57:12	19	122:59	37
9	High Flood/Reservoir Flushing	0:00	0	0:00	0	0:00	0	0:00	0
10	System Outage	89:03	113	109:39	150	76:49	135	275:31	398
11	Generator Rotor/Stator Fault	412:22	1	63:41	1	0:00	0	476:03	2
12	Carbon Brush change/Slip Ring cleaning	1:03	1	1:00	1	0:00	0	2:03	2
13	Excitation Failure	0:00	0	0:00	0	0:00	0	0:00	0
14	Generator Circuit Breaker	0:00	0	0:00	0	0:00	0	0:00	0
15	Generator air cooler change	1:37	1	0:00	0	0:00	0	1:37	1
16	Gas Insulated Switchgear Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
17	Power Transformer Maintenance	0:00	0	0:00	0	42:23	2	42:23	2
18	Transmission Line Maintenance	0:00	0	0:00	0	0:00	0	0:00	0
19	Unit Overhauling/Plant Shutdown	447:00	2	143:13	2	614:57	3	1205:10	7
20	External Factors	0:00	0	0:00	0	0:00	0	0:00	0
21	Running Hours	6326:22	0	6973:55	0	6112:02	0	19412:19	0
	Total Observed Hours	8760:00	0	8760:00	0	8760:00	0	26280:00	0

SAMPLE CALCULATION FOR FY 2021/22

	Data in (hh:mm)	Unit No.1		Unit No. 2		Unit No. 3		Total	
		Repair Hrs.	Count	Repair Hrs.	Count	Repair Hrs.	Count	Repair Hrs.	Count
	Scheduled (SOH)	**1119:24**	**185**	**918:11**	**189**	**2013:21**	**197**	**4050:56**	**571**
	Turbine (TuOH)	0:00	0	0:29	1	0:00	0	0:29	1
	Governor System (GvOH)	0:00	0	0:00	0	0:53	1	0:53	1
	Generator (GOH)	5:30	2	0:00	0	0:00	0	5:30	2
	Unit Circuit Breaker (CBOH)	13:16	1	0:00	0	1:39	1	14:55	2
	Excitation (EOH)	16:37	18	2:22	1	0:53	1	19:52	20
	GIS & Switchyard (SwOH)	0:00	0	6:40	1	0:00	0	6:40	1
	External Factors (EfOH)	0:00	0	0:00	0	0:00	0	0:00	0
	Forced Outage Hours, FOH = TuOH+ GvOH+GOH+CBOH+EOH+SwOH+EfOH	**35:23**	**21**	**9:31**	**3**	**3:25**	**3**	**48:19**	**27**
	Running Hour (RH)	**7629:13**		**7856:18**		**6767:14**		**22252:45**	
	Total Hrs.	**8784:00**		**8784:00**		**8784:00**		**26352:00**	

	Data in hrs.	Unit No.1		Unit No. 2		Unit No. 3		Total	
		Repair Hrs.	Count	Repair Hrs.	Count	Repair Hrs.	Count	Repair Hrs.	Count
	Scheduled (SOH)	**1119.40**	**185**	**918.18**	**189**	**2013.35**	**197**	**4050.93**	**571**
	Turbine (TuOH)	0.00	**0**	0.48	**1**	0.00	**0**	**0.48**	**1**
	Governor System (GvOH)	0.00	**0**	0.00	**0**	0.88	**1**	**0.88**	**1**
	Generator (GOH)	5.50	**2**	0.00	**0**	0.00	**0**	**5.50**	**2**
	Unit Circuit Breaker (CBOH)	13.27	**1**	0.00	**0**	1.65	**1**	**14.92**	**2**
	Excitation (EOH)	16.62	**18**	2.37	**1**	0.88	**1**	**19.87**	**20**
	GIS & Switchyard (SwOH)	0.00	**0**	6.67	**1**	0.00	**0**	**6.67**	**1**

	External Factors (EfOH)	0.00	**0**	0.00	**0**	0.00	**0**	**0.00**	**0**
	Forced Outage Hours, FOH = TuOH+ GvOH+GOH+CBOH+EOH+SwOH+EfOH	**35.38**	**21**	**9.52**	**3**	**3.42**	**3**	**48.32**	**27**
	Running Hour (RH)	**7629.22**		**7856.30**		**6767.23**		**22252.75**	
	Total Hrs.	**8784.00**		**8784.00**		**8784.00**		**26352.00**	

State Probability Calculations for Unit No. 1

State No.	Basic Event	No. of Occur	Total Repair Hrs	MTTR	MTTF	MTBF	Repair Rate	Failure Rate	State Prob
0	Up State								0.868536
1	Scheduled Outage (SOH)	185	1119.40	6.05	41.24	47.29	0.165267	0.024249	0.127436
2	Turbine (TuOH)	0	0.00	∞	∞	∞	-	-	-
3	Governor System (GvOH)	0	0.00	∞	∞	∞	-	-	-
4	Generator (GOH)	2	5.50	2.75	3814.61	3817.36	0.363636	0.000262	0.000626
5	Unit Circuit Breaker (CBOH)	1	13.27	13.27	7629.22	7642.48	0.075377	0.000131	0.001510
6	Excitation System (EOH)	18	16.62	0.92	423.85	424.77	1.083248	0.002359	0.001892
7	GIS & Switchyard (SwOH)	0	0.00	∞	∞	∞	-	-	-
8	External Factors (EfOH)	0	0.00	∞	∞	∞	-	-	-

d0	0.004907
d1	0.000720
d2	-
d3	-
d4	0.000004
d5	0.000009
d6	0.000011
d7	-
d8	-
D	0.005650

State Probability Calculation for Unit No. 2

State No.	Basic Event	No. of Occur	Total Repair Hrs	MTTR	MTTF	MTBF	Repair Rate	Failure Rate	State Prob
0	Up State								0.894388
1	Scheduled Outage (SOH)	189	918.18	4.86	41.57	46.43	0.205841	0.024057	0.104529
2	Turbine (TuOH)	1	0.48	0.48	7856.30	7856.78	2.069108	0.000127	0.000055
3	Governor System (GvOH)	0	0.00	∞	∞	∞	-	-	-

d0	0.026994
d1	0.003155
d2	0.000002
d3	-

4	Generator (GOH)	0	0.00	∞	∞	∞	-	-	-	d4	-
5	Unit Circuit Breaker (CBOH)	0	0.00	∞	∞	∞	-	-	-	d5	-
6	Excitation System (EOH)	1	2.37	2.37	7856.30	7858.67	0.422529	0.000127	0.000269	d6	0.000008
7	GIS & Switchyard (SwOH)	1	6.67	6.67	7856.30	7862.97	0.149999	0.000127	0.000759	d7	0.000023
8	External Factors (EfOH)	0	0.00	∞	∞	∞	-	-	-	d8	-
										D	0.030181

State Probability Calculation for Unit No. 3

State No.	Basic Event	No. of Occur	Total Repair Hrs	MTTR	MTTF	MTBF	Repair Rate	Failure Rate	State Prob		
0	Up State								0.770405	d0	0.076006
1	Scheduled Outage (SOH)	197	2013.35	10.22	34.35	44.57	0.097847	0.029111	0.229207	d1	0.022613
2	Turbine (TuOH)	0	0.00	∞	∞	∞	-	-	-	d2	-
3	Governor System (GvOH)	1	0.88	0.88	6767.23	6768.12	1.132118	0.000148	0.000101	d3	0.000010
4	Generator (GOH)	0	0.00	∞	∞	∞	-	-	-	d4	-
5	Unit Circuit Breaker (CBOH)	1	1.65	1.65	6767.23	6768.88	0.606061	0.000148	0.000188	d5	0.000019
6	Excitation System (EOH)	1	0.88	0.88	6767.23	6768.12	1.132118	0.000148	0.000101	d6	0.000010
7	GIS & Switchyard (SwOH)	0	0.00	∞	∞	∞	-	-	-	d7	-
8	External Factors (EfOH)	0	0.00	∞	∞	∞	-	-	-	d8	-
										D	0.098657

	Unit No. 1	**Unit No. 2**	**Unit No. 3**
Reliability	0.995972	0.998917	0.999611
Availability	0.868536	0.894388	0.770405

LOSS OF SALES OF ELECTRICITY CALCULATION ALL UNITS

FY	Per Unit Capacity (MW)	NEA System Loss %	Unit Rate (NRs. /kWh)	Unit No. 1			Unit No. 2		
				Forced Outage Hrs	Energy Expected Not Supplied (MWh)	Loss of Sales of Electricity (NRs.)	Forced Outage Hrs	Energy Expected Not Supplied (MWh)	Loss of Sales of Electricity (NRs.)
2016/17	48	22.90	10.00	96.15	3,558.32	35,583,192.00	2.08	77.10	770,987.66
2017/18	48	20.45	10.10	19.32	737.59	7,449,647.62	46.92	1,791.47	18,093,819.46
2018/19	48	15.32	10.65	24.28	987.06	10,512,158.94	14.88	604.94	6,442,614.95
2019/20	48	15.27	10.92	20.47	832.38	9,089,642.11	20.22	822.22	8,978,656.33
2020/21	48	17.18	9.68	17.62	700.33	6,779,167.73	38.37	1,525.21	14,764,048.89
2021/22	48	15.38	9.30	35.38	1,437.19	13,365,855.73	9.52	386.55	3,594,873.28
2022/23	48	15.38	9.30	415.03	16,857.66	156,776,206.06	64.68	2,627.28	24,433,707.78

FY	Per Unit Capacity (MW)	NEA System Loss %	Unit Rate (NRs. /kWh)	Unit No. 3			Total of Station	
				Forced Outage Hrs	Energy Expected Not Supplied (MWh)	Loss of Sales of Electricity (NRs.)	Energy Expected Not Received (MWh)	Loss of Sales of Electricity (NRs.)
2016/17	48	22.90	10.00	4.18	154.82	1,548,155.66	3790.23	37,902,335.33
2017/18	48	20.45	10.10	27.63	1,055.15	10,657,014.26	3584.21	36,200,481.34
2018/19	48	15.32	10.65	11.96	486.25	5,178,593.21	2078.25	22,133,367.10
2019/20	48	15.27	10.92	19.53	794.43	8,675,144.20	2449.03	26,743,442.64
2020/21	48	17.18	9.68	32.32	1,284.71	12,435,946.00	3510.24	33,979,162.62
2021/22	48	15.38	9.30	3.42	138.77	1,290,599.06	1962.51	18,251,328.06
2022/23	48	15.38	9.30	48.43	1,967.24	18,295,372.98	21452.18	199,505,286.82

Evaluating the Reliability and Availability of Kaligandaki "A" Hydropower Station (144MW) using a Markov-Based Approach.

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