TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

Thesis No. M-111-MSTIM-2018/2020

Strategy Selection for Reliability-Based Maintenance in Hydropower: A Case Study on Bijaypur-I Small Hydropower Plant

by

Rajan Sharma

A THESIS

SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER IN

TECHNOLOGY AND INNOVATION MANAGEMENT

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

LALITPUR, NEPAL

AUGUST, 2020

COPYRIGHT

TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled "**Strategy Selection for Reliability-Based Maintenance in Hydropower: A Case Study on Bijaypur-I Small Hydropower Plant**" by Rajan Sharma in partial fulfilment of the requirements for the degree of Master in Technology and Innovation Management.

____

Supervisor, Dr Nawraj Bhattarai
Assoc. Professor
Department of Mechanical and Aerospace Engineering

____

External Examiner, Dr. Bibek Baral
Professor
Department of Mechanical Engineering
Kathmandu University

____

Committee Chairperson, Dr. Nawraj Bhattarai
Head of Department
Department of Mechanical and Aerospace Engineering

Date:

ABSTRACT

This study presents the Strategy Selection for Reliability-Based Maintenance in Hydropower: A case study is being carried out within the scope of the master thesis of MSc in Technology and Innovation Management, under the Department of Mechanical and Aerospace Engineering. This study is based on the case study of 4.5 MW Bijaypur-I Small Hydropower Plant located in Pokhara-Lekhnath Metropolitan city of Gandaki Provenance. The main objective of this study is to study the reliability and availability of the Bijayapur hydropower plant to find out the critical failure event that affects the reliability and availability of the plant and to recommend a maintenance strategy that can uplift the reliability and availability of the plant. This paper approaches the selection of a strategy for the implementation of reliability based maintenance, especially in hydropower. To achieve the above mention objectives, firstly the Fault Tree of Bijaypur-I small Hydropower plant was developed based on different failure events recorded on the maintenance log sheet. From the study of the past seven years' failure data of BSHP-I, the reliability and availability of the plant were analyzed. And by computing the fault tree the criticality of each event was determined to find the critical assets. And then suitable maintenance strategies were recommended with the help of Failure Mode and Effect Analysis technique and Critical Analysis Technique. The study concluded that the reliability of BSHP-I was only 0.986 which is lower than the Sunkoshi Hydropower Plant and the water management problem is the main contributing event and the cooling system was concluded as the main contributing component which is marked as critical assets. This study firstly concludes Radial Tube Filter choking is the main failure mode that affects the performance of the cooling system from Failure mode and effect analysis. And recommend the maintenance strategy for as a whole to the cooling system and also highlights some of the strategies

except preventive maintenance, to improve the reliability of the cooling system such as redundancy, increase the time of flushing, use of cyclone separator to separate the dissolved limestone and dissolved sand and to use close loop cooling system instead of an open system. Besides this, the study also suggests the maintenance strategy for BSHP-I by critical analysis of the various component of the hydropower plant which will be helpful to reduce the cost of maintenance by balancing the cost of preventing maintenance and breakdown maintenance.

ACKNOWLEDGEMENT

I would like to acknowledge my sincere appreciation towards my thesis supervisor Associate Professor Nawraj Bhattarai for his genuine supervision throughout the proceedings of the thesis. Likewise, I would like to express my gratitude to Dr Sanjeev Maharjan, Program Co-ordinator, MSc in Technology and Innovation Management for his encouragement before and during my thesis period. I am thankful to the Head of Department and the faculties of the Department of Mechanical and Aerospace Engineering for providing me with this opportunity to conduct the thesis work.

I am grateful to Mr Subash Bhandari, Assistance manager Operation and Maintenance section, Bijaypur-I Small Hydropower Plant, and Er. Rajendra Prasad Bhatta for providing valuable information regarding the operation and maintenance of hydropower, data, and other relevant information. I would also like to thank Er. Sushant Raj Giri, Er. Sudan Neupane and Er. Bishworam Parajuli for their valuable support in completing the thesis work.

Every effort has been made to give credit where it is due for the material contained herein. If inadvertently I have omitted giving credit to those persons, I would like to thank all those who have helped in this project directly and indirectly.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURE

ABBREVIATIONS

AEPC	Alternative Energy Promotion Centre
AHP	Analytical Hierarchy Process
BSHP-I	Bijaypur-I small hydropower project
CbM	Condition Based Maintenance
DHM	Department of Hydrology and Meteorology
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GoN	Government of Nepal
NAST	National Academy of Science and Technology
NEA	Nepal Electricity Authority
PM	Preventive Maintenance
RCC	Reinforced Cement Concrete
RCM	Reliability Centered Maintenance
WECS	Water and Energy Commission Secretariat

CHAPTER ONE
INTRODUCTION

1.1 Background of Study

Reliability engineering is a very fast-growing and one of the important fields especially for two parties, those who deliver goods and services and those who consume these delivered goods and services. It provides the framework that estimates the probability and capability of a system, to perform their required functions for the desired period and in prescribed conditions of operation without failure. Its results work as feedback to different kinds of operations such as to design the product, to manufacture the product, for the quality control, for quality inspection and testing during packaging, transporting and receiving the goods and services to improve the current process and implement the corrective measures. All kinds of industries need to establish the reliability standards of their products and services. They have to set these parameters to an optimum level which yields the maximum satisfaction to their customer so that they can survive in today's competitive market.

Nepal has a large number of rivers, which creates a dense network with a steep topographic condition. Among them, the Karnali, Sapta-Gandaki, and Sapta-Koshi, are considered as the major river. Most of these river uplift from the lap of Himalayan ranges and transverse through the mountain ranges to form deep river valleys. This shows the huge potential of hydropower in Nepal. It is estimated that, Nepal's theoretical Hydropower potential as 83000 MW. And its technical and economic feasibility is stated as about 45000 MW and 42000 MW respectively. (WECS, 2010). NEA along with the Government of Nepal has fostered plans to develop hydropower and electricity consumption areas such as the replacement of fossil fuel-based vehicles with electric vehicles. However, frequent electricity outage due to poor reliability, and most of the areas have no access to power due to difficult topography are considered as the most serious infrastructure bottlenecks. Increasing access to electricity during a timely and cost-effective manner is one of the foremost significant challenges in development facing today. Ironically, Nepal has one among the most important untapped hydropower resources within the world, as neighbours China and India are among the fastest-growing economies within the world, and all south Asian countries are hungry for the clean and reliable Hydropower energy of Nepal.

Bijayapur – I Small Hydropower Project (BSHP-I) is a multipurpose, Run of the river type, 4.5 MW small hydropower project located at Pokhara-Lekhnath Metropolitan city of Gandaki Provenance. It uses the water of Bijayapur Khola and Sheti Irrigation Drainage, which is 2 km from the Prithvi Highway. With rated Design head 65.4 m and discharge 8.3 m3/s is operating since Bhadra 9, 2069 BS. BSHP-I was developed by Bhagabati Hydropower Company (p) ltd, with the financed of Rashtriya Banijya Bank, Nabil Bank, and Nepal Bank Ltd. It has two units of horizontal shaft Francis turbines to generate electricity. It has around 30m long stoned lined free flow weir with two under sluice 2 vertical gates. The headrace channel is RCC Closed Canel with length 242 m. Descender is of RCC Dufour type with 2 basins with forebay at the end. The Desender and the Hydropower is connected by 634 m long 2.5 m Diameter welded Ribbed penstock pipe made of mild steel (IS 2062-B). The powerhouse covers a 23x11 m surface area with an outdoor switchyard. The tailrace is cut and covers Rcc type and is 302 m long which guides the water to the Bijaypur Khola. BSHP-I has a 4 Km 33KV single circuit transmission line which interconnects to the National Grid at NEA 132 kV substation at Lekhnath, Kaski.

BSHP-I has two units with a capacity of 2250 MW each. Each unit consists of sub-components such as the Descending basin, penstock, pressure pipe, governor, generator, cooling system, etc which affects the reliability and availability of the plant. In this study, the reliability and availability of each unit are calculated to find the most critical assets i.e component. So that we can focus on the maintenance of that component, which can help to improve the overall performance of the plant.

1.2 Introduction

It is one of the essential needs of any production system to enhance the reliability of their assets. And to promote uptime and availability is taken as the most important factor within the growing competition in commodity and service industries. This uplifts the importance of maintenance practices in the system. Additionally, due to practising different kinds of maintenance strategies, the overall cost of the system gets increased, which is considered as the foremost important reason for seeking simpler ways of maintaining production assets and also that ensures the reliability of the assets. Reliability centred maintenance is a technique that develops maintenance strategies by focusing on the reliability of assets. It is found that RCM emerged in the 1960s as an option for Preventive Maintenance to ensure the reliability of even basic parts of the aircraft industry. The main defects of PM were its expensive nature and it was not able to predict the upcoming failure and its consequences. So RCM works on the thought of preventing potential failure which could have serious consequences. And responses to the heavy increased maintenance costs due to PM following the introduction of wide-body jets. After that RCM begins to implement in the nuclear energy sector, the oil pumping stations, and gas industries, showing the result of significant savings in maintenance costs and ensure the availability of production systems. And the RCM begins its long way by establishing its influences in many other industries.

RCM is a qualitative technique of maintenance and only focused on one part that is most important in the system and is unable to satisfy all the requirements of all types of industries. So another type of maintenance derived from the philosophy of RCM as Risk-based Reliability Centered Maintenance also known as Reliability-based maintenance. Reliability-based maintenance is a technique that ensures the reliability of the system by adopting the special maintenance strategies to the critical assets where all other assets remain to run to failure or proactive or preventive as per the criticality. As it realizes the best level of reliability within the equipment and thus within the components of the entire system. So that it reduces the value of the equipment lifecycle and equipment criticality within the system and reduces the force spent on an unnecessary maintenance program. So Reliability-Based Maintenance is considered as the integral approach of all the maintenance strategies, which takes all the advantages of RCM, Preventive, Proactive and Run to failure maintenance

1.3 Statements of the Problem

Maintenance is any activity that is carried out to preserve the assets of the organization. Hydropower is additionally such a kind of plant which is greatly littered with the maintenance strategy. In Nepal Department of Electricity Development classify five sort of technical maintenance strategies for the hydropower station, which are Run to failure Maintenance, Preventive maintenance, Proactive maintenance, Predictive Maintenance, and Reliability centred maintenance. Generally, preventive maintenance is taken into account to be worthwhile, despite its drawbacks like the huge cost of implementation and requires specialist labour. Therefore, preventive maintenance is an uneconomical strategy for all types of machinery and equipment of the production system whose breakdown does not affect the performance of the production system in the sense of cost or safety of the employee beyond a limit. In most cases, the breakdown maintenance approach is applied from an economic point of view but it creates uncertainty within the system and greatly affects the reliability and availability of the system. Since most of the hydropower operated in Nepal are small hydropower i.e. ranges from 1-25MW as per the government classification (WECS, 2010), for this hydropower it's non-economical to hire an electromechanical expert which is required to implement preventive maintenance and also preventive maintenance is one among the expensive sorts of maintenance activity. Thus it's better to adopt an integrated method to preserve the function of the assets. This method is usually referred to as Reliability-Based Maintenance. Reliability-Based maintenance is considered collectively of the best known and is the intricated form of maintenance which collectively includes the advantages of all types of maintenance as per their criticality in the production system but remains unimplemented, due to lack of proper methodology and tools. (AfefyIslam, 2010). So it is required to propose a general Reliability-Based Maintenance model suitable for hydropower plants which can organize an appropriate maintenance strategy to uplift the reliability of the hydropower plant.

1.4 Research Objectives

1.4.1 Main Objective

- To Study the Reliability and Availability of the Bijaypur-I Small Hydropower plant for the selection of a Reliability-based maintenance strategy.

1.4.2 Specific objectives:

- To Develop the fault tree of Bijaypur-I small Hydropower plant
- To evaluate the reliability and availability of the Bijayapur-I Small Hydropower plant to find the critical assets of the plant.
- To develop a maintenance strategy to improve the reliability of the plant.

1.5 Rationale of the Study

The government of Nepal features an attempt to increase the rate of per-person energy consumption from 198 kWh to 700 kWhr at the top of the 15th five-year plan (National committee, 2019). The government plan will be successful only when the consumer which are using traditional fuels like firewood to another kind of energy called electricity which features a large range of utilities and applications. Research shows that consumers are willing to possess a sustainable energy transition from traditional fuels to electricity and willing to pay 19 to 25 % of the existing average monthly bill for reliable electricity supply. And a reliable electricity supply is feasible only when the source is reliable. If we analyze this situation of Nepal, Hydropower potential has been estimated at 83000 MW and its technically and economically feasible potential is about 45000 MW and 42000 MW respectively (WECS, 2010). Whereas the present scenario may be a bit different, the Total Design Generation capacity of Hydroelectricity within the FY 075/76 was 331998.00 MWh, and therefore the Actual Generation of NEA owned Power plants within the same period was only 2541116.20 MWh with the lacking of 778863. 84 MWh (Nepal Electricity Authority, 2076) showing the reliability of the hydropower plant. To make sure quality and reliable operation of the equipment, to maximize the supply of kit with the smallest amount number of pack up and Eradication / non-repetition of operational problems, and also to extend the profitability of hydropower, planned maintenance is required. Reliability-Based Maintenance may be a technique to develop strategies to extend the reliability and availability of the system. So this study will foster the method of selection of maintenance strategy which can increase the reliability and availability of the hydropower plant, and also will visualize the clear figure of reliability and availability with the factor which adversely affects the reliability and availability of the hydropower plant.

1.6 Limitations of the Study

The limitation of this study are listed below:

- This Study is based Based on data provided by the management of Bijayapur-I Small Hydropower Plant
- This study does not deal with the implementation side of the strategy as it only recommends the strategy as per the literature.

- The study only focuses on the failure event that was recorded in the maintenance log sheet of BSHP-I so the fault tree present in this study may not respond to other types of failure which did not occur in BSHP-I.
- The study focuses on failure related to small hydropower so similar failure have different criticality in medium and big hydropower

CHAPTER TWO
LITERATURE REVIEW

2.1 Energy Scenario in Nepal

It is a renowned incontrovertible fact that the economic and social development of the country is reflected by the energy consumption pattern of that country. The per capita energy consumption of Nepal is 146 kWh and Iceland have 53832 kWh being within the first position during a world rank and with 23000 kWh per capita Norway being within the second position. (The world bank Group, 2020). Most of the people of Nepal depends heavily on the traditional type of energy resources, and to date, no significant source of deposits are available in a consumable form. In Nepal, the available energy resources are classified into three categories as Traditional energy resources, Commercial energy resources, and Renewable and Alternative Energy Resources. In Traditional Energy resources, a common type of biomass fuel such as solid biomass extracted from different kinds of plants and animals falls into these categories. Hydropower, petroleum, gas, and coal are the main commercial sources utilized in the country. Solar, biogas, and wind energy are the main energy resources, which are categorized as alternative energy resources and are the main source of energy to satisfy the necessity for energy within the countryside of Nepal. (WECS, 2014)

Nepal is being located at a must suitable latitude that receives maximum solar radiation. The typical radiation arises from 3.6 to 6.2 kWh/m^2/day and the sun shines for about 300 days per annum, with a billboard potential of solar energy for grid connection estimated to be 2,100 MW. (NAEEN, 2017). Due to the various topography and the consequent variation within the metrological conditions, it's difficult to generalize the wind conditions within the country. The Department of Hydrogeology and Metrology has concluded from their study that wind might be used to generate electricity within the hills and for irrigation and pumping of beverage within the terai. The collective research of AEPC, NAST, WECS, and DHM within the year 1999-2002, shows that there's not a high potentiality of wind energy apart from some high mountain location such as Khambu, Thakmarpha, and so on shows, the commercial potential of wind energy generation is 3000MW. (NAEEN, 2017).

As per the report presented by Water and Energy Commission Secretariat, the entire energy consumption of the country is fulfil by fuelwood, which is about 71%. Commercial Sector uses whose 94.7% is employed within the residential sector, 2.6% within the Industrial Sector, and 2.7%. Among the varied sorts of energy, Grid Electricity carries only 2.82% of total energy consumption whose main source is Hydropower. (WECS, 2014)

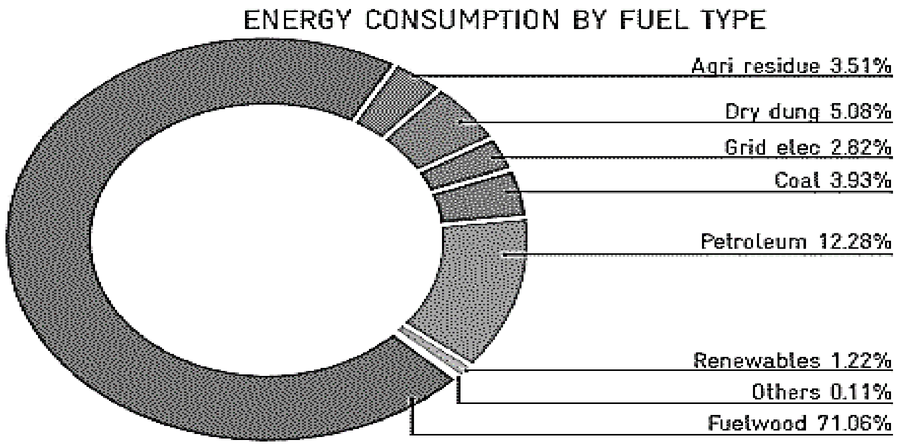


Figure 2-1: Energy consumption pattern of Nepal by fuel type *Source: (WECS, 2014)*

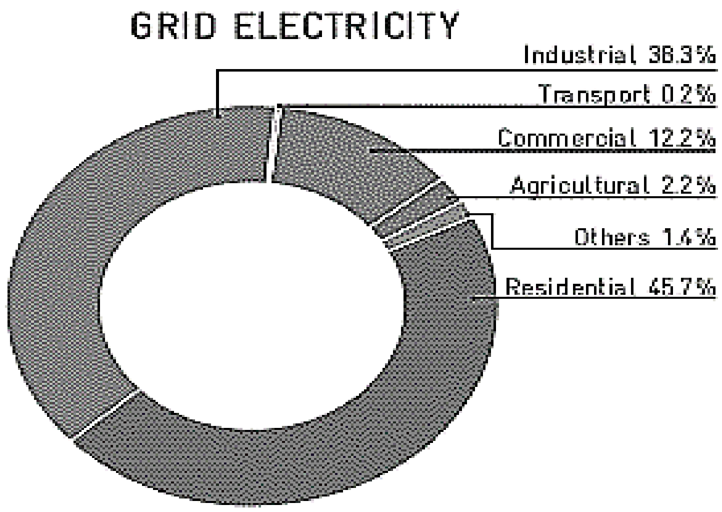


Figure 2-2: Electricity consumption pattern in Nepal. *Source: (WECS, 2014)*

2.2 Hydropower and it's Potential in Nepal

Simply, Hydroelectricity can be defined as the energy derived from the conversion of kinetic energy carried by water into electricity. It is considered a renewable source of energy, as the water cycle continuously renewed by solar radiation. It is found that before the generation and availability of electricity, hydropower was used for mechanical millings and other forms. To date, we can see this type of energy conversion in some parts of the country where electricity is not available. If we realize the worldwide energy generation, about 16.6% of the total world's electricity is covered by hydropower. And this covers almost 70% of all renewable electricity generated until 2018 and expected to increase by about 3.1% annually for the subsequent 25 years. (International Hydropower Association Limited, 2018) . It is projected that the population of the world will be 8.8 billion by 2035 and the needs of energy will be increased by 34% till 2035 than now. If we analyze the data of energy generation in the year 2015, the generation capacity of renewable sources such as hydropower, geothermal, and biomass is found as 1079GW, 14GW, and 52 GW respectively. And projected these variables will be increased to 1473 GW, 132GW, and 275 GW, respectively for 2040 (REN21, 2019).

It is renowned that, Nepal has a high potential of renewable water resources and covers almost 2.27% of the world's water resources. Almost 5% of the total area of the country contains the high Himalayas where all the part is covered by snow all around the year. Nepal possesses more than 6000 rivers and most of which uplift from the lap of the Himalayas. It is found that 33 rivers classify as big river and their drainage areas exceed almost 1000 km^2. It is estimated the annual average discharge is about 7124 m^3/s including the entire basin area. (WECS, 2011) The three major rivers, Koshi, Gandaki, and Karnali incorporates almost 84% of the total amount of water of the country and it is estimated that the storage capacity of Nepal's river is about 202000 Mega m^3. As most of the river flows from the steep gradient and rugged topography so it is estimated that 45,600 MW electricity can be generated technically from these three river basins. This is almost 50% of the entire theoretical potential of the country. (Ismail, 2017).

Most of the hydropower in Nepal is run of the river type due to startup cost, however, it needed to develop the storage type of hydropower for the sustainable development of hydro energy in Nepal. This type of hydropower scheme has great importance and benefited to regulate floods, to provide irrigation facilities to the agricultural land, fishery, navigation, tourism, and to generate revenue by selling electricity during the dry season. (Bhatt, 2017).

2.3 Hydropower Development in Nepal

The history begins with Rana Prime minister Chandra Shamsher Janga Badhur Rana, who establishes the first hydropower in Nepal on May 22, 1911 (9 Jestha 1968 BS) at Pherping. It was of capacity 500kW and named Chandra Jyoti, facilitating the limited consumer of Kathmandu valley. After the establishment of the first hydropower of Nepal, it takes almost 25 years for the establishment of the second hydropower. At Sundarijal Kathmandu, Prime Minister Dev Shamsher establish a 640 kW Sundarijal Hydropower plant in 1936 AD. This was the breakthrough for the development of electricity in Nepal. After that a private company, Morang Hydropower Company was established and it completes the construction of the 1800kW third Letang hydropower plant under the public-private partnership basis. After that different hydropower begins to establish and the development of hydropower speed up from the bilateral agreements with India in Koshi and Gandak Projects (Bhatt, 2017).

After that different hydropower such as Panauti hydropower was constructed with the foreign grant of ex-USSR, Trisuli, Devighat, Gandak, Surajpura-Koshi were constructed from the grant of India, and Sunkoshi hydropower was constructed as the gift of china government during the late 1960s. After that, storage type 92 MW Kulekhani Hydropower Plant (I and II) was commissioned in 1982, and Nepal's largest hydropower Kali Gandaki-A hydropower project with a capacity 144 MW commissioned in 2003 (Bhatt, 2017). After that, the pace of development of hydropower in Nepal gets decreases due to the 10 year-long civil war and political instability.

As per Nepal Electricity Authority, Nepal has almost 42,000 MW economical feasible hydropower potential, 100 MW electricity can be generated from micro-hydro power, an optimum 2100 MW of electricity can be generated from solar energy for the grid, and 3000 MW from the wind energy but it seems many limitations for the extraction of electricity from wind. Nepal’s ninth five-year plan addressed to get 22,000 MW electricity by 2017 and other different bodies estimates to generate 10,000 MW within

10 years and 17,000 MW by 2030. But there's no significant impact on electricity production. As per the report on Nepal Electricity Authority, the Total Design Generation capacity of Hydroelectricity within the FY 075/76 was 331998.00 MWh from the hydropower of total installed capacity 1250MW. Among them, 622 MW of electricity is generated from the NEA owned power station and 561 MW from Independent power producer 61 MW from AEPC. Among the entire Installed capacity, the contribution of hydropower is 90.24% and other sources are 9.76%. (Nepal Electricity Authority, 2076).

2.4 Maintenance in Hydropower

Every element in this universe have their own life and it is not limited to equipment or assets also, which we used in our daily life. This means that likewise, a man dies after being old, machines also unable to functions well after a prescribed period. It is said that a well- maintained equipment with proper maintenance will serve for a longer period effectively and efficiently. So maintenance is that process that helps in keeping specific assets in its designed operating condition so that it can deliver its work with no loss of time due to breakdown or accidental damage. In other words, Maintenance means the activities required to be done to stay equipment during a designed operating condition such as it delivers its work efficiency for the maximum amount of your time. From the above definition, we can conclude that "Maintenance is about preserving the functions of the assets, not only the preserving physical assets" Which is that the new concept and that we need to undergo it. The government of Nepal, Department of Electricity Development classify five sorts of maintenance in hydropower.

Preventive Maintenance: It is the oldest form of maintenance strategy which was developed after world war-II. Also, it is one of the popular maintenance strategies in all the type of industries. Inspection, lubrication, replacement, repair based on time, and prescribed parameters are the basic activities of preventive maintenance. The main intension of Preventive maintenance is to prevent the initiation of the failure. It recurred the failure events before occurs by routine maintenance and comprehensive maintenance procedures. Generally, preventive maintenance is applied to enhance the equipment life and to avoid any unplanned maintenance activities. It attenuates unexpected breakdown and excessive deterioration of the machine parts which helps to achieve more predictable, shorter, and fewer breakdowns in the system. Because of its benefits like it prevents major problems, thus reduces forced outage, assures equipment is being maintained, justified, and understandable, it is widely applicable in most of the hydropower. While it has some limitations such as it is a time-consuming and resource-intensive maintenance strategy and requires special kinds of manpower i.e for mechanical maintenance it requires a mechanical foreman and for electrical, electrical foreman and other as per specified field is required, so it is a costlier strategy and may cause problems in equipment additionally to solving them, e.g., damaging seals, stripping threads (Department of Electricity Development, 2017).

Reliability-Centred Maintenance: It is a qualitative technique of maintaining assets, that contribute more to the system. It has the aim to eliminate the unwanted maintenance activities that do not value add maintenance activities. It facilitates the maintenance strategy as per the need and requirement of the particular assets in the system. It is an ongoing process and is the integral form of all three types of maintenance strategy. It determines the particular maintenance strategy for each equipment of the system and gives a special focus on the critical assets. Its main theme is that not all the equipment/components in the system have equal importance, which leads to different criticality. It recognizes that the design and operation of every equipment differ therefore the likelihood of failure differs from equipment to equipment (Alternate Hydro Electric Centre, 2011). In this strategy, diagnostic tools and measurements used to assess when a component is near failure and will get replaced. In this maintenance strategy, unimportant maintenance activities left to the reactive maintenance approach. It has features such as (Department of Electricity Development, 2017)

- It is difficult to line up initially and also labour-intensive.
- Different condition monitoring equipment may be required to implement RCM effectively.
- It recommends breakdown maintenance for the assets except for critical assets which may attract the concern of managers.
- It is a continual improvement approach of maintenance and some of the activities are based on a trial and error basis, so its effectiveness may be low in the initial phase of implementation.

Predictive Maintenance: This maintenance strategy ensures the power to evaluate when the specific part or component of the machine may fail and need to replace it before it fails the whole system. Generally, it uses some testing equipment to take some data which shows the status of the equipment so that it can help to predict an imminent failure. From this technique, the past and present data records are analyzed, to trace the performance of equipment. So for predictive maintenance strategy, the data during normal operation are required to detect possible defects and fix them before they fail. In hydropower stations, there are many monitoring systems, which may be used to predict problems and possible failures. These include oil analysis, vibration monitoring, temperature, IR values of generation, system loading, leakages of oil and water, and efficiency in power generator output. All of those data are often captured, tracked, and analyzed through computer systems or filling simply the log-book at regular intervals. The results of the analysis of knowledge can predict the longer term. (Department of Electricity Development, 2017). When predictive maintenance strategizes are implemented in a plant it will predict the functioning conditions of the plant and equipment and helps to return the machine to the functioning condition before failure is probably going to occur. This may lead to various cost savings like less maintenance time, helps to predict the material planning, reduce the value of spare parts and supplies, and also helps to minimize the assembly time. But this type of maintenance strategy has several limitations like the need for the specialized labour force, high start-up costs, and the restrictions of some equipment.

Proactive Maintenance: It is a maintenance technique that is more effective if it is applied to improve performance. It adopts the philosophy "not to repeat the problem". So it utilizes the "root cause failure analysis technique" to access the root cause of the failure and apply the strategy so that that problem does not repeat in the future. (Alternate Hydro Electric Centre, 2011).

Reactive (Run to Failure) Maintenance: It is popular as the name of breakdown maintenance. In this strategy, assets are allowed to work until they break down. It is the oldest form of maintenance strategy which is being applicable from the first Industrial revolution. It is considered as an economical but non-reliable type of maintenance strategy, which does not require special manpower to implement, like other types of maintenance strategy. Sometimes it is also called crisis maintenance or hysterical maintenance. So in any plant, it should be a very small part of a contemporary maintenance program. It has advantages like Minimal planning, Easy to know, economical in maintenance aspect while it has disadvantages like it is unpredictable and inconsistent because the failure is in random nature and planning of staff and resources are often difficult. Also if this strategy adopts, the maintenance department must hold spare parts in inventory to fulfil the demand for spare parts in intermittent failures. (Department of Electricity Development, 2017)

Besides these classifications, maintenance can be classified into four categories as per their development phases. Firstly the word maintenance used in the 1940s, so the period of 1940 to 1955 is classified as the first generation of maintenance. In this period, maintenance refers to those activities which are related to fixing the part or component when they get the breakdown. So basic and routine maintenance activities and corrective maintenance were the types of maintenance that were developed in this period so they are classified as the first generation of maintenance. After this period from 1955 to 1975 AD, the philosophy of maintenance has changed. In this period maintenance was defined as activities that protect the equipment or component from breakdown. So different kinds of maintenance strategies were developed. Some of them are planned/ preventive maintenance strategy, time-based maintenance strategy, the system for planning and controlling work strategy, etc. These strategies have the same moto to stop the possible future breakdown in any machinery parts. After 1975, the word becomes globalized, and due to rapid technological advancement and the awareness in the general consumers, the producer needs to provide their goods and services with additional features called reliability. So to survive in this competitive global market, the producer has to ensure their goods and services are reliable. For this, they search for a suitable maintenance strategy which is economical and ensures the system is reliable. In this era, maintenance has been defined as the activities which help to ensure the assets will provide the desired function in a specified time. So in this period, different kinds of maintenance strategies were developed such as condition-based maintenance, Reliability centred maintenance, proactive and strategies thinking strategies, etc. And categories as the third generation of maintenance. Furthermore, after 2000 onward, the philosophy of quantifying risk comes into account, as per this philosophy different kind of maintenance such as Risk-based maintenance, Risk-based life assessment, Reliability-based maintenance, Risk-based Reliability centred maintenance was developed and are considered as the fourth generation of maintenance. The main theme of these maintenance strategies is to quantify the risk and measure the activities that are intended to preserve the function of an asset. (N.S & J, 2007).

2.5 Reliability Engineering

Reliability engineering is an engineering discipline, it deals with different scientific tools and techniques that can apply in the system so that the component, product, process, or plant will ensure that they can perform their prescribed function in the specified time, in a specified environment without any failure. So its emphasis on the dependability of different parameters within the lifecycle management of the product. It also helps to identify the actual ability of a system or component to function under stated conditions for a specified period. So reliability engineering helps to understand a product lifecycle from a reliability point of view, i.e, any product has to survive for several years of its life by ensuring its designed function, despite all the threatening stresses such as temperature, pressure, vibration, shock, and other environmental factors that may be applied to it. From this, the term reliability can be generalized as how long an item will perform its intended function without a breakdown. (Kiran, 2017).So it is the probability that something will work efficiently once when we want to do it. From this it is clear that the definition of Reliability has four important elements:

Probability: It is a value between 0 and 1 specifies the number of times a particular event can occur divided by the total number of trials.

Performance: It defines the criteria for selecting the event. Performance specifies the conditions when the criteria are considered as success or fail for the satisfactory operation of the system.

Time: It is an important parameter to define the reliability of a system. It denotes the time until when the system will work without failure.

Operating conditions: Another important parameter that describes the reliability is its operating condition. It is obvious that a machine designed to operate at a temperature of 40^0C may not give the same performance and may not possess the same reliability in the operating temperature of 10^0C. So these operating conditions describe the environment of operation that corresponds to the stated product life. (Kiran, 2017)

2.5.1 Basic Reliability Terms

Failure: Failure is defined as the event that an asset unable to provide its intended function satisfactory in a specified condition. (Smith, 2001)

Failure Rate: It is the frequency of failure event that repeats in a specified period. The period may be in the day, month, year, or millions of hours. (Smith, 2001)

Hazard: It describes the potential to create an event. So it refers to the potentiality that can create a failure event in the system. (Smith, 2001)

Risk: Risk refers to the occurrence of undesirable events from hazards. There are different hazards but may not have occurred on the system, which means the likelihood is minimum so the risk is also minimum. So risk refers to the likelihood of hazard to create an undesirable event (Smith, 2001)

Mean Time to Failure (MTTF): It refers to the time that the system operates before the first failure after the installation under specified conditions. (Smith, 2001)

Mean Time to Repair (MTTR): It is the time required to bring the system upstate when it gets failure. (Smith, 2001)

Mean Time Between Failures (MTBF): It is the average time that the system operates between two failure events. Mathematically, this is the sum of MTTF and MTTR. (Smith, 2001)

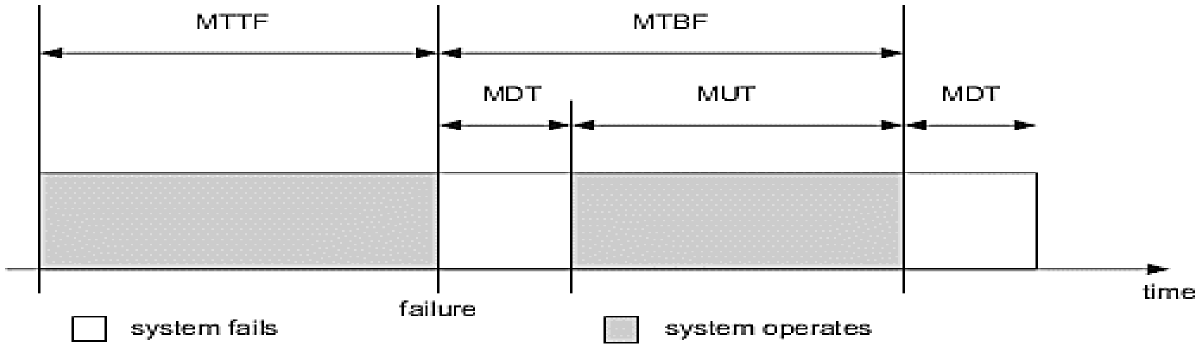


Figure 2-3: Representation of MTTF, MDT, MTBF and MUT Source: (Smith, 2001)

2.5.2 Reliability Characteristics

Non-Repairable Systems: In non-repairable systems, such as bearing, o-ring, etc the reliability and availability represent the same things and these possess only Mean time to failure and total life is the time to the first failure.and as they are no reparable so they do not have repair rate. (Smith, 2001)

Repairable Systems: It refers to reparable items such as Machinery, vehicles, etc. In such a system, Reliability is the function of failure rate and availability is the function of reliability and maintainability. And these system possesses both failure rate and Repair rate. And Mean time between failure is considered as an important reliability parameter. (Smith, 2001)

2.5.3 Maintainability:

It refers to the easiness to restore the system to its original operating condition after it fails to operate its designed function. In an organization, it determines the effectiveness of maintenance personnel. And in the design stage, it is the measure of the power of a system that restores to its operating condition when maintenance is carried out by a qualified person. Maintainability is often measured with Mean Time To Repair (MTTR), MTTR is average repair time and is given by

$$MTTR = \frac{Total\ Maintenance\ Down\ Time}{Total\ Number\ of\ Maintenance\ Actions.}$$ *Eq. 2-1 (Smith, 2001)*

Maintainability of a system can be calculated by using the following relation

$$M(t) = 1 - e^{-t/MTTR}$$ Eq 2-2 *(Smith, 2001)*

Where: t = Allowable downtime

MTTR= Expected Mean Time To Repair.

2.5.4 Availability

Availability refers to the ability of the system, that the system retains its function whenever required. So it is a probability that an item is available when required. Availability is the committable state of a system, that the system will provide its function in its specified environment. There are three types of availability. Inherent Availability (A_I), Achieved Availability (A_A), and Operational Availability (A_o). Inherent Availability is the potential availability of the system and also refers to the steady-state availability. It assumes repair begins immediately after failure. And expressed in mathematical form as in equation 2.3. Another availability is Achieved availability. It is slightly realistic than Inherent availability, as it considers the time required for preventive maintenance and mathematically expresses as in eq. 2.4. Operational availability is the most realistic type of availability among all. It considers all the time taken by preventive maintenance and the maintenance response time. Operational availability can be express mathematically as in eq. 2.5

$$A_I = \mu / (\lambda + \mu) = MTBF / (MTTR + MTBF)$$ *Eq. 2-3 (Smith, 2001)*

Where: λ = Failure rate = 1/ MTBF

μ = Repair rate = 1/MTTR

$$A_A = MTBMA / (MTBMA + MMT)$$ *Eq. 2-4 (Smith, 2001)*

Where: MTBMA = mean time between maintenance actions both preventive and corrective.

MMT = mean Maintenance Action Time

$$A_0 = MTBMA / (MTBMA + MDT).$$ *Eq. 2-5 (Smith, 2001)*

2.6 Reliability Models:

Exponential Model: The exponential distribution model is the most elementary and widely used as a reliability prediction model, that models machines with the constant failure rate. The exponential model is employed during the 'Useful Life' period of an item's life, i.e., after the 'Infant Mortality 'phase before Wear out begins (Chaturvedi, 2018). The probability distribution function is written as:

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

$$R(t) = 1 - \int_0^t f(t)dt = e^{-\lambda t}$$ *Eq. 2-5 (Chaturvedi, 2018)*

The Weibull Model: The exponential distribution model is usually limited to some particular applications only because of the memoryless property. So the Weibull distribution model is used in the prediction of the reliability of components of a system. The Weibull distribution model (Weibull 1951) is a generalization of the exponential distribution model and is widely used to predict the different kinds of failure and their useful life in the component such as ball bearing, Vaccum tube, etc. The Weibull distribution is exceptionally flexible. This model is suitable for modelling component lifetimes which have unpredictable hazard rate functions. This model has taken wide space for representing various sorts of engineering applications in the reliability study. The Weibull distribution features as it can be used in reliability work by adjusting the distribution parameter so it can make suit to many life distributions. The Weibull reliability function is:

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}}$$ *Eq. 2-6*

Where β is the shape parameter and α is the scale parameter or characteristic life. (Chaturvedi, 2018)

The Normal (or Gaussian) Model: Gaussian model or Normal distribution model for reliability study is based on the central limit theorem, which plays a crucial role in classical statistics. In reliability engineering, the normal distribution is used to measure product susceptibility and external stress. This two-parameter distribution model i.e. Gaussian model is used to explain systems, where the system failures occur due to wear out of several mechanical components of the system.. The normal distribution function is:

$$f(t) = \frac{1}{\sigma\sqrt{2x}} e^{-[\frac{(t-\mu)^2}{2\sigma^2}]} \qquad \textit{Eq. 2-7}$$

$$R(t) = \int_t^{\infty} f(t)dt \qquad \textit{Eq. 2-8}$$

Where μ is the location parameter equal to the mean and σ is the scale parameter equal to the standard deviation. (Chaturvedi, 2018)

The Lognormal Model: The log-normal lifetime distribution model is considered as a very flexible and versatile model for reliability study. It can be used empirically to fit many sorts of failure data like a population with wear out characteristics. This distribution has a great application in reliability engineering to model the uncertainty in failure rate and to model failure probabilities. The log-normal density function is given by

$$f(t) = \frac{1}{\sigma x\sqrt{(2\pi)}} e^{-[\frac{(lnx-\mu)^2}{2\sigma^2}]} \qquad \textit{Eq. 2-9}$$

$$R(t) = \int_t^{\infty} f(t)dt \qquad \textit{Eq. 2-10}$$

Where μ is mean & σ is the standard deviation of the failure data. (Chaturvedi, 2018)

The Poisson Model: When it is needed to deal with the events where the sample size is not specified then the Poisson distribution model is used instead of the binomial distribution model. This is also known as discrete random variable distribution. This distribution model is widely used to determine the number of spare parts to establish the reliability of a redundant system to complete a particular objective. The reliability Poisson distribution, R(k) (the probability of k or fewer failures) is given by

$$R(x) = \sum_{x=0}^{n} \frac{(\lambda t)^2 e^{-\lambda t}}{x!} \qquad \textit{Eq. 2-11}$$

Where λ is the constant failure rate of the system, and x represents the number of events. (Chaturvedi, 2018)

2.7 Reliability Evaluation Model:

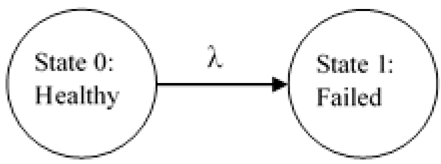


Figure 2-4: State of system

Source: (majeed, 2006)

Markov model defines different possible states, the possible paths of transition between the states, and the rate parameters of these transitions. In reliability analysis, the transitions usually contain downstate i.e failures of the system and success or upstate where the system provides specified function. The symbol λ is used to denotes the rate of transition from downstate to upstate. And the probability of success or upstate at a particular time t=1 is defined as P1(1)=1 and if the system is at downstate at that particular time then the probability is represented as P0(1) = 1. And if the probability of State 0 decreases at the constant rate λ, which suggests that if the system is in State 0 at any given time, the probability of creating the transition to State 1 during subsequent increment of time 'dt' is λdt. (mathpages.com, 2019). But this technique of modelling the hydropower is not possible. If we model forcefully it leads the wrong result. So in the general operating mode of hydropower, there are two state up-state and own-state as shown in the space diagram.

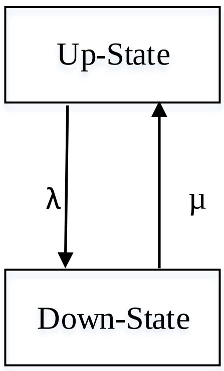


Figure 2-5: Hydro-unit state model   Source: (Majeed, 2006)

But it must be understood that, the hydro unit transit to down-state not always due to failure. This means that there are two parameters to define an up-state and down-state i.e failure rate and the repair rate. All the rates of events that transit the hydro-unit from up-state to down-state are defined as the failure rate. But all the transition from downstate to upstate is not considered as the repair rate. The hydro-unit may transit from up-state to down-state, either due to forced or scheduled outages. So in the case of Schedule outage, we do not need to work in the system to restore the system. So the system model can be represented as in the space diagram. The following assumptions are made to derive the Markov model.

- The repair rate and failure rates are exponentially distributed.

- Units will restore immediately to up-state after repair and there is no relation between the scheduled and forced outages. Each units will return to up-state immediately after the repair action.

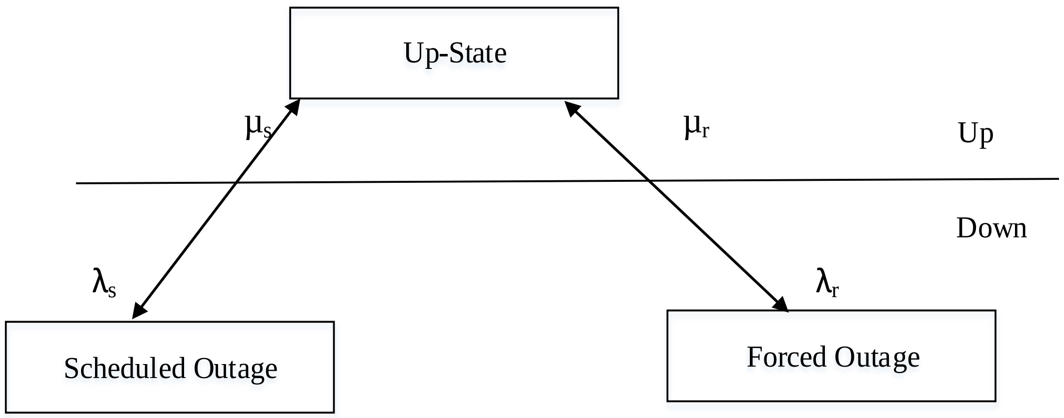


Figure 2-6: Markov state model for hydropower

(majeed, 2006)

After determining the state model, the next step is to select the model to calculate reliability. As the failure in any machine is random, the failure can be stated in exponential distribution, Weibull distribution, binomial distribution, Poisson distribution. Among these methods, the exponential distribution method is the widely used and basic method for the prediction of reliability for constant failure rate. The Exponential Model is used during the 'Useful Life' period of an item's life, i.e., after the 'Infant Mortality 'phase before Wear out begins. (Jena, 2015)

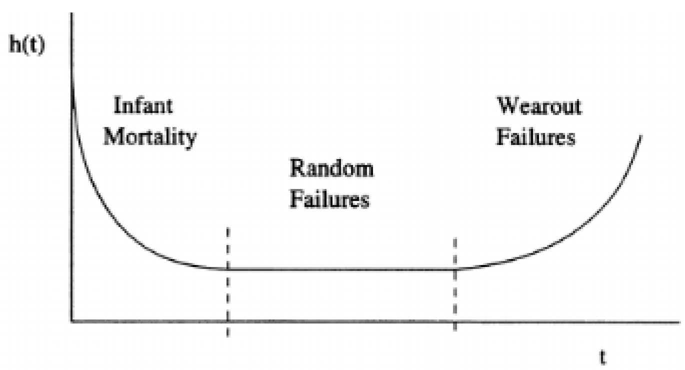


Figure 2-7: Bathtub curve for failure analysis Source: (Jena, 2015)

Method of evaluation of reliability techniques they are categories by two approaches 1) Analytical 2) Simulation. Analytical approaches give information about mathematical modelling & evaluate reliability indices by a mathematical solution. Whereas simulation technique gives information about to estimates the reliability indices through the simulation of actual process & random behaviour of the system (like Monte Carlo). Different kinds of system representation models are used in different industries and applications. Some of the system representation models and methods used for the evaluation of reliability in a system are listed below.

- Analytical Hierarchy process-based Failure mode and effects analysis (FMEA)
- Reliability Hazard analysis
- Reliability Block Diagram and Boolean algebra
- Weibull analysis
- Fault tree analysis
- Reliability Growth analysis
- Markovian analysis approach (Jain, 2017)

Analytical Hierarchy process-based Failure mode and effects analysis (FMEA) is one of the useful tools in modelling the system to evaluate reliability. This technique firstly studies the failure mode and its effect hierarchically. This helps to identify imminent failure modes that could result in malfunctioning of the equipment. It prioritizes failure mode as per their occurrence, severity, and detectability. After this, the failure modes are categorized to evaluate their effects. A different probability distribution can be used to predict the reliability parameter for some failure modes that were present in the log-sheet of the equipment. (Siqueira, 2005)

Failure Mode Effects and Criticality Analysis (FMECA), a semi-quantitative analysis, is additionally widely applied in fault diagnosis. Furthermore, several quantitative probability analysis models were developed for risk and fault diagnosis, like statistical deduction, reliability analysis, and model simulation. It offers some advantages like it offers a scientific review of all the contributing parts of them to spot failure modes, their causes, and the effects due to that particular failure in the system. Moreover, it ranked consistent with criticality and therefore the output of FMECA acts as the input of Hazard Analysis, Event Analysis, and Reliability diagram. But it has limitation like it is limited at single failures and consume longer and need the knowledge of all the failure so need expert person therein field. (Mohd , Khamidi , & Kurian, 2011)

Failure Mode and Effect Analysis (FMEA) is one of the techniques used for failure analysis by reliability engineers in 1950 to review the problems in the military system. It is also popularly known as the bottom-up approach. It proceeds with a problem of FMEA and inductively goes forward with reasoning form the single problem to the conclusion. An FMEA is usually the primary step during a study of the reliability of the system. It connects given initiating causes to their results or consequences. The result ultimately hit the failed component. In this technique, all the components of the system are analyzed with their failure mode and the effect or consequences to spot the exact failure modes, cause, and effect of that problem. So all the components are the suspects for every problem and the failure modes and their effects are recorded in the FMEA worksheet. As it starts from failure initiators and then proceeds upwards to work out the resulting system effects of a given initiator, so it is considered as a limitation of FMEA that it is limited to a single failure, time-consuming, and needed experienced manpower for complete the analysis. And also it is a complicated technique if the system has a large number of the component if we required to analyze the failure of the whole system at a time (Mohd , Khamidi , & Kurian, 2011).

Another method of reliability evaluation is the Reliability Block Reduction technique. The reliability block diagram (RBD) is a success-oriented network diagram. It is used to describe the function of the system. In this method of evaluation, firstly the system is divided into its functional component and represented in the form of block. And the block is combined with the system success pathway. This method is more popular in the reliability evaluation of active elements that are used in the electronic system. And rarely used in the mechanical system. The model is then solved by enumerating the various success paths through the system. The principles of Boolean logic is used to reduce blocks into an overall representation of system success. In this type of technique, if the component has a different function, then this component must be represented separately. This makes the diagram more ridiculous and confusing, which is, therefore, the most significant limitation of RBD. Also, it requires an expert person and needs special knowledge of block diagram reduction technique and it uses many formulae and consumes time (Mohd, Khamidi, & Kurian, 2011). Among these techniques during this study, AHP based FTA technique is employed because it is proscribed to the initial initiating event and can overlook subsystem dependency (Souza, 2008). It can be used in the current case. Fault tree analysis is a systematic technique that is used to identify the root cause of any failure event. This is a deductive technique for the analysis of any failure event. It starts from a single top event which is at the top of the flow chart and expands downward to spot the various contributing causes until it gets the basic causes. The basic cause of the failure is also known as the basic event and also it is the root cause of that failure top event. Different fault conditions are identified from every event except for basic events. All of these events are connected with the help of different logic gates as per the cause and effect relationship between events. This system can simplify understanding the various modes of failure in hydropower without the FMEA technique. As there are many components and their failure mode are different in different operating condition, so it can be used in the option of FMEA for reliability analysis on the turbine and generator of power generating plant and hence to find the probability of failure. (Budonieya, Premi, & Patel, 2014) The basic structure and symbol used in FTA are shown in the figure.

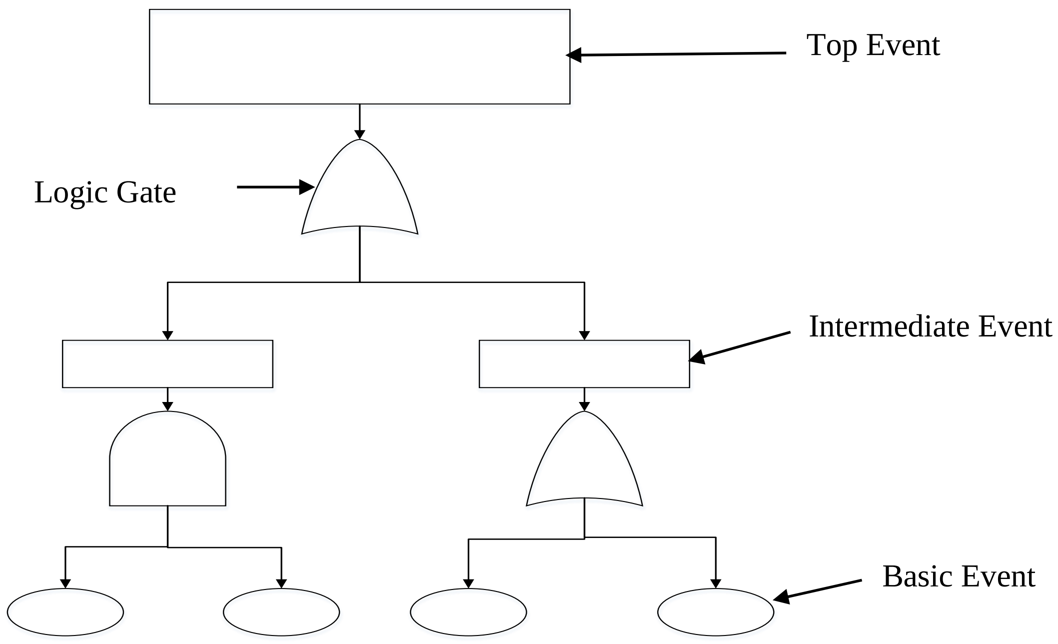
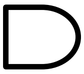
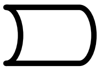
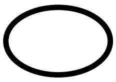
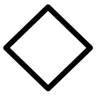
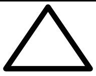


Figure 2-8: Fault Tree Basic Structure Source: (Smith, 2001)

Table 2-1: Symbols used in Fault Tree Analysis

Symbol	Name	Function
	AND Gate	Use to represent the parallel event. All the events required to produce output
	OR Gate	Use to represent a series event. Anyone of the event is sufficient to produce output
	Oval	Use to represent the basic event
	Rectangle	Use to represent the top and intermediate events.
	Diamond	To represent Undeveloped event i.e for the event whose cause is undeveloped till now.
	Triangle	to represent a suppressed tree, it specifies that the tree is detailed in another figure

To compute the fault tree, to find the Mean Down Time and failure rate of the top event the following relation can be used:

OR gate:

$$\lambda = \lambda 1 + \lambda 2 + \ldots\ldots\ldots$$

$$MDT = \frac{\lambda 1 * MDT1 + \lambda 2 * MDT2 + \cdots\ldots\ldots}{\lambda 1 + \lambda 2 + \cdots\ldots\ldots\ldots}$$

Eq.2-13 (Smith, 2001)

AND gate:

$$\lambda = \lambda 1 * \lambda 2 * (MDT1 + MDT2)$$

Eq.2-14 (Smith, 2001)

$$\frac{1}{MDT} = \frac{1}{MDT1} + \frac{1}{MDT2} + \ldots\ldots\ldots$$

2.8 Failure in Hydropower

Different types of failures may occur in a small hydropower plant. Some of the failures that may arise in hydropower are listed below.

- Fails to generate field by the stator winding
- Short circuit in the switching equipment.

- Malfunctioning of control equipment such as AVR, Relays, Power elements, etc
- Transformer fails to step-up voltage
- Cracks and breakage in shovels and other failures in the turbine.
- Bearing failure
- Lubrication and cooling systems malfunctioning
- Flooding on power plant due to excessive flow in the river
- The fire within the machine hall
- Fault on the Guide-vane
- The waterway cannot supply flow
- Disabled cooling system
- Disabled turbine
- Generator malfunctioning
- Fault in the Transmission system
- Faulty on governor and control system
- Tailrace cannot discharge flow
- Structural failure due to materials used in dam construction
- Cracking and Settlement of concrete or embankment of dams
- Internal erosion and Piping in the embankment of dams (Solomon, 2017)

CHAPTER THREE
RESEARCH METHODOLOGY

3.1 Theoretical Framework

To run the applicability of the methodology proposed in this paper. Bijayapur hydropower was selected. Which is located in Kaski District with a capacity of 4.5 MW. The reason behind the selection of the Bijaypur-I small hydropower project is because of its special features. Such as, it is multipurpose hydropower which uses the drainage of the Sheti irrigation project and some portion of Bijaypur Khola. As BSHP-I is dependent on the consumption of water in irrigation and the performance of two preceding hydropower Sheti-Fewa Small Hydropower plant and a small modular hydropower Task Hydropower. In the dry season, it depends totally on the water from irrigation cannel since the water of Bijayapur Khola goes to another irrigation project of the Bijayapur area. In the wet season, it uses both water of Bijayapur Khola and the Irrigation Cannel. And in other circumstances, the river Sheti flows from a soft soil basin so its water contains limestone rather than a sand particle. And another amazing thing is that it is operated on the lap of Pokhara city, the Headrace Cannel run across the Pokhara city. Different interest groups played differently at different times, which is the main challenge in hydropower development in Nepal. (Shrestha, 2017). As in Nepal most of the small hydropower is facing the same problem and trend to make the cascaded type of plant such as upper Modi, middle Modi, lower Modi by using the same flow is increasing in present days. So to analyze the situation of such hydropower BSHP-I is considered as the case of study. Study Design of the work can be classified in different phases to meet the objectives of the study.

3.2 Study Design

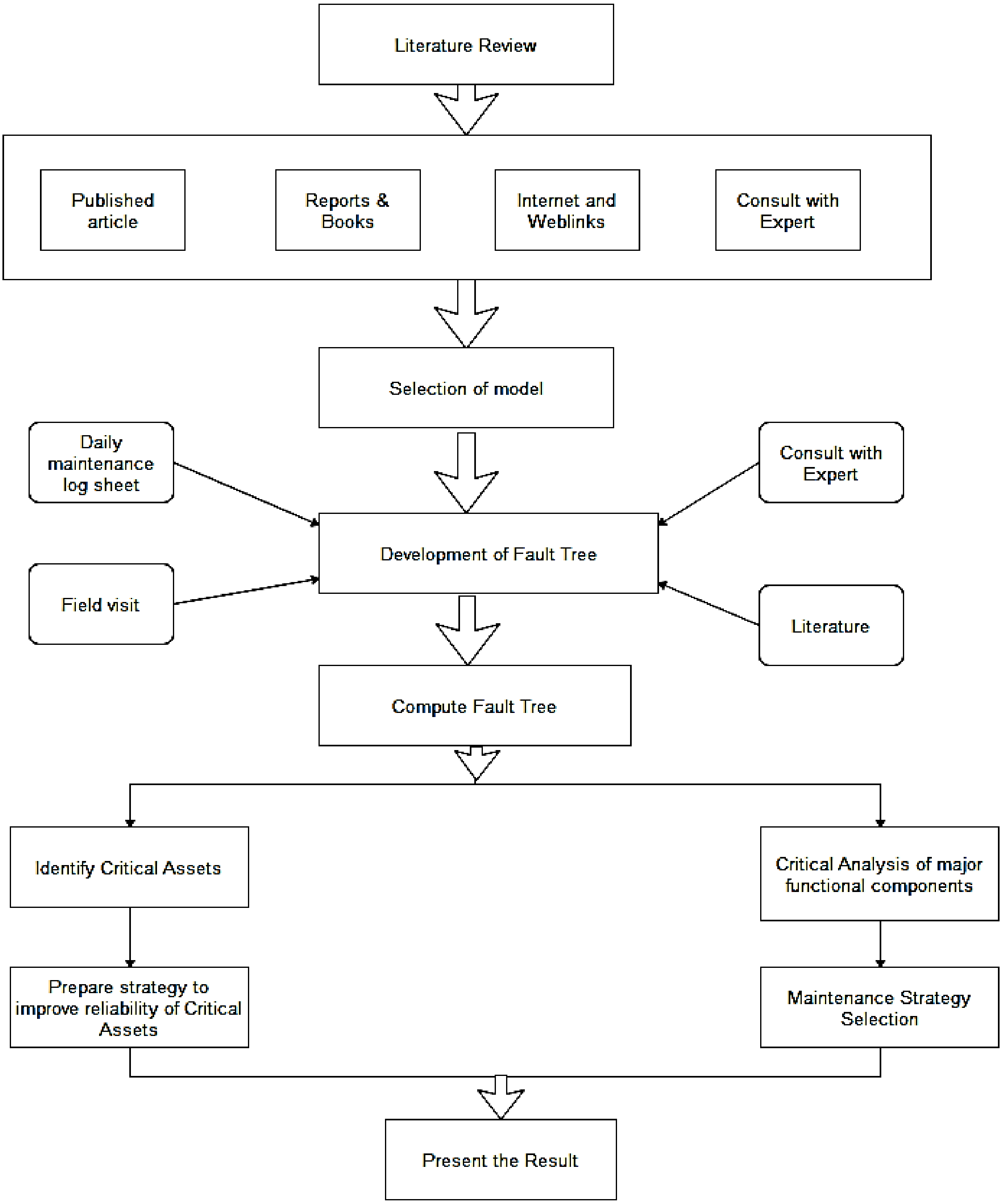


Figure 3-1: Research Framework

Different kinds of literature were studied regarding the topic to find the research gap and to collect the information regarding the topic. The sources of information were taken from the scientific research article related to reliability engineering and research on different problems of hydropower. And different books published related to reliability engineering and manuals and reports published by the different organization which is working in the field of hydropower and energy were studied, internet and different website were also the secondary sources of information, and expert advice are the direct sources which are used during the selection of the model for analysis and selection of the site of study.

After the study of literature, it was concluded to adopt the Markov three-state model for the analysis of reliability and availability of hydropower. Which states that as there are two states up and down in all the systems but hydropower has three states. Upstate, downstate due to scheduled outage, and downstate due to electromechanical failure. Analytical Hieratical Process-based Fault Tree Analysis technique was used to compute the reliability and to find the critical assets of hydropower. AHP based FTA is used to identify the basic causes of the main event. Firstly the different basic events of hydropower were analyzed and these conditions are evaluated to find how they might connect to generate an undesired event. These events are connected with the help of logic gates showing the relation between the different events. Thus prepared fault tree helps to compute the reliability and availability of the whole as well as individual component of the system. It uses simple data such as, the number of failure and number of hours that affect the plant due to that particular failure. These are taken from the maintenance log sheet and the report of the generation of the hydropower plant.

The Fault tree was developed with the help of different types of failure recorded in the log sheet of BSHP-I and consult with the operator and operation manager of BSHP-I. And the fault tree was finalized by consulting with experts related to hydropower maintenance and different scientific research regarding the electromechanical failure and fault tree of hydropower. Data were collected from the log sheet maintained at BSHP-I, to extract the information required for determining the pattern and past trend of failures that cause the units of BSHP-I out of service. Detail walkthrough study on the powerhouse was also done to get details about the plant and operational data from fiscal year 069/70 to 075/76 were collected from the log sheet maintained at BSHP-I. and the raw data are arranged as shown in Annex I and Annex II.

After the collection of data and development of fault tree of BSHP-I, the fault tree was computed to find the reliability parameter such as system reliability, System availability, System Unavailability, Mean downtime, Mean time between failure, Mean time to failure and maintainability

Then the reliability parameter reliability and availability were analyzed to find the critical assets. As the critical asset is that, whose contribution is higher in reliability and availability of BSHP-I. During the process of finding critical assets both unit i.e Unit-I and Unit-II were treated separately and the reliability improving strategy was prepared with the help FMEA technique and based on the prior research regarding that problem in other hydropower. And also to develop the maintenance strategy for other components whose contribution is also seen as vital were identified as the critical component for critical analysis. And the particular maintenance strategy was recommended to improve the performance of the BSHP-I.

CHAPTER FOUR
RESULT AND DISCUSSION

4.1 Fault Tree of BSHP-I

As Fault tree Analysis is exceptionally incredible as a methodical approach for recognizing root causes, in addition to it, it also gives a visual correspondence model that most people can promptly comprehend and follow with a little information on the tool, the system design, or the situation of the occurrence of the event. The top event of the fault tree is “Bijayapur-I Small Hydropower Plant fails to generate electricity”. This top event related to the main function of the hydropower plant. The deductive method was used to identify the lower level of the fault tree. The failure of BSHP-I that can lead the top event can be classified into two categories. Scheduled/Planned Outage and Forced/Electromechanical outage as per the literature. Where Forced/EM outage refers to all of the failures that are related to the electromechanical component of hydropower. That can be controlled by regular maintenance. Scheduled/planned outage includes all other outages other than failure in the EM system that affects BSHP-I to generate electricity which is shown in figure 1. These are due to the reason for unit repair and maintenance such as preventive/ planned maintenance, Reserve through the system and transmission line maintenance, and Ideal, when the flow of water is in the river, becomes less and both the units cannot be run simultaneously.

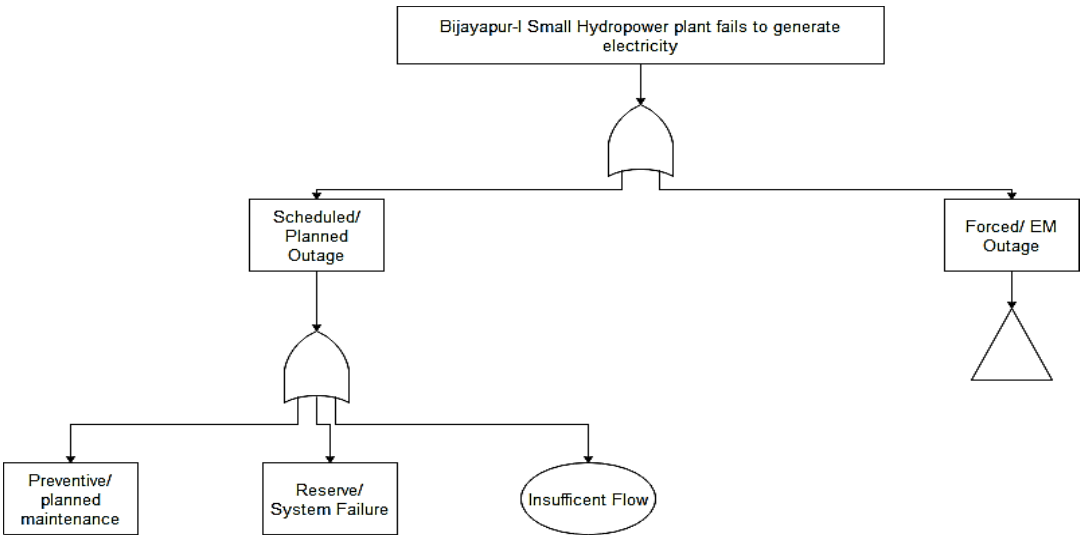


Figure 4-1: Fault Tree of BSHP-I with the top event and its subsystem

On the fault tree, Boolean logic operators OR and AND gates are used to correlate the events of the fault tree. In this study, causes for a particular event is searched based on a survey of past failure record on log sheet of BSHP-I, the literature on the relevant topic, consult with the operation and maintenance team of BSHP-I and other relevant expert work in this field. Then a cause for further events was searched, and this procedure was repeated until the basic events in the lowest hierarchical level i.e basic event of the tree are identified. For this case, it is identified that BSHP-I gets shut down for the following action as related to preventive/planned maintenance as shown in figure 2. As in BSHP-I most of the thrashes were plastic bags and soft mud sand layers in the radial gate of the dam. And also the flushing action for descending basin that was clean as per the requirement of the plant. Also Overhauling the turbine section, replacement of equipment of substation and regular inspection of penstock pipe and cannel are the succeeding event that are categories under planned maintenance due to which the performance of BSHP-I is adversely affected.

Similarly, sometimes BSHP-I can be shut down due to unplanned causes which are not due to BSHP-I such as NEA system failure, main grid maintenance, flood, and LDC instruction are categorized as reserve/system failure which is another cause of Scheduled/Planned outage. Sometime the power plant should be shut down due to failure in the system of the NEA control system as the power generated from the BSHP-I is connected to the NEA grid at the substation of Lekhnath. Also since due to the construction work at Pokhara international airport, the drainage is diverted to the Bijayapur Khola which creates a problem in the operation of the powerhouse since it has a small descending basin and the link canal is small. Slight flood in Bijayapur Khola adversely affects the performance of BSHP-I. and is another important event that causes BSHP-I. main transmission line and substation maintenance are also some events that disturb the performance of BSHP-I which are performed by NEA and not in control of BSHP-I so are categorized as system failure or Reserve/system failure. Also sometime BSHP-I gets shut down due to the instruction of the load distribution centre despite there is no failure in BSHP-I. Another important cause that causes failure in BSHP-I is due to insufficient flow since BSHP-I is multipurpose hydropower which uses the drainage of the Sheti Irrigation Project and some portion of Bijayapur Khola. So the amount of water depends upon the water consumption in Irrigation and the condition of modular hydropower Sheti Hydropower and Task small hydropower. If any problem occurs in the Sheti hydropower it will bypass the water to the river causing the insufficient flow of water for the full operation of BSHP-I. The events for the scheduled outage is as shown in the figure.

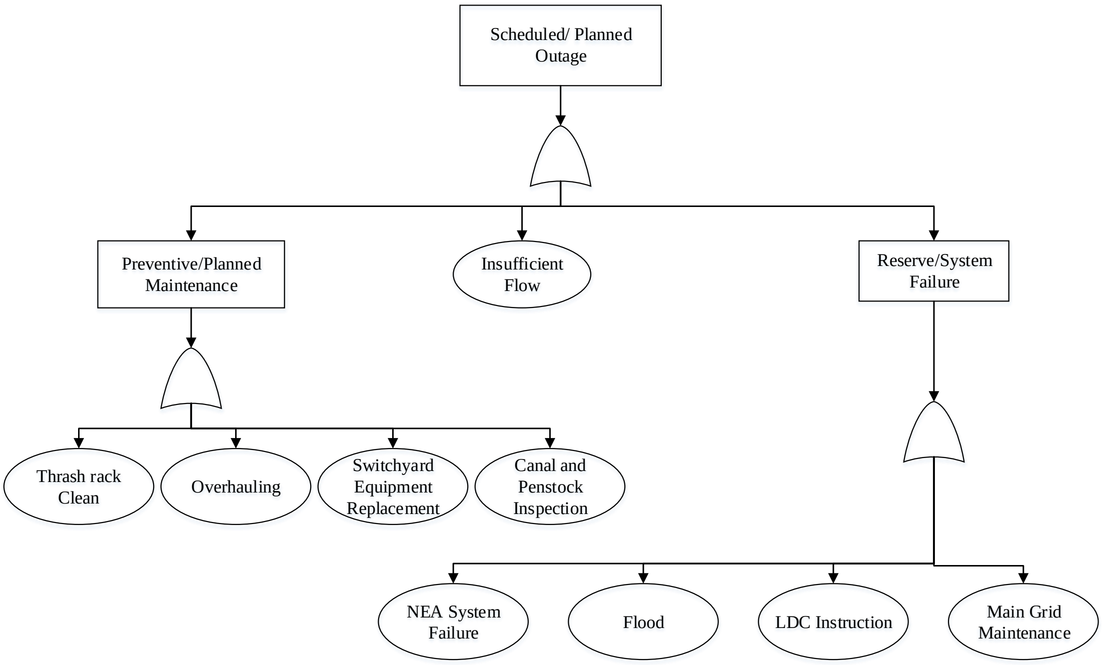


Figure 4-2: FTA of scheduled/ planned outage

As mention earlier, another type of failure that leads the top event is forced outage. Also, it is called electromechanical outage/failure. This failure is governed by three subsystems i.e. problem in the turbine section, the problem in the transmission system, and generator malfunctioning as shown in the figure.

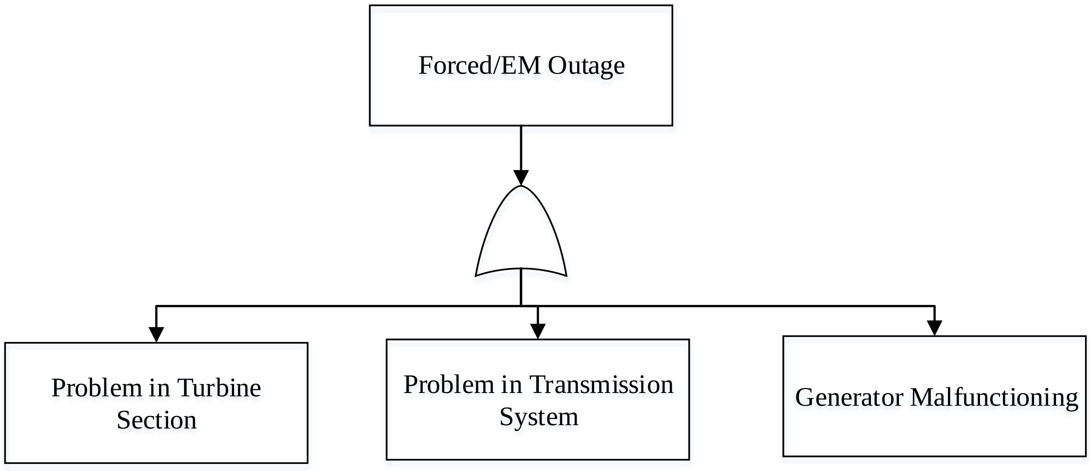


Figure 4-3: FTA of Electromechanical outage showing its subsystem

The problem in the turbine section is one of the contributing factors that lead to failure in BSHP-I to generate electricity. In this section, the stream of water from the penstock is used to rotate the prime mover (two units of horizontal shaft francs turbine) to generate electricity. The main component of the turbine section is penstock, Intake gate, Guide-vane, Governor, and cooling system. The basic problem in this section was noted as overheat warning, failure in bearing, leakages of water through the turbine guide bearing, failure of guide vane, clogging of the spiral case, excessive shaft vibration, reduction of pressure in governor, governor misleading the output signal, etc. After the analysis of the problem faced in the turbine section, the fault tree was deduced as shown in the figure.

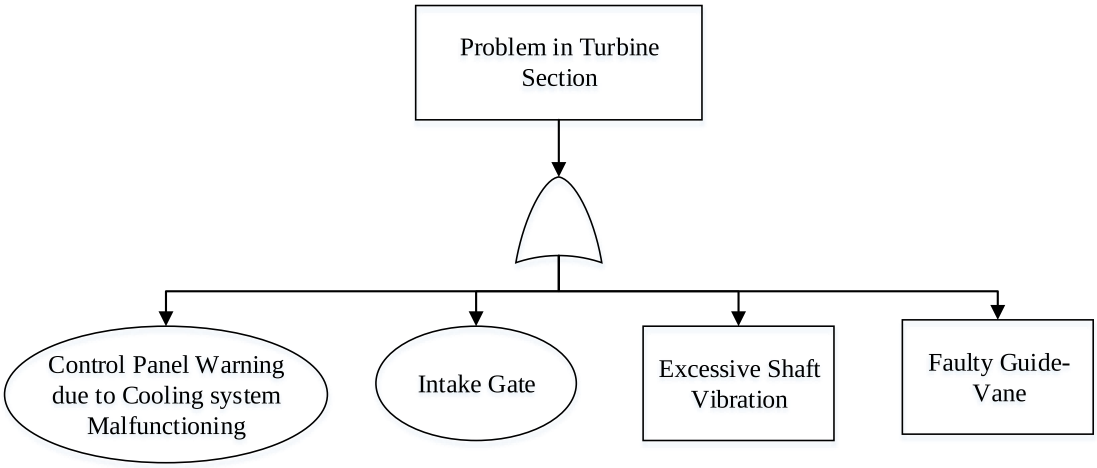


Figure 4-4: FTA of Turbine section

Since one of the cause found that affect the performance of the turbine section is control panel warning due to overheating in bearing, guide vane, etc. As BSHP-I uses water cooling system, the different component of the turbine section is cooled by circulating cold water by passing it through a radial tube filter. Another basic event that affects the performance of the turbine section is the problem in the intake gate. Some of the problem categories as a problem in intake gate erosion in the grating system of the radial gate, the problem in the valve, the problem in penstock pipe, deposition of limestone layer in the bypass valve, penstock pipe due as the water contains an excessive amount of limestone solution and the slope of penstock is small.

Faulty guide vane is another subsystem that causes problems in the turbine section. The subsystem that leads the faulty guide vane is spiral case clogging. As the spiral case is casting a welding port equipped with a fixed guide vane in it. Sometime spiral cases may clog by unwanted foreign material such as sand, stone, etc. In BSHP-I, the clogging problem is due to the deposition of limestone dissolve in the water of the Sheti river. As the guide-vane, the governor as per the load controls opening and closing automatically. So guide vane will operate correctly if the hydraulic system does not operate guide-vane which may occur due to failure in the pump which pumps the hydraulic fluid to operate the guide-vane leaver or if there is leakage in the hydraulic pipe due to external stress or excessive pressure. Sometime the guide vane will not operate if the shear key that holds the guide vane and drum in contact is broken /failure or the servomotor seals and guide vanes bushes worn-out.

The main control part or brain of the guide vane is the governor. If any problem occurs in governor, it will lead to failure of operation of guide vane. Governor will fail if the hydraulic system output signal contains noise due to problems in RTD, or if the oil filter is damaged or the throttle valve gets damaged. Also, the governor will malfunction if the interruption of governor power speed. The Governor's power speed will be interrupted if there is too low oil pressure i.e the level of oil in the tank is low and if there is leakage of oil in the pipeline. In most cases, the viscosity of governor oil increases with the decrease in temperature results in low pressure in the winter season.

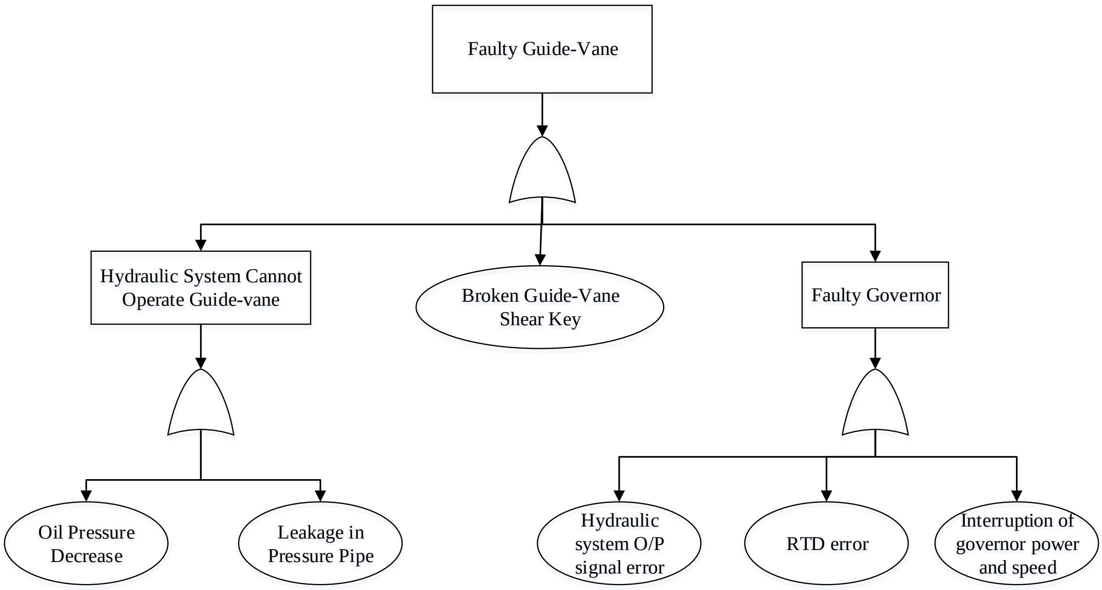


Figure 4-5: FTA of Faulty Guide vane

Another subsystem which is the cause of the problem in the Turbine section is the excessive shaft vibration, which can be caused due to the broken linkage between the Shaft and Runner, or if the runner is jammed by driftwood or the deposition of the limestone layer. Also, this can occur due to vibration in the Runner due to blade damage. Runner hub damage, Runner touches the side of the casing, the casing of the runner deform due to some of the problems that occur due to the excessive shaft vibration. In addition, shaft vibration can occur if the shaft is worn-out or if some bending occurs. Another cause of shaft vibration is due to failure in bearing. Bearing will fails if the temperature of the bearing increase due to the failure in the cooling system. In addition, it can fail due to failure in the lubrication system. If any of the bearing up-thrust bearing, lower bearing, or upper bearing, which creates the linkage between shaft and runner fails there will be excessive shaft vibration creating the failure in the turbine section, which is shown in the figure.

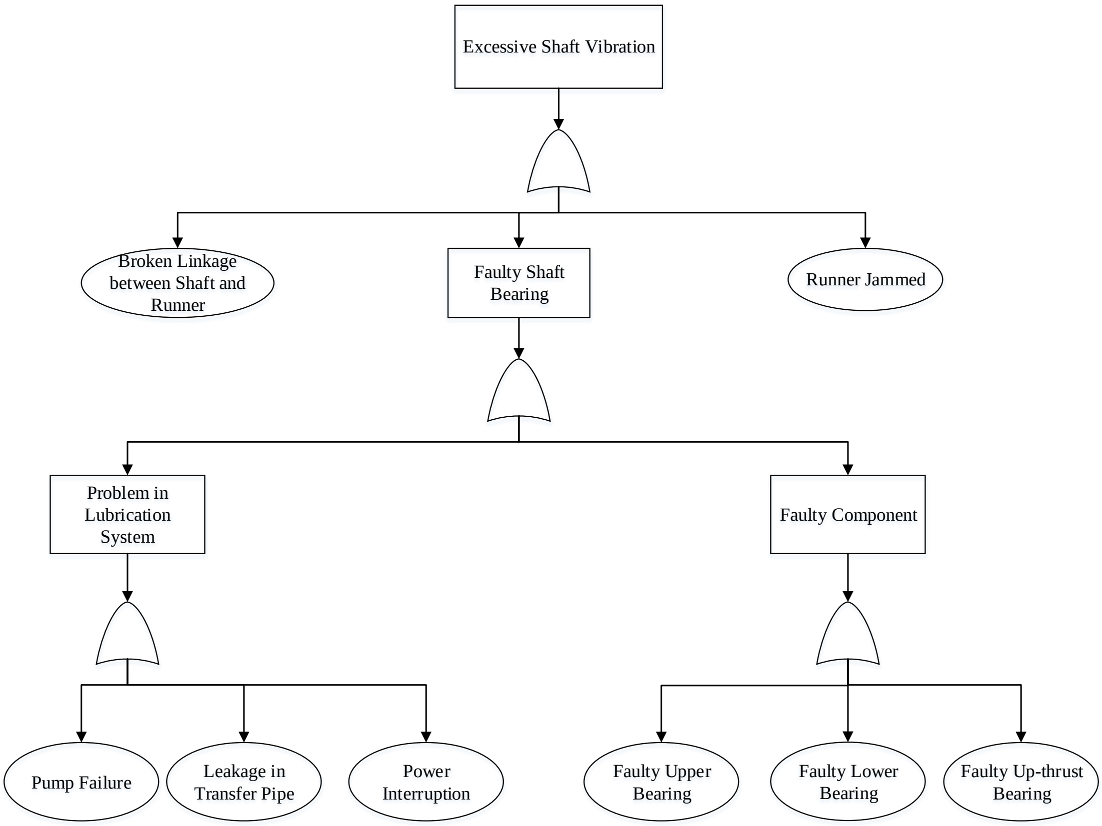


Figure 4-6: FTA of Excessive Shaft Vibration

The transmission system is used to transmit the generated power from the powerhouse to the substation (main grid). BSHP-I has its substation in the powerhouse and 4 km long single circuit 33 kV Transmission line. The problem in the transmission section is due to failure in the following subsystem i.e. transformer failure, switch equipment failure, and transmission equipment failure. As shown in the figure.

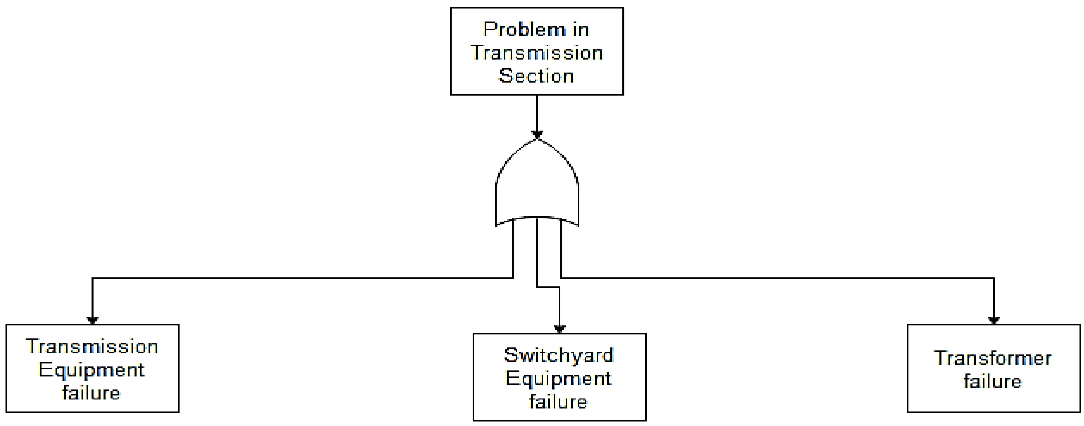


Figure 4-7: FTA of Transmission Section

As transmission types of equipment may fail due to failure in transmission tower, sometime due to landslide transmission tower may gets damaged also due to heavy rain and stormed, it may damage the transmission tower. Trees near the transmission line are also another cause, that may fall in the transmission line which not only damages the transmission line may also affects the transmission tower. Due to collision of large birds may also damage the transmission line, the insulator of the transmission tower, which may affect the transmission system.

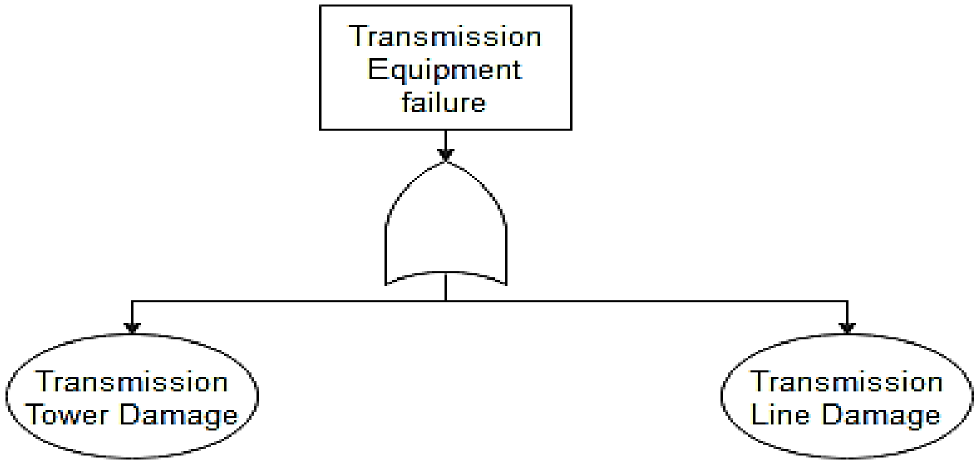


Figure 4-8: FTA of Transmission Equipment failure

Switchyard equipment includes all the types of equipment that are needed to protect the transmission system. It includes the insulator to isolate the transmission line and tower and also guide the transmission line, different types of circuit breaker which protect the system from different kind of uncertain failures and natural disaster such as lightning, short circuit due to collision of birds in the transmission line, etc. and different kinds of isolation switchgear system. In BSHP-I most of the problems were found in breaker failure which includes failure in SF6 breaker leakage problem and CT and PT coil malfunction.

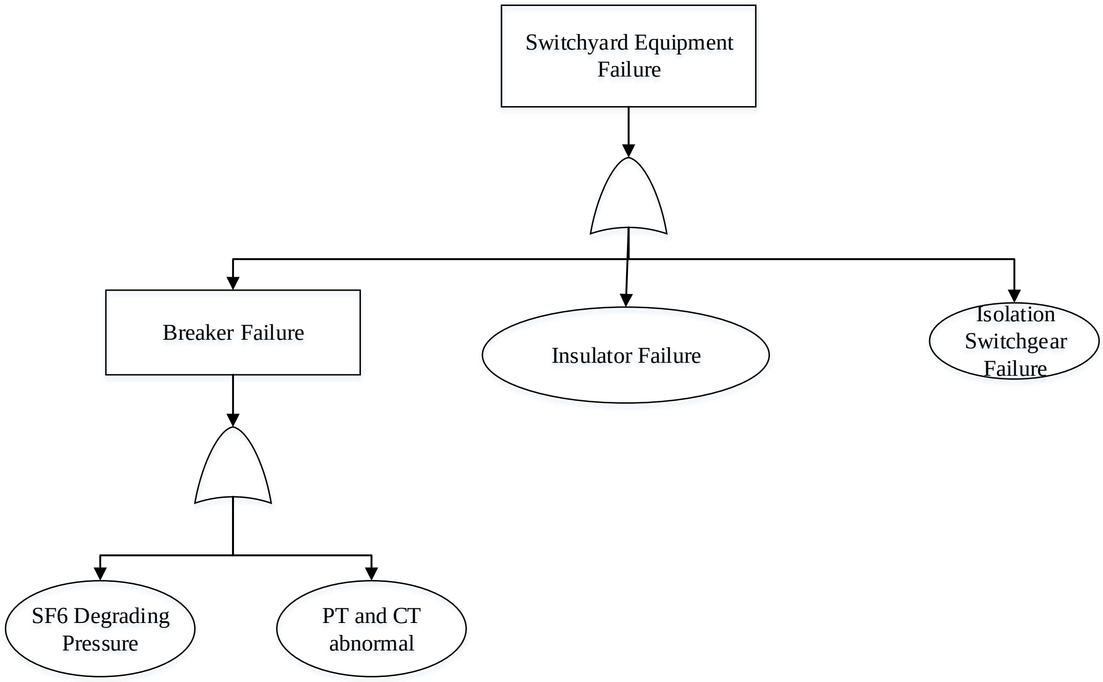


Figure 4-9: FTA of switchyard equipment failure

A transformer is another important component of the transmission system, which is used to step-up the generated voltage. As in BSHP-I electricity is generated in 1100 volt which is step-ups to 33 kV. There will be a failure in the power transformer if it is unable to convert the low voltage to a very high voltage of electricity. This is the event, which is governed by the failure in the subsystem such as bushing, winding, core, OLTC, and tank. The bushing is used to pass current to winding and from winding to outside the transformer. And they may fail if the conductive part or insulating part gets corroded or break. Another subsystem OLTC is used to change the tapping connection of the transformer winding while the transformer is energized. It may be located either inside or outside its compartment. OLTC may fail if the Tap selector switch fails to switch the connection or the control device fails or if there is any failure in the drive mechanism of OLTC. Any failure on these components will lead to the failure in On Load Tap Changer Another subsystem is the transformer core, which is made of steel. The main function of a transformer core is to provide a low-reluctance path for the magnetic flux linking the windings of the transformer. The transformer will malfunction if there are any defects in the steel core. Another cause of transformer failure is due to failure in the transformer winding. In Transformer, there are two windings both are connected in delta connection. It comprises paper, copper wire, and pressboard. The paper and pressboard are impregnated with oil. The main function of these components is to decapitate heat that generated in the winding of the transformer and avoid short circuit. The heat thus generated is transferred into transformer oil and the transformer oil transfer the heat to the transformer housing or other cooling system of the transformer. The transformer oil can withstand its property to 150^0C but the insulating paper will degrade in 90^0C so in the transformer the cooling oil must flow continuously to ensure the insulation temperature is below the limit. So there must be appropriate Cooling systems that should be designed to protect the main component overheating during operation. As in BSHP-I, the cooling system was of an oil-cooled type, for this Oil level indicator was used. The oil level indicator acts as electrical switches for tripping off the transformer and alarm if the oil level falls below a certain limit. Another subsystem for transformer failure is tank rapture. As the main purpose of the oil tank is to store the transformer oil and supply it to the system when needed. So any failure in tanks leads to a decrease in oil level, result in initiating a trip to the transformer.

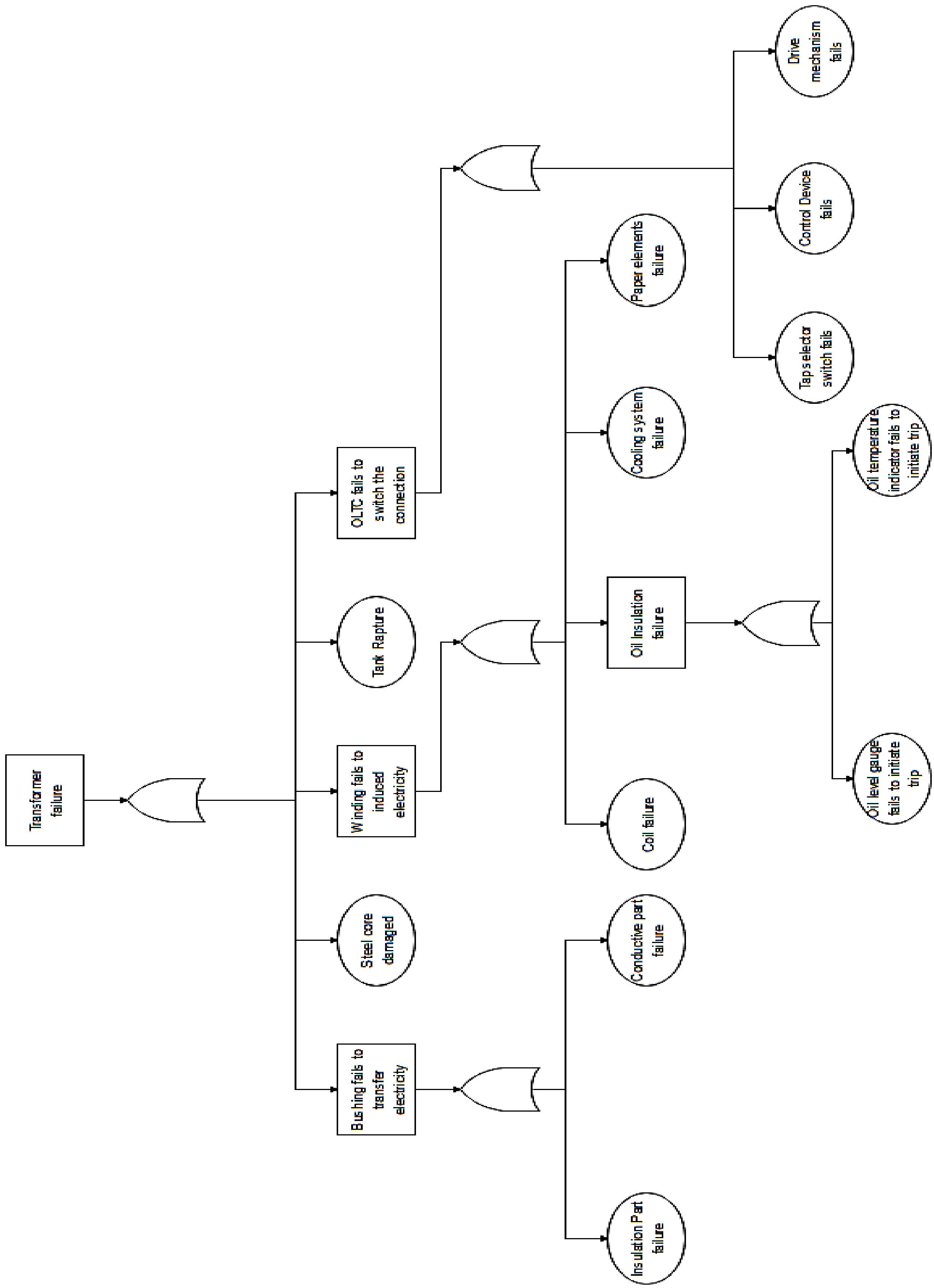


Figure 4-10: FTA of Transformer failure

The malfunction of the generator section is another cause that leads to the top event. As electric generator converts the mechanical energy into electrical energy. Three subsystems cause the malfunction of the generator section as shown in the figure.

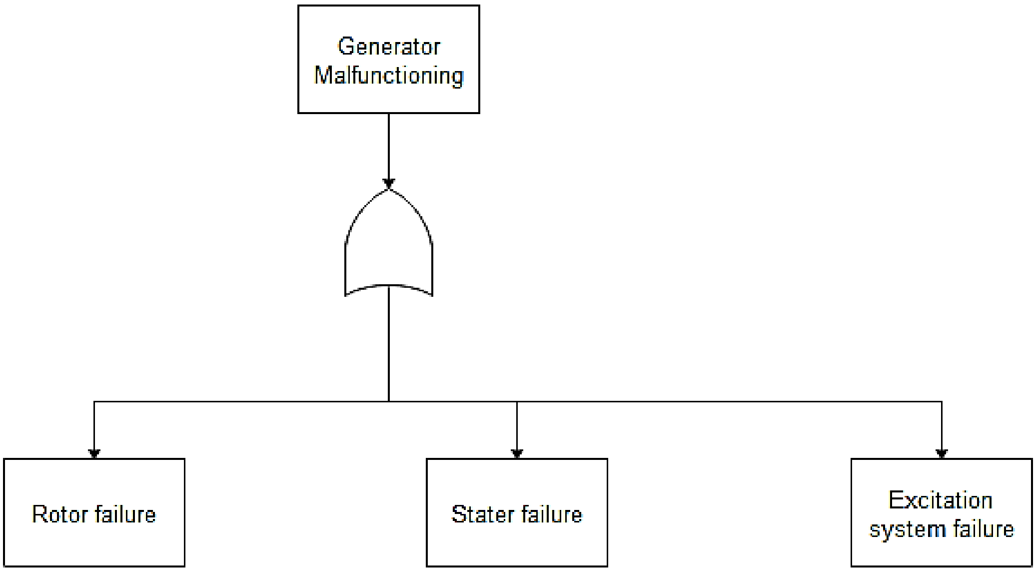


Figure 4-11: FTA of Generator Malfunctioning

Rotor failure is one of the causes of malfunction of the generator section. Overheating, loose and vibration of component, impact damage, contamination, the eccentric problem are some of the problems that lead to rotor failure. In BSHP-I some of the failures of components noted in the log sheet that leads to rotor failure are rotor hub, radial arms, and rotor rim failure, failure in field poles, keys, collars, poles face failure, field winding failure, cooling system failure, break ring failure and so on as shown in the figure.

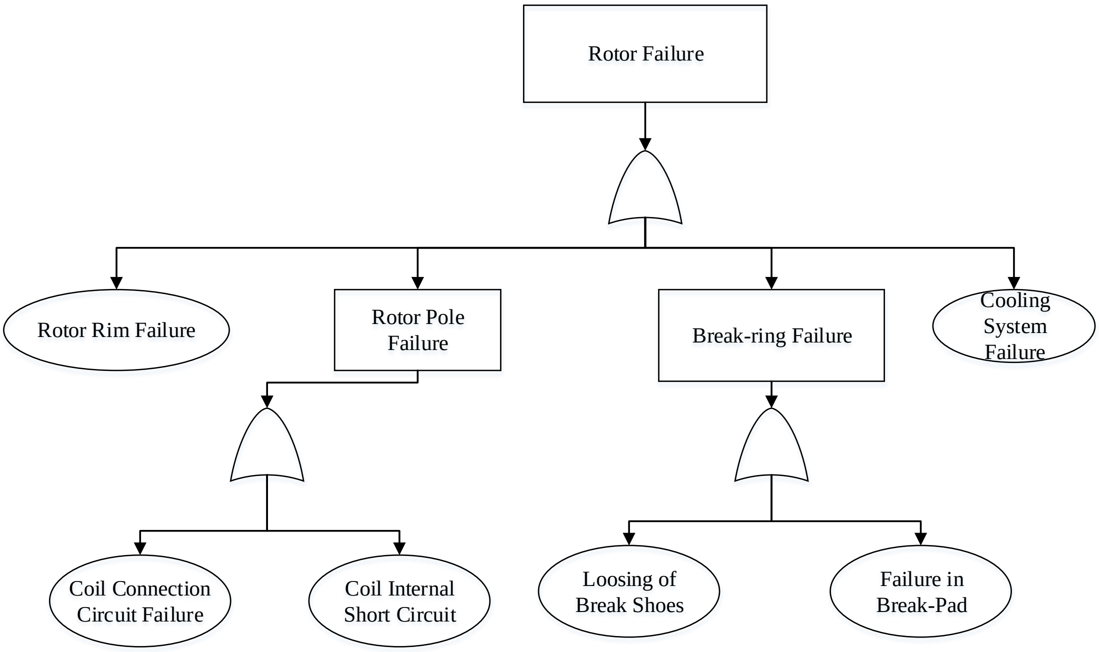


Figure 4-12: FTA of rotor failure

Stator failure is another subsystem that leads to the malfunction of the generator. As the stator has three subsystems i.e stator frame failure, core failure, and stator coil or winding failure which cause failure in the stator of generator. The stator frame is designed to support the clamping force needed to retain the stator punching to retain the correct core geometry to maintain the significant air gap between stator and rotor. Variation in the air gap causes variation in the split-phase current which may cause unwanted trips the system leads to failure in the system. In BSHP-I there noted several types of stator winding problems such as insulation cracking, surface corona, contamination, winding moment, loose bracing and blocking, and loose wedges or slot fillers. These problems may occur due to the failure in different components such as stator frame, steel core, insulation of stator, winding of the stator as shown in the figure.

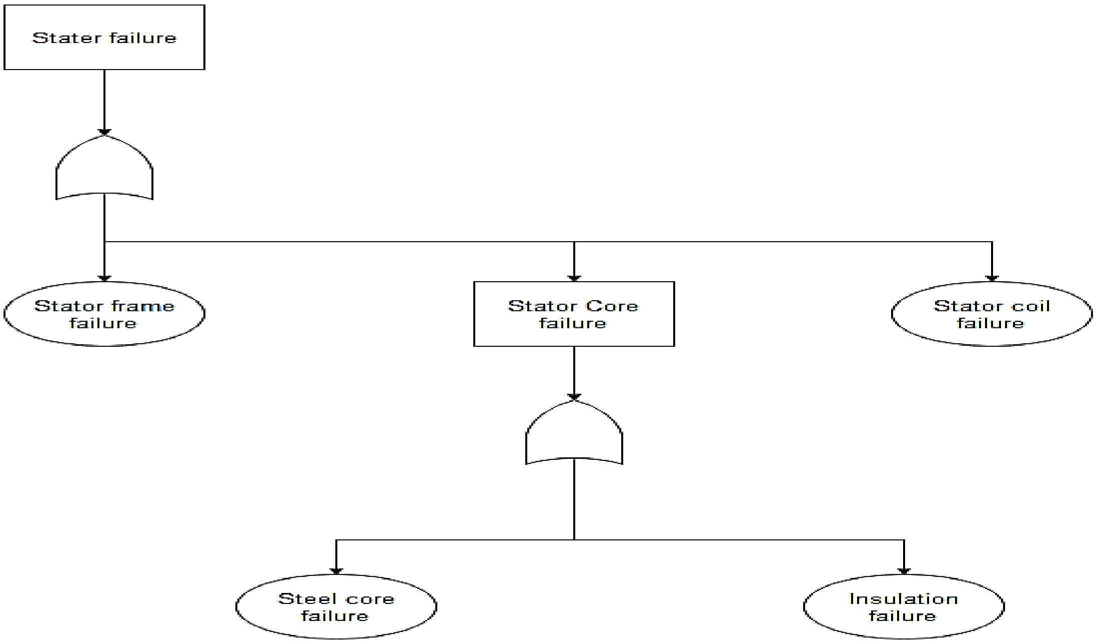


Figure 4-13: FTA of Stator failure

Another subsystem that leads to failure in the generator is the excitation system. In BSHP-I, a self-excited DC generator is used for the excitation of the rotor coil, where the shaft of dc generator is coupled with the rotor shaft of the turbine and with the help of MOSFET it is exciting to the rotor. The role of the excitation system is very important in any hydropower plant, which is supported by the component such as VCB, PCB, Battery, DC generator, Relay, etc. as shown in the figure. Any failure in these components will leads to failure in the excitation system.

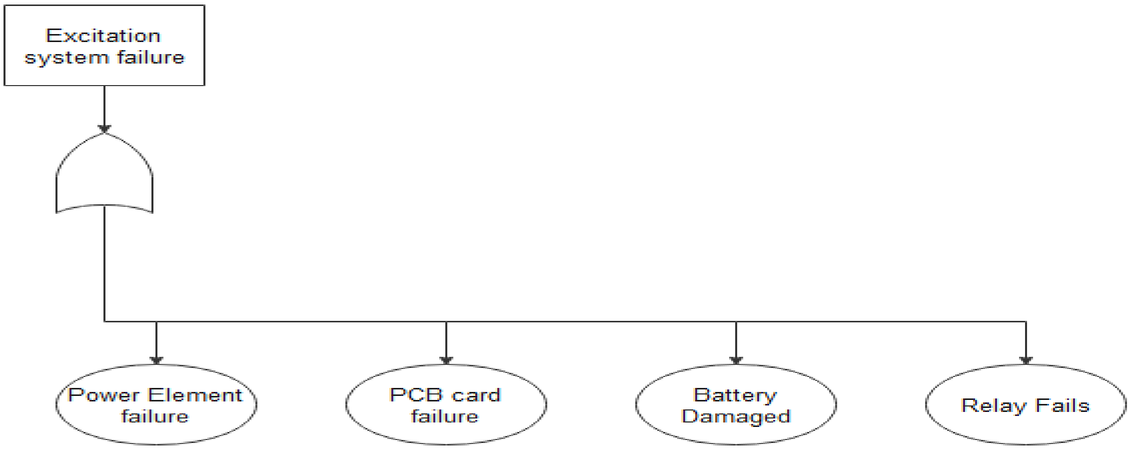


Figure 4-14: FTA of Excitation system failure

4.2 Analysis of Reliability and Availability of Unit-I and Unit-II

Reliability is the measure of how long a machine performs its intended function, so it is the function of the number of failures in a specified period. Whereas availability is the measure of the percentage of time a machine is operable. So it is the function of the total downtime. The evaluation of reliability and availability of unit –I of BSHP-I for the periods of seven years is shown in the figure below. Where in fiscal year 2069/70 the total no. of the operating hour is 6350.3 hours with 35 failures with reliability 0.882 and availability 0.956. In the fiscal year, 2070/71 total no. of failure was observed as 35 as some of the forced failure cases were increased with the reliability of 0.894 and the availability was 0.953 with total failure hour 348.18 hours. In fiscal year 2071/72, the reliability of unit-I was observed as 0.902 with the 32 failures observed in that fiscal year in unit I whereas the availability of the plant decreased as it was observed as 0.938 with the total failure hours 466.43 hours. From this, it can be said that the maintainability of the plant in this fiscal year is higher than the previous year. The reliability and availability of unit-I were observed as 0.920 and 0.940 in fiscal year 2072/73. Where the total no. of failure observed was 26 and 449.8 hours of failure. As in fiscal year 2073/74 the reliability and availability of BSHP-I unit I was observed as 0.932 and 0.773 respectively. In this period the plant was operated for 5719.1 hour, at this period 22 failures were observed with 1696.1 hours of plant shut down due to different failures due to different reasons. In fiscal year 2074/75, the reliability of unit I was observed as 0.947 with total failure recorded as 17. And availability was observed as 0.963 with total failure hours 276.6 hours. Similarly, in fiscal year 2075/76, the reliability and availability found very poor where reliability was 0.911 and availability was 0.681. In this period unit-I was operated for only 5035.8 hours and 29 failures were observed.

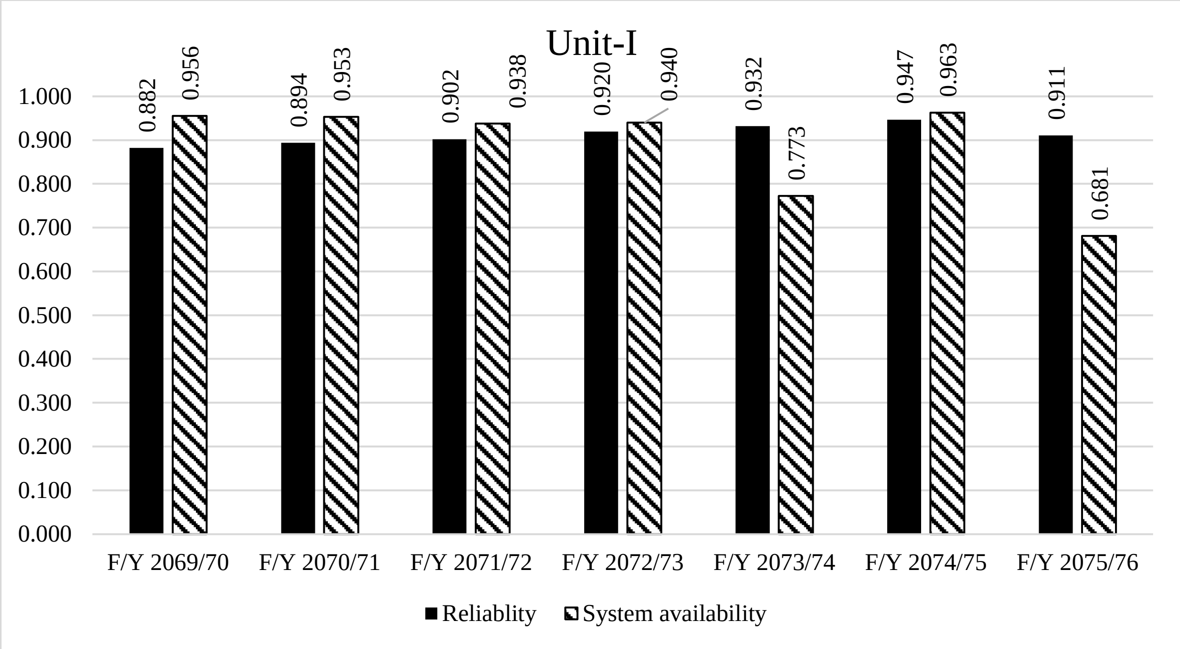


Figure 4-15: Reliability and Availability Evaluation of Unit-I

As the failure or state 0 has been classified as scheduled or planned outage and forced or electromechanical outage. The contribution of scheduled and forced outage for the performance of the BSHP-I unit-I is shown in the figure below. The figure below indicates that in the beginning year of plant production the contribution of electromechanical failure is low but it increased in succeeding years so it needs an effective maintenance strategy. In the fiscal year 2069/70, in this period the contribution of the scheduled outage is 57%. As in this period, unit-I was operated for 6350.3 hours where 166.9 hours is due to scheduled outage such as system failure, thrash rack clean, insufficient flow, etc. and the plant stops for 128.5 hours due to different failures in the electromechanical section. Similarly, in fiscal year 2070/71 plant operated for 7067.8 hours and 52% of the failure is due to scheduled outage i.e unit-I fails for 180.72 hours due to scheduled outage event and 167.46 hours fails due to the failure in the electromechanical problem. In the succeeding fiscal year i.e 2071/72 the failure in the electromechanical system increases. In this fiscal year, Unit-I operates for 6949.6 hours where it fails 184.4 hours due to the cause of scheduled outage whereas 282.3 hours due to failure in the electromechanical system. The contribution of schedule outage in availability is 40% and the forced outage is 60%. In the fiscal year 2072/73, the contribution of the scheduled outage was observed as 70% with total failure hours 316.97hours due to the event related to scheduled outage. And 30% contribution of the forced outage which is due to 133.01 hours failure in the electromechanical component. In fiscal year 2073/74 Unit-I operates for only 5719.1 hours where the contribution of the scheduled outage is 94% and the failure of the electromechanical component is 97.41 hours. Similarly, in fiscal year 2074/75, it is found that the contribution of the forced outage is increased to 41% and the scheduled outage is 59%. In this period unit-I was operated for 7139.4 hours where the electromechanical failure was 113.65 hours and 162.95 hours due to the causes of the scheduled outage. Whereas in fiscal year 2075/76 Unit-I was observed in operating condition for only 5035.8 hours with 1218.5 hours outage related to the scheduled outage event and 1161.7 hours due to the failure in the electromechanical component. So in the performance of unit-I, in this fiscal year, the contribution of the scheduled outage is 51% and the forced outage is 49% the same as the previous year.

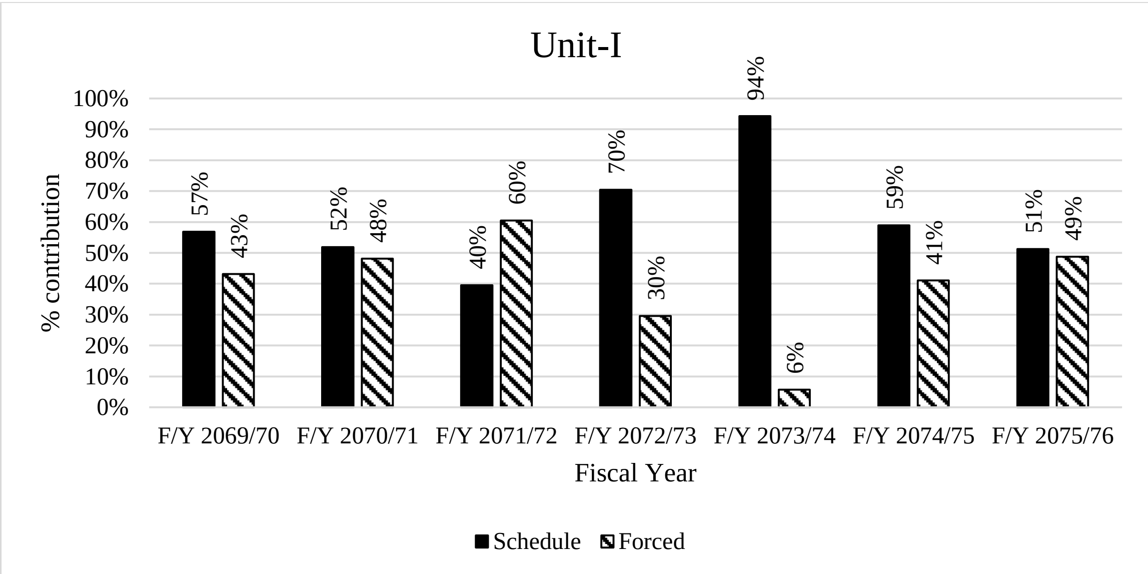


Figure 4-16:Contribution of Scheduled and Forced Outage in performance of Unit-I

During the analysis of unit-I different reliability-parameters were calculated which is shown in the table. This shows that maintainability is poor in fiscal year 2077/74 and 2075/76. From the analysis of data, it is found that in these periods there is long time breakdown in unit –I due to maintenance in the dam which was damaged by the flood and earthquake of 2072 and due to the problem in AVR in generating section as maintainability is the parameter which shows the probability of restoration of the system in specified time.

Table 4-1: Reliability parameter of Unit-I in seven fiscal year

	F/Y 2069/70	F/Y 2070/71	F/Y 2071/72	F/Y 2072/73	F/Y 2073/74	F/Y 2074/75	F/Y 2075/76
System Unavailability	0.027	0.026	0.034	0.043	0.189	0.027	0.269
MTBF	312.857	273.750	324.444	365.000	515.294	584.000	302.069
MTTR	8.650	7.389	11.562	16.255	120.304	16.458	111.205
Maintainability	1.000	1.000	0.998	0.988	0.450	0.987	0.477

As we are intended to find the critical assets. The figure below shows the contribution of the different subsections in the forced outage of unit-I of BSHP-I. As there is no significant failure observed in the generating section in fiscal year 2069/70 and 2070/71 there occurs a single failure in 2069/70 and 2070/71 which disturb the line for only half an hour. In fiscal year 2071/72, the contribution of generating section in the forced outage is 28% which is due to failure in AVR two times in that period as it fails for 79.72 hours. And other failures observed in this section were stator failure, PCB failure, cooling system failure, etc are major failures which contribute unit –I forced outage from the side of the generating section. In fiscal year 2069/70, the contribution of the turbine section for forced outage or electromagnetic failure is 79% this year as three failures disturb the plant for 101.66 hours. Similarly in the fiscal year 2070/71, the contribution of the turbine section in a forced outage is 74% and the number of failures observed in this period was 14 and disturb for 124.38 hours. The contribution of the turbine section in fiscal year 2071/72 is found as 62% with nine breakdowns with breakdown hours of 175.36 hours. Similarly from the fiscal year 2072/73 to 2075/76 the contribution of the turbine section in forced breakdown found as 71%, 64%, 34%, and 97% respectively. On fiscal year 2072/73 turbine section fails for 94.23 hours wherein F/Y 2073/74 fails for 62.43 hours and 38.7 hours and 1128 hours respectively in F/Y 2074/75 and 2075/76. In most cases, the problem such as a decrease in pressure in the governor, problem in guide-vane, shaft excessive vibration, etc is the major problem that leads to failure in the turbine section. In BSHP-I there is only one transmission system for both the unit. The power generated from both the generator is mixed in a single transmission line through proper phase matching. If any failure occurs in the Transmission line both the unit will be affected. The contribution of failure in the transmission section in a forced outage is 21% in the fiscal year 2069/70. Where there were six failures were recorded in the transmission system and it disturbs 26.35 hours in the power production. Similarly, the contribution of the transmission system for unit-I is found as 25% for the forced outage in fiscal year 2070/71. In this period the plant disturbs 42.58 hours due to failure in the transmission section. The analysis shows that the contribution of the transmission system is 28% and 12% in the fiscal year 2071/72 and 2072/73 with the total breakdown time of 29.95 hours and 22.96 hours respectively. In fiscal year 2073/74 transmission system contribution is 25% for the forced outage of unit-I where the total breakdown time is of 24 hours. In fiscal year 2074/75, its contribution is increased to 66% as the number of failures observed in this period is six and the plant disturb due to breakdown in the transmission section is 74.45 hours. Whereas six failures of 26.05hours of failure were recorded in fiscal year 2075/76 which contribute only 3% in the forced outage of unit I.

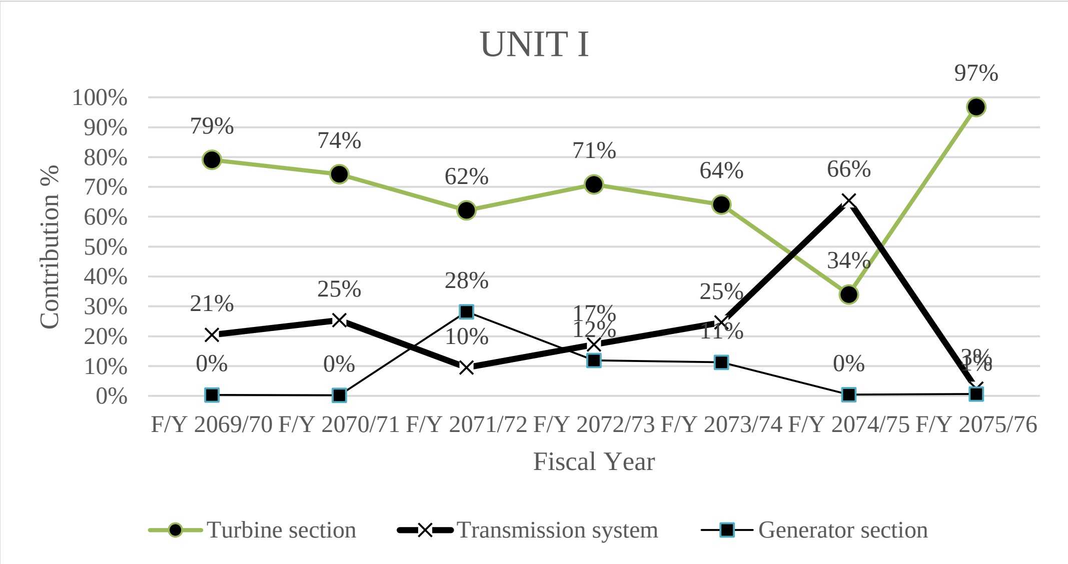


Figure 4-17: Contribution of the different component in the forced outage of Unit-I

Similarly, as BSHP-I has two units that run parallel so reliability and availability of unit –II also done similarly as unit-I. The reliability and availability evaluation of unit –II of BSHP-I for the periods of seven years is shown in the figure below. Where in fiscal year 2069/70 the total no. of the operating hour is 6334.7 hours observe 35 failures in this period with reliability 0.882 and availability 0.953. In the fiscal year, 2070/71 total no. of failure was observed as 33 as some of the forced failure cases were increased with the reliability of 0.899 and the availability was 0.946 with total failure hour 405.07 hours. In fiscal year 2071/72, the reliability of Unit-II was observed as 0.941 with the 19 failures observed in that fiscal year in unit II whereas the availability of the plant decreased as it was observed as 0.970 with the total failure hours 220.35 hours. From this, it can be said that the maintainability of the plant in this fiscal year is higher than the previous year. The reliability and availability of unit II were observed as 0.923 and 0.945 in fiscal year 2072/73. Where the total no. of failure observed was 25 and 409.98 hours of failure. As in fiscal year 2073/74, the reliability and availability of BSHP-I unit II were observed as 0.956 and 0.779 respectively. In this period the plant was operated for 5705.4 hours, at this period 14 failures were observed with 1650.2 hours of plant shut down due to different failures due to different reasons. In fiscal year 2074/75, the reliability of unit II was observed as 0.929 with total failure recorded as 23. And availability was observed as 0.952 with total failure hours 356.8 hours. Similarly, in fiscal year 2075/76, the reliability of Unit II was found as 0.923 and availability was 0.829. In this period unit-I was operated for only 6135.2 hours and 27 failures were observed.

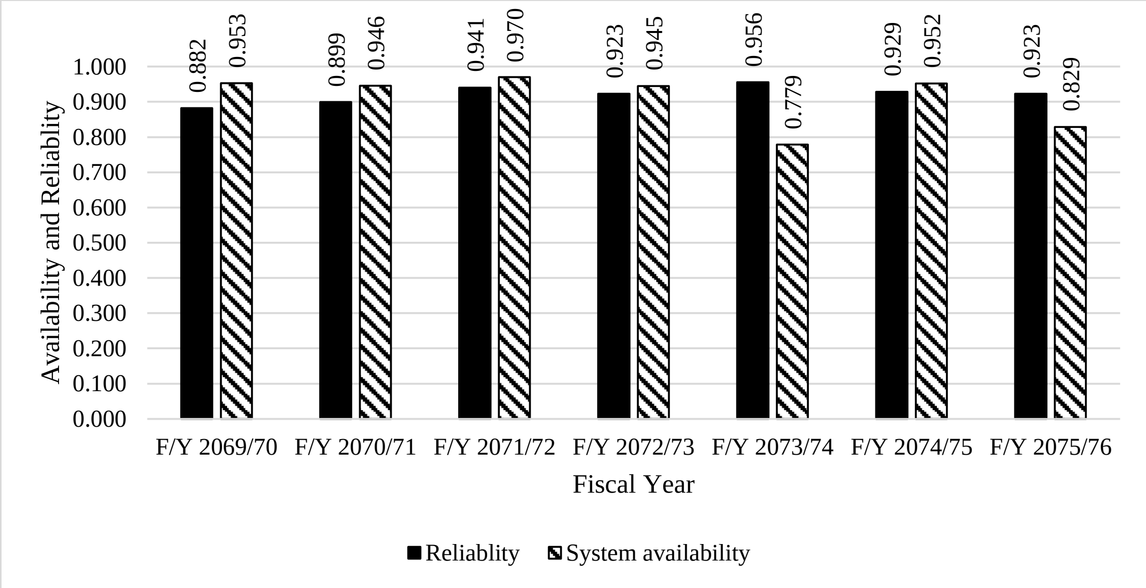


Figure 4-18: Reliability and Availability Evaluation of Unit-II

After calculation of reliability and availability of BSHP-I Unit-II, to identify the critical path it is necessary to narrow down the failure causes i.e intermediate event of the fault tree. As in Unit-I in Unit-II, the failure or state 0 has been classified as scheduled or planned outage and forced or electromechanical outage. The contribution of scheduled and forced outage for the performance of the BSHP-I Unit-II is shown in the figure below. In the fiscal year 2069/70, in this period the contribution of the scheduled outage is 54%. As in this period, Unit-II was operated for 6334.7 hours where 144.12 hours is due to the forced outage. Similarly, in fiscal year 2070/71 plant operated for 7010.9 hours, 45% of the failure is due to scheduled outage i.e Unit-II fails for 180.72 hours due to scheduled outage event, and 224.35 hours fails due to the failure in the electromechanical problem. In the succeeding fiscal year, i.e 2071/72 Unit-II operates for 7195.7 hours where it fails 184.4 hours due to the cause of scheduled outage whereas 35.95 hours due to failure in the electromechanical system. The contribution of schedule outage in availability is 84% and the forced outage is 16%. In the fiscal year 2072/73, the contribution of the scheduled outage was observed as 77% with total failure hours 316.97hours due to the event related to scheduled outage. And 33% contribution of the forced outage which is due to 93.01 hours failure in the electromechanical component. In fiscal year 2073/74 Unit-II operates for only 5705.4 hours where the contribution of the scheduled outage is 97% and the failure of the electromechanical component is 51.96 hours. Similarly, in fiscal year 2074/75, it is found that the contribution of the forced outage is increased to 54% and the scheduled outage is 46%. In this period Unit-II was operated for 7059.2 hours where the electromechanical failure was 193.85 hours and 162.95 hours due to the causes of the scheduled outage. Whereas in fiscal year 2075/76 Unit-II was observed in operating condition for only 6135.2 hours with 1218.8 hours outage related to the scheduled outage event and 62.3 hours due to the failure in the electromechanical component. So in the performance of Unit-II, in this fiscal year, the contribution of the scheduled outage is 95% and the forced outage is 5%.

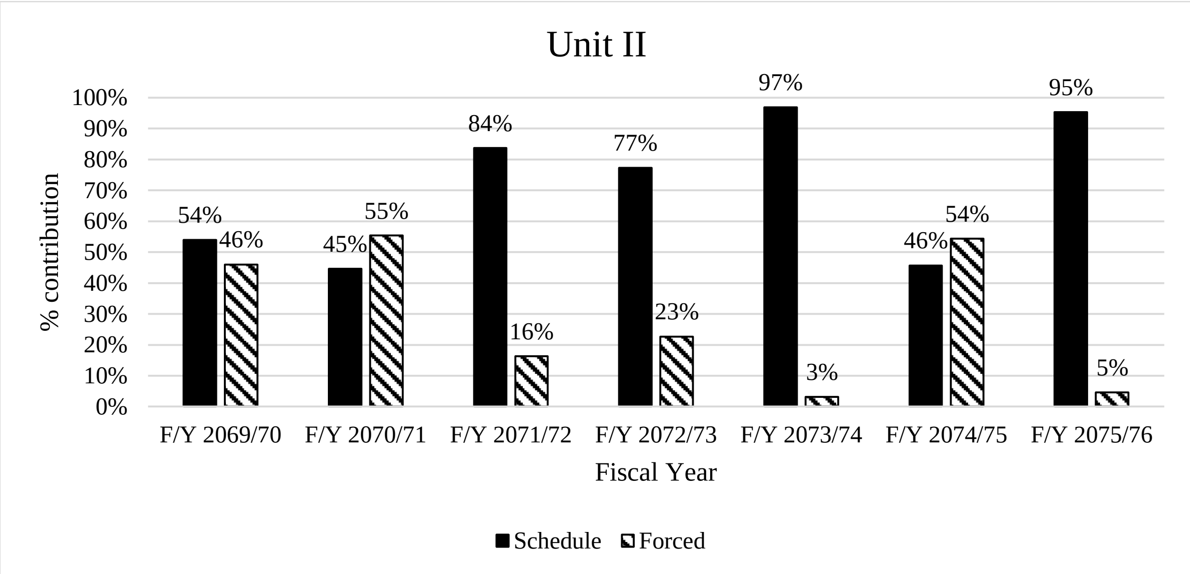


Figure 4-19: Contribution of Schedule and forced outage in the failure of BSHP-I Unit-II

From the analysis of the data different parameters of reliability engineering were calculated which are shown in the table. From the analysis, it is found that the meantime to repair in fiscal year 2073/74 is greater than another fiscal year due to the Civil maintenance work in the dam section which was affected by the earthquake and flood of 2072 in the Sheti river. And the maintainability of the plant is around 99% in all the fiscal year except 2073/74 and 2075/76. This implies that there is no major problem in Unit-II which takes a large time to restore the system. In the fiscal year 2075/76, the maintainability of Unit-II found only 76.6% which is due to the unexpected failure in the voltage regulator panel of the generator section and problem in the transmission system.

Table 4-2: Reliability parameter of Unit-II from F/Y 069/70 to F/Y 075/76

	F/Y 2069/70	F/Y 2070/71	F/Y 2071/72	F/Y 2072/73	F/Y 2073/74	F/Y 2074/75	F/Y 2075/76
System Unavailability	0.030	0.030	0.024	0.042	0.188	0.035	0.145
MTBF	292.000	273.750	365.000	350.400	547.500	461.053	292.000
MTTR	8.996	8.510	9.024	15.212	127.021	16.960	49.594
Maintainability	1.000	1.000	1.000	0.991	0.433	0.986	0.766

To analyze further to find out the root critical event, it needs to find the contribution of the different subsystems of the forced outage so that we can make the strategy that can improve the performance of the plant. The contribution of the different subsystems of the forced outage is shown in the figure. As in beginning year i.e in the fiscal year 2069/70, the contribution of the turbine section is greater than the other subsystem. As its contribution is 81%, where 17 failures, were recorded with total breakdown hours was 116.7 hours. Also, in the same period, there is no contribution of the generator section in forced outage where the transmission section has an 18% contribution in the performance of Unit-II of BSHP-I and 1% contribution of the generator section. In fiscal year 2070/71, there were 12 failures with 181.27 hours of the breakdown were recorded in the turbine section. In this period the contribution of the turbine section is 81% and the transmission section is 18%, where the transmission section fails eight times in this period with total breakdown recorded as 42.58 hours. And one minor failure with a breakdown of half an hour was recorded in the generator section. Similarly, in fiscal year 2071/72 two failures were recorded in the turbine section and the generator section, and the contribution turbine and generator section on availability of plant is found as 22% and 3 % respectively. And the contribution of the transmission section in this fiscal year is found 75%. In this period there were four failures occurs with a total breakdown of 26.95 hours in the transmission section. In fiscal year 2072/73, the contribution of the turbine section is 73% and the transmission section is 25% and the generator section is observed as 2%. Where in this period generator section fails for 2.32 hours and the transmission section fails for 22.96 hours and the turbine section fails for 67.73 hours. In fiscal year 2073/74, it is found that the contribution of the generator section slightly increased as it shares 10% of failure that affects the reliability and availability of Unit-II of BSHP-I. In this period generator sections fails for five hours. Whereas the transmission section fails for 24 hours and the turbine section fails for 22.96 hours. In fiscal year 2074/75, the contribution of the transmission section is found 38% and the generator section's contribution is 9%, and the turbine section is seen as 53%. Where the total failure observed was 102.4 hours in the turbine section, 74.45 hours in the transmission section, and 17 hours in the generator section. In the fiscal year 2075/76, it was observed that the generator section fails for 18.6 hours, the turbine section fails for 14.05 hours and the transmission section fails for 29.65 hours as the contribution in a forced outage is shown in the figure below.

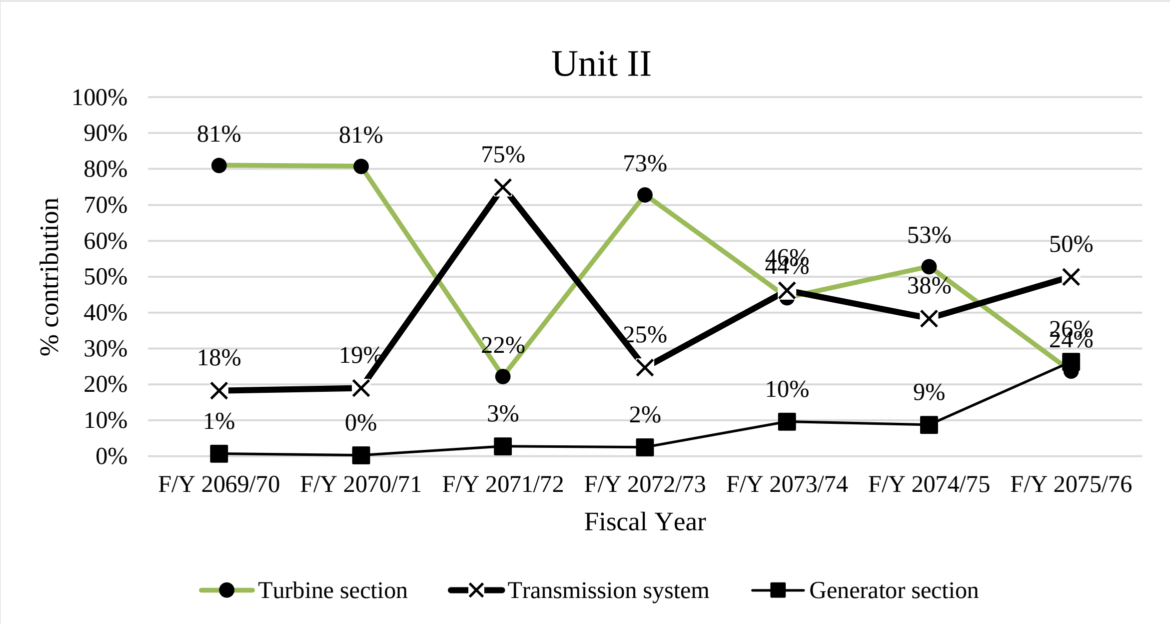


Figure 4-20: Contribution of the different subsystem in a Forced outage in Unit-II form F/Y 069/70 to F/Y 075/76

After the analysis of seven years of data, it can be concluded that the contribution of schedule outage in availability is much higher than the forced outage. In this period plant for Unit-I, there were all total 225 failures were recorded which disturb the plant for 8295.3 hours. And 96 failure was recorded as scheduled outage and the plant disturb for 5049.9 hours due to the cause of scheduled outage events. And 3245.4 hours disturb due to the failure in the electromechanical system. In this period 129 failures ware recorded in the electromechanical component of unit-I. Similarly in Unit-II,176 failures were recorded which disturb the plant for 4637 hours. Among which 69 failures were in the scheduled outage and 107 outages were categorized as the forced outage. The contribution of the scheduled outage and forced outage in the availability of the plant is shown in the figure. And we can predict the reliability contribution of the following subsystem. From the calculation, it is found that the contribution of scheduled outage in the reliability of unit I is 41%, and forced outage offers a 59 % contribution. And in the case of Unit-II, the contribution of the scheduled outage is 39% and 69 % respectively. For both, the unit contribution of the forced outage is more for the reliability of BSHP-I. So as reliability based maintenance we are intended to find the reliability sensitive branch of the fault tree which is directed towards the forced outage.

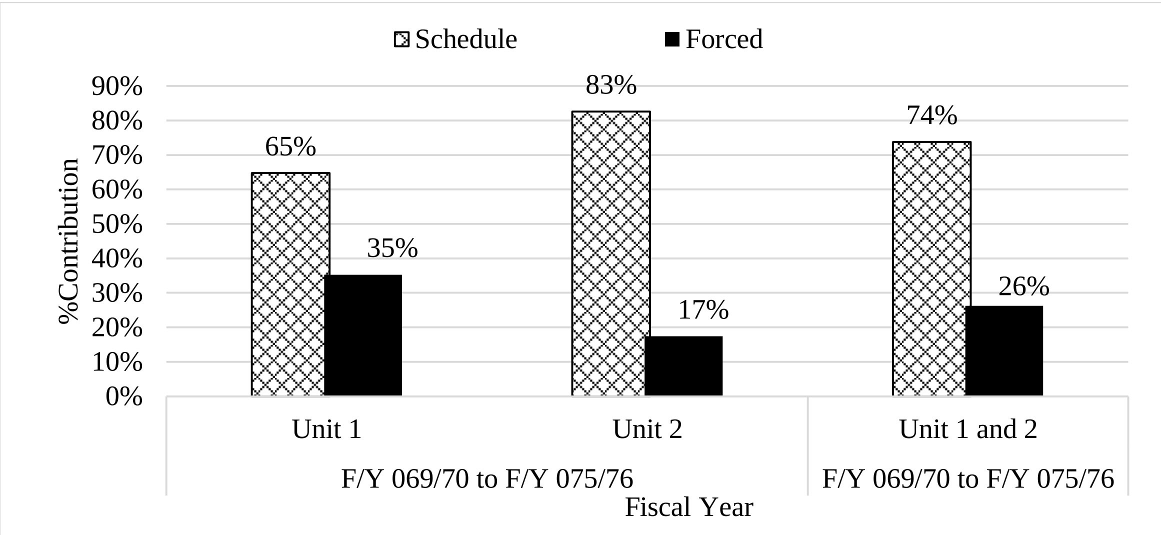


Figure 4-21:Overall contribution of schedule and forced outage in the availability of Unit-I and Unit-II

As in Forced outage, we have three subsystems, i.e problem in the turbine section, the problem in the transmission section, and Generator malfunction. This implies that these three causes are responsible to create failure in BSHP-I which are discussed early in the fault tree development section. The figure shows the reliability and availability contribution percentage of each subsystem of Unit-I in the Electromechanical system. From the analysis of the past seven years data, it is found that the reliability and availability of unit-I collectively found as 0.9268 and 0.9034 respectively where the contribution of the turbine section is 54 and 83 percent respectively. After the analysis it is found that the reliability of the turbine section is 0.976408 and the availability of the generator section of the Unit –I is found as 0.9994146 and the transmission system is 0.985237. Similarly, the availability of the turbine section is 0.971873, the generator section is seen as 0.998114, and the transmission section is 0.995973. From the above data and data presented in figure, it can be clear that the contribution of the turbine section to decrease reliability and availability is greater than the other section for unit-I of BSHP-I.

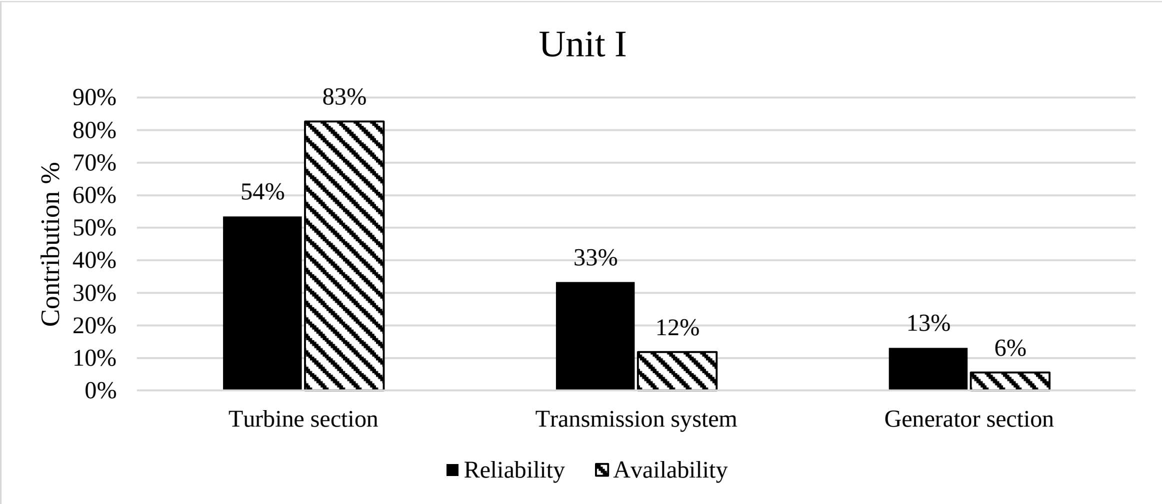


Figure 4-22: Overall contribution of EM subsystem in Reliability and availability of Unit-I

Similarly in Unit-II figure shows the contribution of three subsystems of Unit-II in the Electromechanical system. As from the analysis of the past seven years data, it is found that the reliability and availability of Unit-II collectively found as 0.933 and 0.9244 respectively where the contribution of the turbine section is 48 and 64 percentage respectively that means reliability and availability of found as turbine section is 0.980237 and 0.991631 respectively. Similarly, for the generator section, the reliability and availability are found as 0.99298 and 0.999259 respectively. And reliability and availability of the transmission section are the same as Unit-I. BSHP-I has a single transmission line for both the unit to transmit generated electricity to the Lekhnath substation. In the case of Unit-II, we can conclude that the reliability and availability of the turbine section are less than other subsystems and figure clearly shows that the contribution of the turbine section for the forced outage is higher so it implies the critical path in reliability based maintenance.

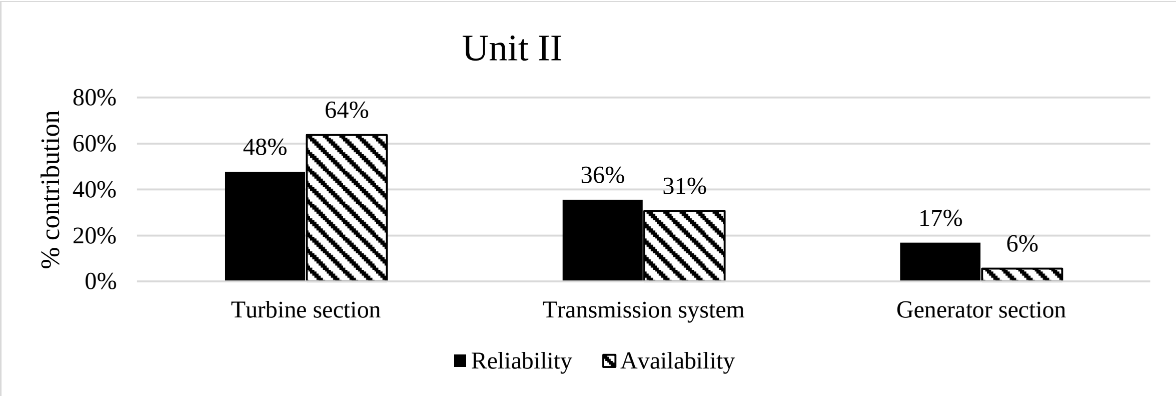


Figure 4-23: Overall contribution of EM subsystem in Reliability and availability of Unit-II

As from the fault tree analysis, the failures in the turbine section are caused due to main four causes such as cooling system failure, the problem in the intake gate system, due to faulty guide vane, and due to excessive shaft vibration. From the analysis, it is found that the contribution of the cooling system in reliability is 72% in unit I which is more than the other subsystem which is shown in the figure. As in the cooling system, all total 40 failures were observed with total breakdown hours of 501 hours were recorded in the past seven years of study. Whereas there were only 9 failures in the intake gate system, eight failures in the guide-vane, and 4 failure due to excessive shaft vibration. However, the breakdown time is higher due to excessive shaft vibration which affects the plant for 1116.36 hours where faulty guide vane and intake system fails for 39.4 hours and 68 hours respectively. As faulty guide vane and excessive shaft vibration are the intermediate events of fault tree whereas cooling system and intake system are the basic events. As the contribution of the cooling system is more than other events so the cooling system is the critical assets of Unit-I.

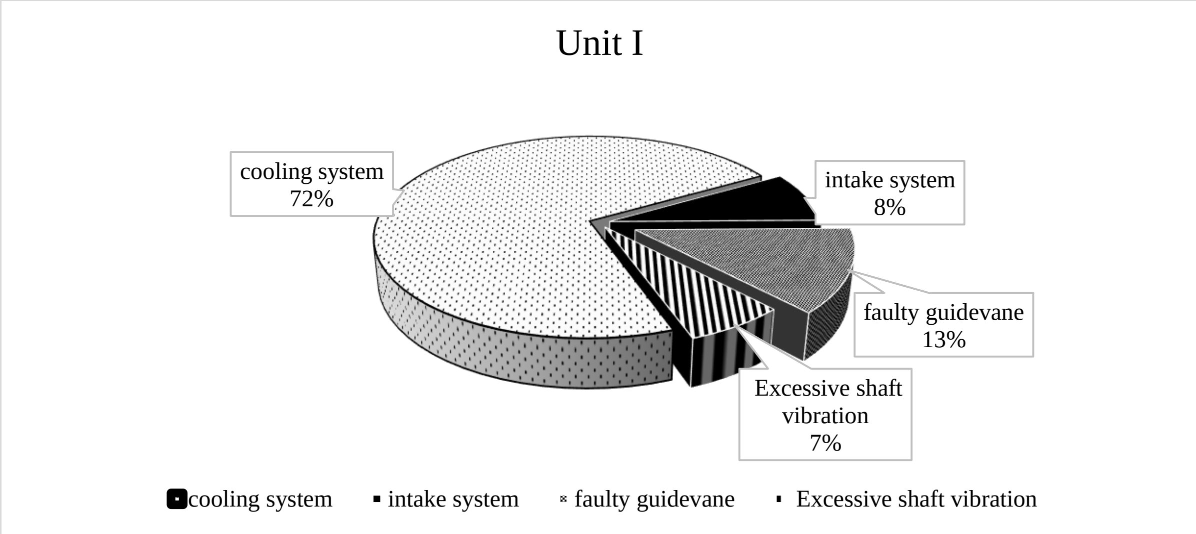


Figure 4-24: Contribution of the different subsystem of the turbine section of unit-I in reliability

Similarly, from the analysis, it is found that the turbine section has higher reliability than other components. And as explained in Unit-I in Unit-II also the contribution of the cooling system in reliability is more than other subsystems. The contribution of the cooling system is found 64% which is more than other subsystems of the problem in the turbine system in the fault tree. From the analysis of data, it is observed that 33 failures with 295 hours of the outage were recorded in the past seven years which was taken into consideration. While faulty guide-vane is also another subsystem which contributes 27% in the reliability of the plant where it fails for 14 times and disturbs 118.18 hours. There was only a single failure due to Excessive shaft vibration and the problem in the intake gate occurs for three times in the seven years of analysis. And the contribution of the different subsystems is shown in the figure below. As the cooling system is the basic event of the fault tree so the cooling system is observed as the critical asset in unit II.

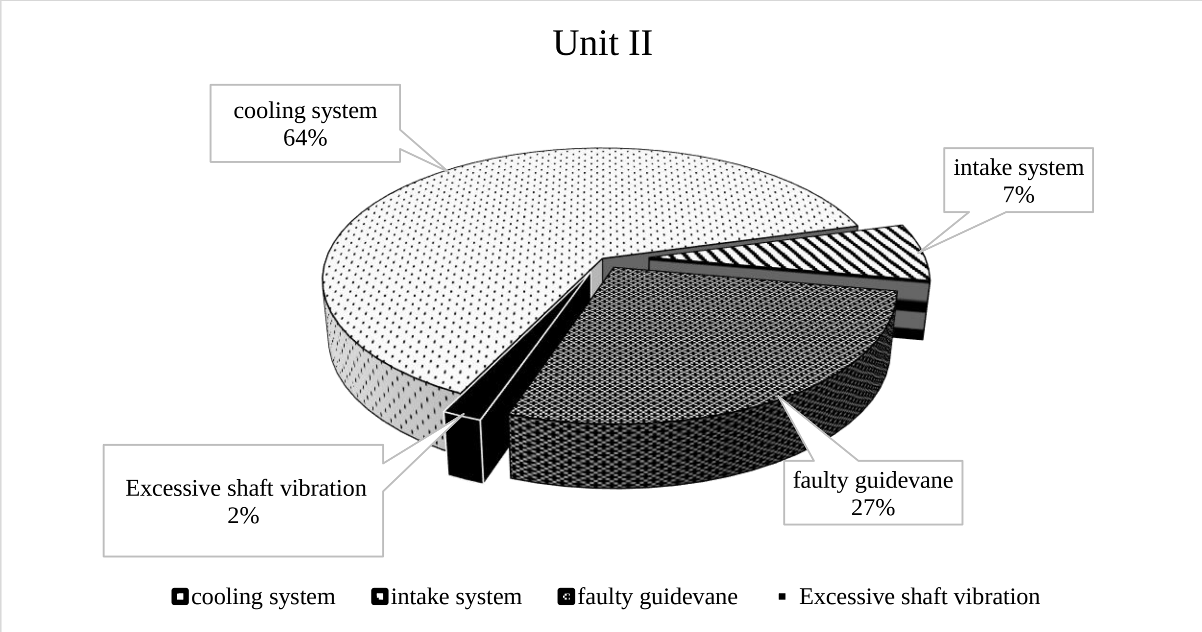


Figure 4-25: Contribution of different component of the turbine section of Unit-II in reliability

4.3 Failure Mode and Effect Analysis

From the above result and discussion, it is clear that the electromechanical subsystem in both the unit of BSHP-I suffers from the problem in the cooling system. So by analyzing the cooling system of BSHP-I as per the philosophy of Reliability-Based Maintenance, the maintenance strategy should be focused on the cooling system. Now to get the required maintenance strategy, FMEA of the cooling system has done as shown in the table. Firstly the cooling system is classified into its functional component. As an open-loop water cooling system was used in BSHP-I. And it consists of functional components such as a Motor-operated valve, circulation pump, Radial tube filter, Heat Exchangers, and Non-Return Valve. The Failure mode, the potential cause of failure, and the potential effect of that failure mode were analyzed. The particular cause and effect were rated based on their occurrence, detection, and severity. The score for each event is given between 1 to 10. As 1 represents the less chance of occurrence, easily detectable type of failure, and less impact on plant i.e easily maintainable in less time. Similarly, 10 represents the event is repeated frequently, also it is difficult to detect thoroughly and high impact on production. The total score was calculated by multiplying the score obtained in occurrence, detection, and severity.

Table 4-3: Failure Mode and Effect Analysis of Cooling system

S.No.	Functional Component	Sub-component	Potential Failure Mode	Detection (1-10)	Potential Failure Effect	Severity (1-10)	Potential Cause	Occurrence (1-10)	Total Score
1	Motor Operated Valve	Stem	Stiffness of stem moment	6	Overheating of the motor, contractor tripping	3	Excessive motor torque, Dirt, Lubrication	4	72
			Breaking of Stem Nut	3	Vibration and leakage	2	Excessive torque form motor	3	18
		Torque Switch	Wrong Adjustment/Setting	5	Uncontrolled Flow	6	Defect in Assembly	2	60
		Contractor	No electrical connection	3	Valve does not operate	7	Dirtiness of contacts	5	105
		Relay	Poor performance in switching	3	Malfunctioning of valve	8	Dirtiness of Contacts	4	96
		Limit Switch	Wrong Setting	3	Mechanical Vibration and improper flow	8	Wrong Approximation, and Dirt	2	48
		Micro Switch	Stiffness of Mechanism	6	Disturb inflow	4	Excessive force in switch	2	48
			Dirtiness of Contract	3	Moter does not operate in time	7	Lack of proper cleaning	4	84
		Hand Drive	Breaking of declutching lever key	2	Risk to Operate Valve	8	Improper design and material selection	2	32
2	Non-Return Valve	Valve	Water Hammer	4	Failure in Pump due to two-way flow	7	Erosion	3	18

Contd..

			Excessive Vibration	2	Leakage in Joint	3	Water Hammer	3	18
3	Radial Tube Filter	Cartridge	Choking	5	blockage of water	9	Heavy Limestone in water	10	450
		Tube	Leakage	6	Less Flow of water	8	Corrosion	4	192
			Layer Deposition		Pressure increase		Limestone in water		
		Joints	Leakage	3	Flow Decrease	8	Corrosion and Deposition	4	96
4	Circulating Pump	Mechanical Seal	Leakage	3	losses of pumping efficiency	5	Worn out	2	30
		Bearing	Worn out	4	excessive pump vibration, increase shaft radial moment, eventual pump shutdown	6	Shaft alignment, aging	4	96
		Shaft	Worn out and Corroded	6	Vibration, Bearing damage and Coupling Failure	5	Alignment, Bearing Failure, defect in assembly	2	60
		Impeller	Worn out	6	Reduce Suction Power, increase Vibration	5	sit particle in water, cavitation	2	60
		Electrical Cotractor	No electrical connection	2	Pump stop	7	Corrosion, loose contact	4	56
		Coupling	Worn out	3	Noise and Vibration	4	Mis-alignment	4	48

Contd...

5	Heat Exchanger	Tube	Choking	6	No Circulation of water	8	Layer deposition of unfiltered limestone	6	288
			Corrosion	6	Leakage	8	Reaction with different particle in water	2	96
		Tube Sheet	Tube sheet failure	4	Vibration	4	Defect in assembly, turbulent in tube flow	2	32

4.3.1 Reliability Strategy

The main purpose to analyze the failure mode, their effect, and potential causes of occurrence was to generate general maintenance scheduled and specific strategies that can improve the reliability and availability of the cooling system. From the Failure Mode and Effect Analysis, the criticality score of each functional component and sub-component were analyzed. In the motor-operated valve, the failure mode with No electrical connection from the contractor has a higher score, this means that we have to take care more for this failure mode of this component for the smooth operation of the motor-operated valve. Similarly, both the failure mode water hammering and Excessive vibration of the Non-Return valve have a similar score and the score seems quite low as compared to other components of the cooling system, which indicates that, we can general types of maintenance strategy for this component. The recommended maintenance strategies are shown in the table below.

Table 4-4: Recommended Preventive Maintenance Strategy for the Cooling system

S.No.	Functional Component	Sub-component	Action Recommended	By Whom			When			
				Electrical Foremen	Mechanical Foremen	Plant	Daily	Weekly	Monthly	Conditionally
1	Motor Operated Valve	Stem	Scheduled inspection and functional test		√		√			
			Measurement and monitoring of motor power	√			√			
			Measurement of stem force if applicable		√			√		
			Scheduled Cleaning and Lubrication of Stem		√			√		
			Measurement and monitoring of motor power and stem force	√			√			
			Replacement of stem if necessary			√				√
			Schedule Measurement and Monitoring of torque Switch Tripping	√					√	
		Torque Switch	Redesign the Motor operated valve if necessary			√				√
			Schedule cleaning the contract point, change if necessary	√				√		
			Schedule Functional Test	√				√		
		Contractor	Schedule measure the temperature and clean and tight the contact point	√				√		
			Schedule functional Test and replace if necessary	√		√			√	
		Relay	Schedule measure the temperature and clean and tight the contact point	√				√		

Contd..

		Limit Switch	Schedule Functional Test	√		√			√	
		Micro Switch	Schedule Functional Test	√		√			√	
		Hand Drive	Schedule Functional Test and redesign if necessary		√	√			√	
2	Non-Return Valve	Valve	Schedule functional Test and replace if necessary		√				√	
			Use spring-loaded valve if possible			√				√
			Pump operates with inspecting the system		√		√			
3	Radial Tube Filter	Cartridge	Schedule flushing of Filter		√		√			
		Tube	Measure the flow		√			√		
			Measure the thickness of the tube by ultrasonic wave		√			√		
		Joints	Inspect the leakage and clean and tight if necessary		√		√			
4	Circulating Pump	Mechanical Seal	Inspect the leakage and replace if necessary		√		√			
		Bearing	Schedule Functional Test and replace if necessary		√	√			√	
		Shaft	Schedule Functional Test and replace if necessary		√	√			√	
		Impeller	Schedule Functional Test and replace if necessary		√	√			√	
		Electrical Contractor	Schedule functional Test and replace if necessary	√				√		
			Schedule to measure the temperature and clean and tight the contact point	√			√			
		Coupling	Schedule to measure vibration and adjust the alignment		√			√		

Contd..

5	Heat Exchanger	Tube	Measure the flow		√		√			
			Measure the thickness of the tube by ultrasonic wave		√			√		
		Tube Sheet	Inspect the vibration of the tube hose		√			√		

From the analysis of Failure Mode and Effect of the different components concerning their occurrence, the possibility of detection, and severity of that failure, Radial tube filter with subcomponent Gritting, tube, and Joints have a higher score. This shows that the main reason for failure in the cooling system is due to failure in the Radial tube filter. And the failure mode was chocking, and deposition in the tube, as the water used in the cooling system, is directly taken from the penstock pipe which contains a large amount of limestone that cannot be settled in descending basin. So the above mentioned preventive strategies may not be sufficient to improve the reliability of the cooling system. So with the help of different literature, the strategies are recommended to improve the reliability and availability of the cooling system. And these strategies can be implemented in the plant after detailed cost-benefit analysis which is not done in this study.

Redundancy: From the economic point of view, ease of maintenance, and ease of adaptation of existing equipment, it would be desirable to make the largest possible units redundant (Flehinger, 1958). In this case, if we add a parallel panel of filter, the reliability of the cooling system can be improved form 0.989 to 0.999 and availability from 0.953 to 0.997.

Frequency of flushing: As the reliability of the cooling system is 0.989 for 24 hours. If the flushing frequency is increased to 3 times than now the reliability will be increased to 0.998 and availability improved to 0.989

Cyclone Separator: In power station victimized by silts water, frequent choking of strainers has been experienced requiring their cleaning every week and in some situations even every day. The solution lies in incorporating additionally the cyclone separators on the discharge side of the cooling water pumps the cyclone separators draw water through tangential slots and accelerate the filtration process taking advantage of the centrifugal force. It is claimed that they can arrest 90% of silt particles of size as small as 74 microns. (S.P. Kaushish, 2001)

Closed-circuit cooling water system: In arrange to dispense with the unfavourable impact of residue, a closed-circuit cooling framework could be considered, consisting of a water tank of adequate capacity, heat exchangers, and circulating pumps. Initial filing and makeup water can be drawn from the shaft sealing water supply, to keep circulating in a closed cycle through coolers and heat exchangers. Closed-circuit frameworks could be temperate in the long run since they can be outlined to consume less power compared to that required for pumping water from the tailrace or indeed compared to the misfortune of generation related with penstock tapping. (S.P. Kaushish, 2001) Also, this issue can be overcome by presenting a near close-loop together with an open-loop circuit of cooling water supply. The cooling water will pass through the Tubular Heat Exchanger. And the Tubular Heat Exchanger is submerged in Draft Tube water where heat exchange might take place. (Shah & Shrestha, 2015)

4.4 Evaluation of Reliability of BSHP –I

Since there are two units in BSHP-I, each unit of BSHP-I consists of a 2.25 MW horizontal shaft Francis turbine and generator. And the transmission line is common for both the unit. As it has a 4 km long single circuit transmission line and one substation in the hydropower premises which is connected in parallel to the main grid so if one unit is operated the station will able to deliver electricity if the transmission system is in functioning condition. By adding all of the failure and failure time of all the subsystems and applying the same process of calculating it for seven periods of time it is found that the reliability of the generator section of Unit-I is 0.99297975 and for Unit-II is 0.99297975. Similarly, the reliability of the turbine section of unit I is found as 0.97335553, and Unit-II is 0.9802704. As there is a common transmission system and whose reliability is calculated as 0.98523726. Also, there is another subsystem which affects the reliability of the BSHP-I is the scheduled outage. From the calculation it is found that the reliability of this subsystem is for the Unit-I is 0.96917 and for Unit-II is 0.97335. The subsystem can be expressed in the block diagram below.

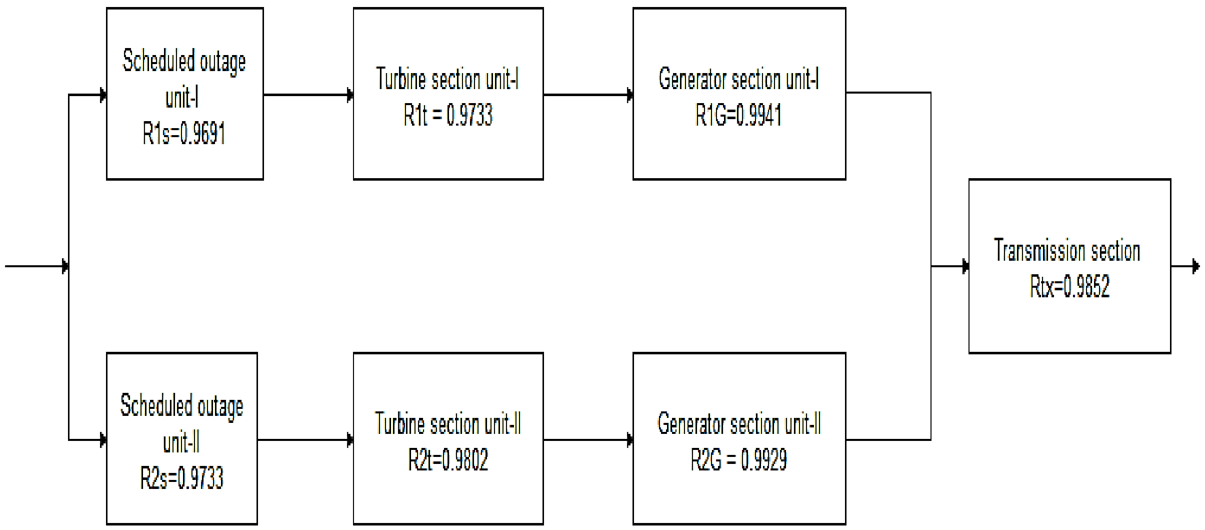


Figure 4-26: Reliability Block diagram of BSHP-I

Since in a parallel system, the total unreliability of the system is the product of the individual unreliability of the system. i.e. $Q = Q1 \times Q2$ and series system total reliability of the system is the product of reliability i.e $R = R1 \times R2$

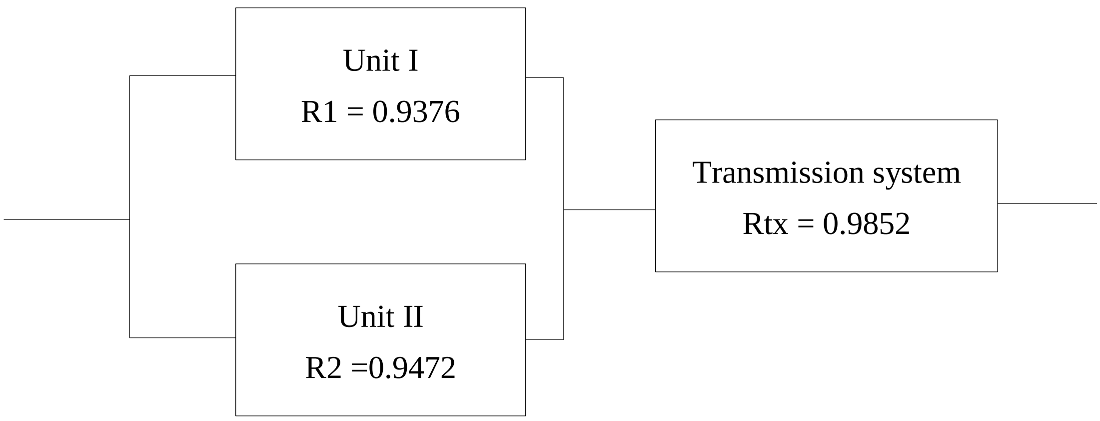
So for Unit-I reliability of the system except is $R1 = R1s \times R1t \times R1G$

$R1 = 0.9691 \times 0.9733 \times 0.9941 = 0.9376$

For Unit II reliability of the system except the transmission system is

$R2 = R2s \times R2t \times R2G$

$R2 = 0.9733 \times 0.9802 \times 0.9929 = 0.9472$



If Q = unreliability of system and We know that, $Q = 1 - R$

Then unreliability of unit I $Q_1 = 1 - R_1 = 1 - 0.9376 = 0.0624$

And unreliability of unit II= $Q_2 = 1 - R_2 = 1 - 0.9472 = 0.0528$

If Q = unreliability of BSHP-I = $Q_1 \times Q_2 = 0.0624 \times 0.0528 = 0.003294$

Then reliability of BSHP-I except transmission system = $1 - Q = 1 - 0.003294 = 0.9967$

If we include transmission system then the reliability of the whole system of BSHP-I = $R \times R_{tx}$

Therefore, reliability of BSHP-I = $0.9967 \times 0.9852 = 0.9819$.

The reliability of BSHP-I is found as 0.9819 similarly availability of the system is found as 99.25%.

4.5 Critical Analysis

Criticality analysis is a tool that can be used to access the different kinds of failures in different kinds of equipment and their impact on the overall performance of the system. It helps to rank the different component, which can be used to develop maintenance strategy and other initiatives that improve the performance of the system. For these different components of Unit-I and Unit-II of BSHP-I were selected from the fault tree of BSHP-I as per the contribution in the performance of the hydropower. Reliability parameters such as Reliability, availability, mean time between failure (MTBF), and mean time to repair (MTTR) is analyzed to select the critical component of Unit-I and Unit-II which is shown in the table.

Table 4-5: Reliability parameter of different component of Unit-I of BSHP-I

S.No	Component	MTBF (hrs)	MTTR (hrs)	Availability (percentage)	Reliability
1	Intake system	12514.29	1.16	99.991%	0.9981
2	Cooling system	1251.43	11.72	99.072%	0.9810
3	Governor	30660.00	3.00	99.990%	0.9992
4	Lubrication System	61320.00	74.49	99.879%	0.9996
5	Bearing	61320.00	362.13	99.413%	0.9996
6	Insulator	30660.00	32.23	99.895%	0.9992
7	Breaker of the Transmission system	4088.00	7.15	99.825%	0.9941
8	Transmission Equipment	4088.00	3.03	99.926%	0.9941
9	Rotor	30660.00	8.46	99.972%	0.9992
10	Excitation system	4716.92	7.60	99.839%	0.9949
11	Runner	30660.00	6.18	99.980%	0.9992
12	Transformer	20440.00	4.08	99.980%	0.9988
13	Guide vane	10220.00	5.57	99.946%	0.9977

The equipment criticality (EC) is assessed based on the impact of the fault event in reliability, availability, power generation and the cost of maintenance. And these are quantified with scores up to 3 as shown in the table. The formula for calculating equipment criticality is $EC = (30P + 30R + 25A + 15C)/3$ where,P: is the production, R: is the Contribution in Reliability, A: is the equipment availability, C: is the maintenance cost. The equipment criticality is expressed in percentage. The parameters are computed form the fault tree and the score is based on different literature and contribution of the parameter in the whole performance of Unit-I and Unit-II of BSHP-I. The maintenance strategies are selected based on the criticality of the component. As if criticality is below 50% it is recommended to run to failure maintenance, and if the criticality is above 65% these components are recommended for preventive maintenance. And rest of the components scored between 50% to 65% are recommended to adopt condition-based maintenance i.e proactive maintenance strategy (Gomaa, 2003). Those components, which are not included in this analysis, are already filtered from the fault tree so they are recommended to adopt run to failure maintenance strategy.

Table 4-6: Critical Analysis of different component of Unit-I

S. No	Component	Contribution to Reliability	Availability	Impact on Production	Cost of maintenance	% criticality
1	Intake system	2	1	1	1	43.3
2	Cooling system	3	3	2	1	80.0
3	Governor	2	1	2	2	58.3
4	Lubrication System	1	2	2	1	51.7
5	Bearing	1	3	2	3	70.0
6	Insulator	2	2	1	1	51.7
7	Breaker of the Transmission system	3	2	3	1	81.7
8	Transmission Equipment	3	1	3	2	78.3
9	Rotor	2	1	2	2	58.3
10	Excitation system	3	2	2	2	76.7
11	Runner	2	1	2	2	58.3
12	Transformer	2	1	3	2	68.3
13	Guide vane	3	1	1	1	53.3

From the analysis, it is concluded that BSHP-I should adopt a preventive maintenance strategy for the Cooling system, Bearing, Breaker, Transmission equipment, Excitation system, and transformer as their criticality is greater than 65%. And other components such as the Governor, Lubrication system, Insulator, Rotor of generator section, Runner, and guide-vane of the turbine section needs proactive maintenance through condition monitoring. And intake system seems less critical than others so run to failure approach can be adopted. This will help to reduce the non-value-added cost incurred by adopting preventive maintenance in all the assets, that will save the cost by adopting breakdown maintenance and proactive maintenance instead of preventive maintenance for the rest of the component of the plant.

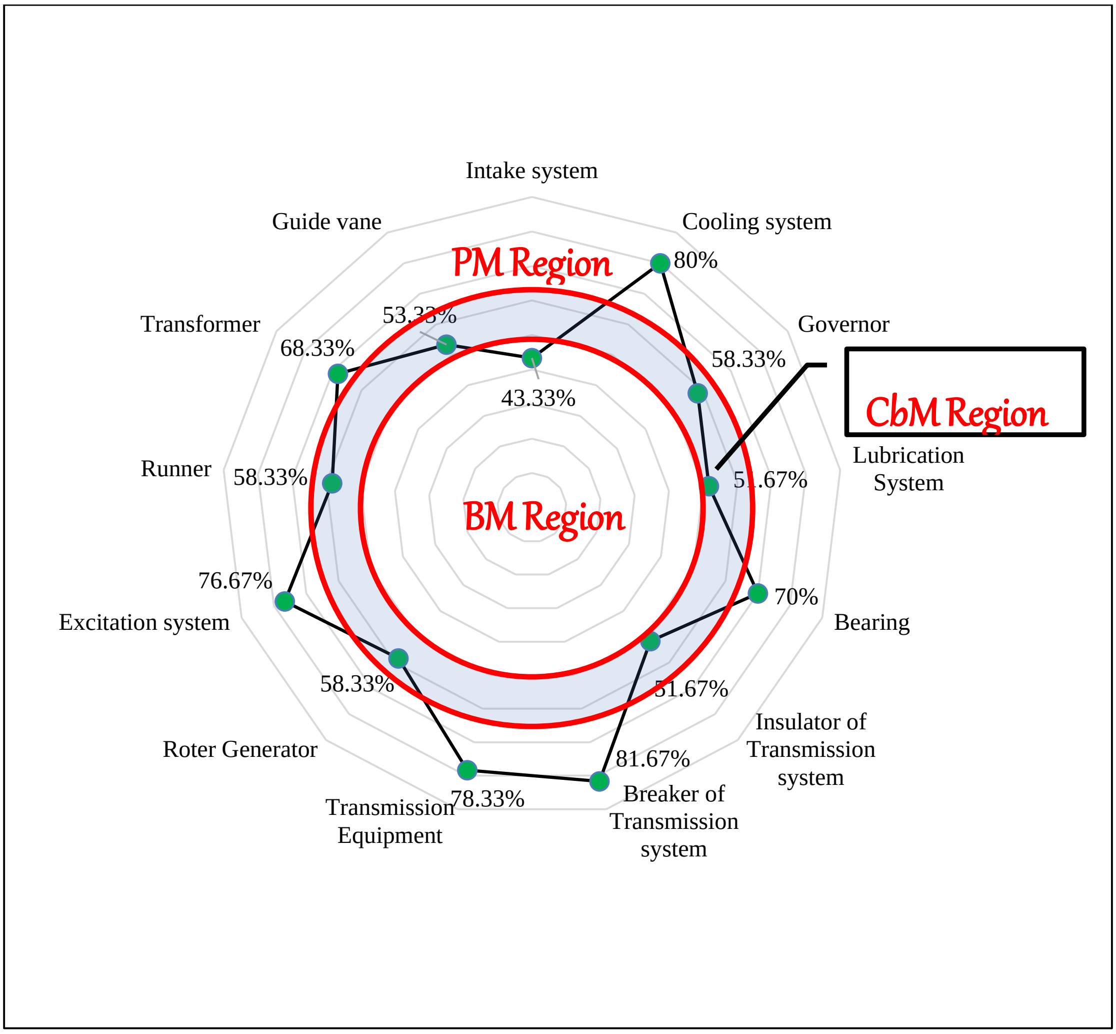


Figure 4-27: Recommended Maintenance Strategy for Unit-I

Similarly, for Unit-II also some of the critical components were selected. For the analysis, we select ten component of Unit-II which are intake system, cooling system, Governor, Insulator of Transmission system, Breaker of the Transmission system, Transmission Equipment, Rotor of Generator, Excitation system, Transformer, and Guide-vane of the turbine section as these subsystem seems the major contributing component in fault tree analysis. The reliability parameters of the component are as shown in the table below.

Table 4-7: Reliability parameter of different component of Unit-II

S.No	Component	MTBF (hrs)	MTTR (hrs)	Availability (percentage)	Reliability
1	Intake system	17033.33	0.96	99.994%	0.9986
2	Cooling system	1703.33	9.69	99.434%	0.9860
3	Governor	15330.00	15.77	99.897%	0.9984
4	Insulator	30660.00	32.23	99.895%	0.9992
5	Breaker of the Transmission system	4088.00	7.15	99.825%	0.9941
6	Transmission Equipment	4088.00	3.03	99.926%	0.9941
7	Rotor Generator	30660.00	2.30	99.992%	0.9992
8	Excitation system	4088.00	1.99	99.951%	0.9941
9	Transformer	20440.00	4.08	99.980%	0.9988
10	Guide vane	8760.00	6.03	99.931%	0.9973

And their contribution with the selected parameter for critical analysis such as contribution in Reliability of power plant, contribution in Availability, Impact on the production of electricity when failure, and maintenance cost in case of failure. Which is shown in the table below. From the analysis, it shows that in Unit-II of the BSHP-I Cooling system, Excitation system, Breaker of the Transmission system and Transmission Equipment seems more critical as their criticality ranges above 65% and the Intake system, Insulator of the Transmission system, and other remaining components which are not shown in the table are less critical as their criticality is less than 50%. Based on this criticality we can select maintenance strategy as selected in Unit-I of BSHP-I

Table 4-8: Critical Analysis of different component of Unit-II

S. No	Component	Contribution to Reliability	Availability	Impact on Production	Cost of maintenance	% criticality
1	Intake system	2	1	1	1	43.3
2	Cooling system	3	3	2	1	80.0
3	Governor	2	1	2	2	58.3
4	Insulator	2	1	1	1	43.3
5	Rotor Generator	2	1	2	2	58.3
6	Excitation system	3	1	2	2	68.3
7	Transformer	1	1	3	2	58.3
8	Guide vane	3	1	1	1	53.3
9	Breaker of the Transmission system	3	2	3	1	81.7
10	Transmission Equipment	3	1	3	2	78.3

As per the criticality of component the recommended maintenance strategy is shown in the figure below. This shows that the Cooling system, the Excitation system, Breaker of the Transmission system, and Transmission Equipment need preventive maintenance strategy as their criticality is higher than other components in BSHP-I Unit-II and condition-based maintenance will be suitable for the component such as the Governor, the rotor of the generator, Transformer, and Guide-vane. And the analysis concludes the remaining component can be adopted run to failure maintenance as these seem less critical in the analysis.

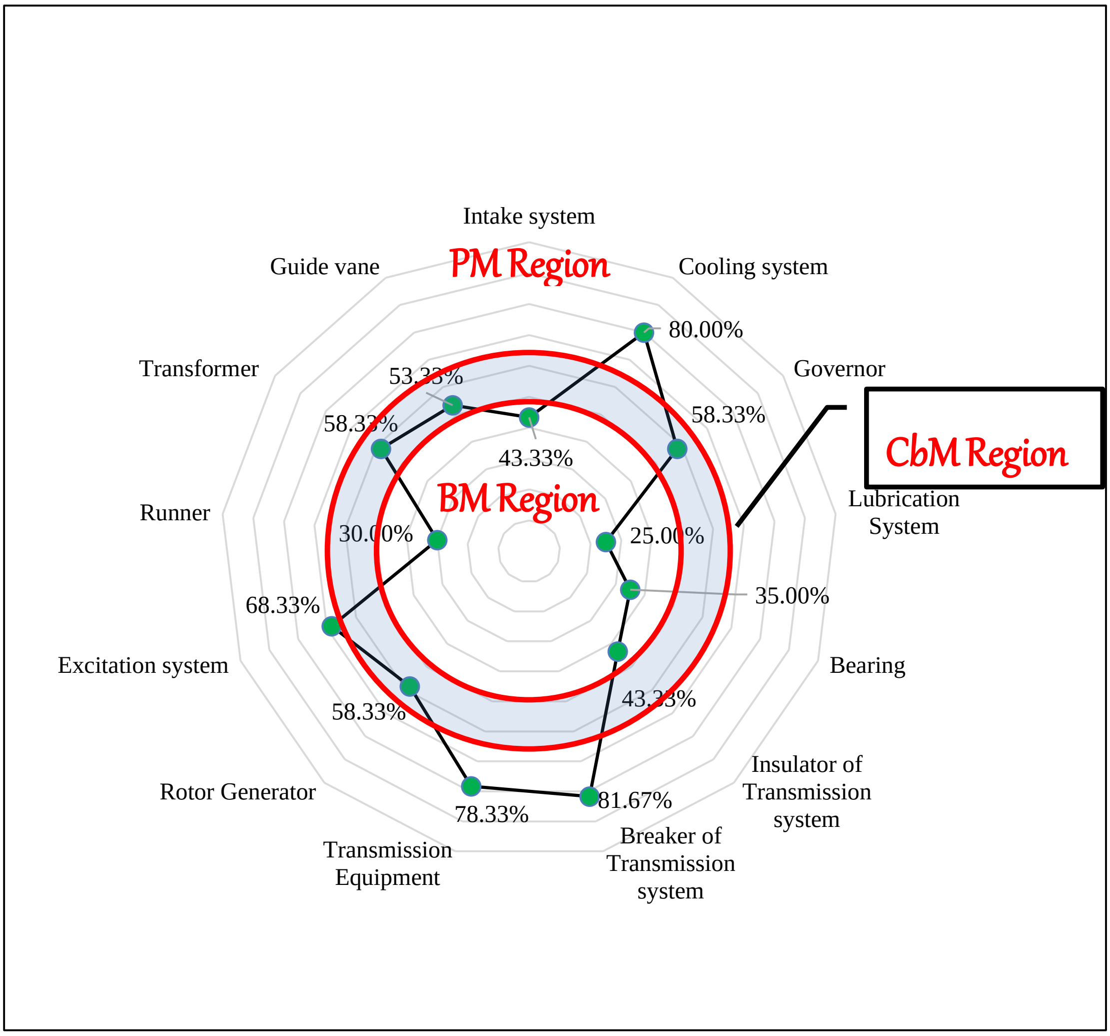


Figure 4-28: Recommended Maintenance Strategy for Unit-II

4.6 Research Validation

As the analysis of this study shows that the reliability of BSHP-I is only 0.987 which can be compared to the other similar research done in Sunkoshi small hydropower. This shows that the reliability of the system 0.9999 which is so high then the reliability of BSHP-I. As comparing the same period the failure rate of Sunkoshi hydropower is less than BSHP-I. It is observed that in BSHP-I, a single unit operates maximum for 46507 hours where one unit of Sunkoshi hydropower runs for a minimum of 46606.7 hours which shows that Sunkoshi hydropower's uptime time is higher than BSHP-I. From this, we can easily predict that there is less number of failure in Sunkoshi hydropower. And in BSHP-I most of the time plants get scheduled shutdown due to insufficient flow, as the hydropower operates from the drainage from the irrigation canal and as per the condition of the Sheti hydropower. And due to the problem in the cooling system due to blockage of the flow of water in the filter tube due to excessive limestone dissolved in water, the plant gets forcefully shut down for the maintenance so the result seems quite similar to the previous analysis result.

CHAPTER FIVE:
CONCLUSION

Reliability and availability analysis of Bijaypur-I small hydropower from the available seven years data was done successfully. Before the analysis of the reliability and availability of BSHP-I, a complete fault tree of the hydropower was develop. The fault tree includes the fault/event noted in the log sheet of BSHP-I. The top event of the Fault tree is taken as " BSHP-I fails to generate electricity", which was followed by two failure event Scheduled outage and Electromechanical outage as per the Markov three-state model of hydropower. From the analysis, almost 53 basic events were noted and were represented by the oval shape. Two parallel events were connected with AND gate whereas series events were connected with a logical OR gate. In this fault tree, there were altogether 29 logical OR gates are used to connect different Intermediate and Basic failure events of BSHP-I, and as there were no parallel event or Redundant component in both Unit-I and Unit-II no any logical AND gates were used as there were. Fault conditions were identified as per the AHP based FTA technique and Fault trees were developed with the help of logic gates and the effect and cause relationship as shown in the figure in Annex III.

Form the analysis of available data, it is concluded that both the unit of BSHP-I suffers from scheduled outage each fiscal year. The contribution of forced outage i.e due to the failure in Electromechanical system found only 30% where the scheduled outage covers almost 70% of the failure in BSHP-I. From the analysis, the result shows that the reliability of Unit-I and Unit-II is 0.9268 and 0.933 respectively. And the availability is found to be 90.34 and 92.44 percent respectively which is quite low if we study individually. From this, we can safely conclude that the reliability of Unit-II is more than Unit-I as there was less EM failure in Unit-II in the past seven years. Collectively, the reliability of BSHP-I found as 0.9819 and availability as 99.25%, as the generating section of both the units is redundant. This shows that most of the time BSHP-I operates for part load only. Also, comparing the result with Sunkoshi small hydropower plant, it can be concluded that, the reliability of BSHP-I is quite low, as BSHP-I has insufficient flow for the major period. From the past data, it shows that about 6.6% of the total time, plant disturb due to water management problems. And due to electromechanical failure plant gets shut down for 2.67% of the total time. In the EM subsystem, the problem in the cooling system due to soluble limestone in the water of Sheti River seems higher contribution and covers a significant percentage in the reliability and availability of the plant. So this paper concludes the cooling system is the main contributing component of both the unit of BSHP-I, so it is the critical assets of the plant and Insufficient flow is the critical event for BSHP-I.

In the sense to develop the strategy to improve the reliability of the BSHP-I, the study recommends the basic maintenance strategy as per the score obtained in the FMEA of the cooling system. As the Radial tube filter found more critical in the cooling system from Failure mode and effect analysis of cooling system so to improve the performance of the cooling system, the study concluded four strategies, first one increases the flushing time. The study concludes that with the increase in the flushing of radial tube filter frequency by three times i.e. one time in a week it will significantly improve the reliability and availability of the cooling system. The second option is by installing another radial tube filter parallel to the existing system, which will redundant the system and improve the reliability of the cooling system. Installing of the cyclone separator is another option that is recommended as per the previous research article. Furthermore, it recommended using a close loop cooling system rather than an open loop that is currently used in BSHP-I.

The study also concluded that it will be insufficient to improve the reliability and availability of the whole system by implementing a strategy for a single component. So this paper approach a critical analysis of the major component whose contribution is significant from the analysis of the Fault tree of Unit-I. This study identifies the major component of BSHP-I and analyzes the criticality of the component with the help of the fault tree of BSHP-I and the result presents the technical maintenance strategy as recommended by the Department of Electricity Development. This will help to reduce the overall cost of maintenance as the extra cost incurred by adopting preventive maintenance will get balanced with the cost-saving by adopting breakdown maintenance and proactive maintenance for the rest of the component of the plant

REFERENCES

International Hydropower Association Limited. (2018). *Hydropower Status report: Sector trend and insight.* United Kingdom: International Hydropower Association.

Alternate Hydro Electric Centre. (2011). *Guidelines for small hydro Development Roorkee.* Delhi: Government of India.

Bhatt, R. P. (2017). Hydropower Development in Nepal- Climate change, Impacts, and Implications. In B. I. Ismail, *Renewable Hydropower Technologies* (pp. 76-79). IntechOpen.

Budonieya, R., Premi, R., & Patel, P. (2014). System Failure Analysis In Hydropower Plant. *International Journal on Emerging Technology*, 54-58.

Chaturvedi, S. (2018). Reliability Model And Failure Parameter Grouping For Maintenance Analysis Of Hydropower Plants: A Review. *International Journal of Advanced Research in Science and Engineering*, 957-965.

Departamento de Arquitectura y Tecnología de Computadores. (2000). *Study of existing Reliability Centered Maintenance (RCM) approaches used in different industries.* Spain: Departamento de Arquitectura y Tecnología de Sistemas Informáticos (DATSI) .

Department of Electricity Development. (2017). *Guidelines For Operation And Maintenance Of Hydropower Plants, Substation, And Transmission Lines.* Singhadurbar, Kathmandu: Government of Nepal.

Flehinger, B. J. (1958). Reliability Improvement through Redundancy at Various System Levels. *IBM Journal of Research and Development, 22*(doi:10.1147/rd.22.0148), 148-158.

Gomaa, A. (2003). Maintenance Planning and Management," A Literature Study. *American University in Cairo* (pp. 50-64). Cairo: American University in Cairo.

Gupta, G., Mishra, R., & Mundra, N. (2018). Development of a framework for Reliability centered Maintenance. *International Conference on Industrial Engineering and Operations Management* (pp. 2383-2391). Bandung, Indonesia: researchgate.net.

Ismail, B. I. (2017). *Renewable Hydropower Technologies.* Croatia: InTech open.

Jain, p. K. (2017). Reliability Model Assortment For Maintenance Analysis Of Hydropower. *International Journal of Advanced Research in Science and Engineering*, 954-957.

Jena, M. C. (2015). A Study On Reliability, Validation Of Bathtub Curve, And Concept Of Madhab's Hat Curve Of Reliability. *Scholedge International Journal Of Multidisciplinary & Allied Studies*.

Kiran, D. (20017). Reliability Engineering. In D. Kiran, *Total Quality Management* (pp. 391- 404). Butterworth-Heinemann.

Majeed, A. a. (2006). Availability and Reliability Evaluation of Dokan Hydro Power Station,2006. *IEEE/PES Transmission and Distribution Conference and Exposition* (p. doi.10.1109/TDCAL 2006.311494). Latin America: https://www.researchgate.net.

mathpages.com. (2019, 12 21). *home/kmath232*. Retrieved from mathpages.com: https://www.mathpages.com/home/kmath232/part2/part2.htm

Meles, T. H. (2017, 10 3). Need for improved reliability of electricity supply in Ethiopia. (T. E. The initiative, Interviewer)

Mohd, S., Khamidi, F., & Kurian, J. (2011). Critical Review of a Risk Assessment Method and its Applications. *International Conference on Financial Management and Economics* (pp. 83-87). Singapore: IACSIT Press.

N.S, A., & J, M. (2007). Risk-based maintenance technique and application. *Journal of Hazardous material*, 653-661.

NAEEN, S. G. (2017, October 6). *Opinion*. Retrieved from The Himalayan Times: https://thehimalayantimes.com/opinion/renewable-energy-huge-potentials/

National Planning Commission. (2019). *Concept paper of 15th five-year plan.* Kathmandu, Nepal: Government of Nepal.

Nepal Electricity Authority. (2076). *NEA annual report - 2076.* Kathmandu: Nepal Electricity Authority.

Rausand, M. A. (2012). Failures and Failure Classification. In D. o. RAMS Group, *Reliability of Safety-Critical System: Theory and Application* (p. Chapter 3). https://www.ntnu.edu/documents/624876/1277046207/SIS+book+-+chapter+03+-+failures+and+failure+classification/36f29566-bd55-4a91-b002-1e17a177c035. Retrieved from NTNU.edu: https://www.ntnu.edu

REN21. (2019). *Renewable 2019: Global Status report.* Paris: Renewable Energy Policy Network for the 21st century.

S.P. Kaushish, B. N. (2001). Silting Problems in Hydropower Plants. *A.A Balkema Publisher*, (pp. 15-16). Bangkok, Thailand.

Shah, S. K., & Shrestha, D. R. (2015). Design Modification of Cooling Water System for Hydropower Plants [A Case Study of Middle Marsyangdi Hydropower Plant in Nepal]. *Global Journal of Researches in Engineering: F Electrical and Electronics Engineering, XV*(VI), 9-16.

Shrestha, D. H. (2017). Facts and Figures about Hydropower Development in Nepal. *Hydro Nepal Issue no: 20*, 1-5.

Siqueira, I. P. (2005). “Manutenção Centrada na Confiabilidade – Manual de Implementação. *Qualitymark, Rio de Janeiro,* .

Smith, D. J. (2001). *Reliability, Maintainability, and Risk* (Sixth edition 2001 ed.). London, England: Butterworth-Heinemann. Retrieved 2019

Solomon, W. (2017). *Electromechanical System Failure Analysis in Hydropower Plant.* Addis Ababa, Ethiopia.: Addis Ababa Institute Of Technology, Addis Ababa University.

Souza, R. d. (2008). FMEA and FTA Analysis For Application Of The Reliability Centered Maintenance Methodology: Case Study On Hydraulic Turbines. *Abcm Symposium Series In Mechatronics - Vol. 3*, 803-812.

The world Bank Group. (2020, 2 1). *Electric power consumption (kWh per capita)*. Retrieved from The World Bank: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

Vishnu, R. C., & Vb., R. (2016). *Reliability-Based Maintenance Strategy Selection in process Plants: A Case Study.* Global Colloquium in Recent Advancement and Effectual Researches in Engineering, Science, and Technology.

WECS. (2010). *Energy sector Synopsis Report.* Kathmandu, Nepal: Nepal Water and Energy Commission Secretariat.

WECS. (2011). *Water Resources of Nepal in the Context of Climate Change.* Singha Durbar, Kathmandu, Nepal: Water and Energy Commission Secretariat (WECS).

WECS. (2014). *Energy sector Synopsis Report.* Kathmandu, Nepal: Nepal Water and Energy Commission Secretariat.

ANNEX

ANNEX-I

Maintenance Data of BSHP-I Unit-II

Table: Maintenance Data of BSHP-I Unit-II

Fiscal Year	075-076 unit 2		074-075 unit 2		073-074 unit 2		072-073 unit 2		071-072 unit 2		070-071 unit 2		069-070 unit 2	
Basic Event	No of failure	Total time of failure (hrs.)	No of failure	Total time of failure (hrs.)	No of failure	Total time of failure (hrs.)	No of failure	Total time of failure (hrs.)	No of failure	Total time of failure (hrs.)	No of failure	Total time of failure (hrs.)	No of failure	Total time of failure (hrs.)
Thrasrack clean	2	1.2	1	0.2	2	0.4	3	1.6	3	2.4	3	2	2	2.3
Overhauling														
Switchyard/Transmission equipment	2	3.7			1	2.5	1	0.87	1	0.67	1	8.33	2	1.45
canal and penstock inspection														
Insufficent flow	3	1071.12	2	155.35	3	1592	3	226.06	2	136.89	4	142.53	2	128.78
system failure			2	6.4	1	3.76	0	0	1	7.25	1	7.38	1	15.73
flood							4	77.44	4	37.19	2	19.85	2	14.17
LDC instruction														
Transmission line and station maintenance	4	142.5	1	1			1	11			1	0.63	1	6.77
Intake gate/flushing gate/cooling system	2	6	4	43	1	15	4	45	2	8	10	143	13	87
Broken guidevane shear key	1	4.38	1	4.6	1	3.98								
oil pressure decrease	1	3.67			1	3.98	1	4.5			1	1.1	1	1.07
leakage in pressure pipe							0	0					2	27.88
Hydraulic system output signal malfunction			1	6.8									1	0.82
Interruption of governor power problem in the pump							1	18.23			1	37.17		
The broken linkage between shaft and runner			1	48										
Runner problem									1	5				

Contd..

Faulty Component in shaft bearing fails	1	3												
Pump fail	1	5												
motor damage					1	8								
Power interruption														
Steel core damage					1	8								
Insulation part fails					1	8								
Conductive part fails					1	8								
Coil fails														
Paper elements fail														
Cooling system fails											1	9.05		
oil level gauge fails to initiates trip									1	2				
Oil temperature indicator fails to initiate the trip			1	0.5										
Tap selector switch fails	1	1.6												
control Device fails	1	1.6												
Insulator Failure			2	64.4										
Isolation Switch Gear failure	1	14.5	1	1.5							1	1.93		
SF6 Degarding of Pressure									1	2.58	1	1.85	1	15.88
Potential and Current Transformer Abnormal			1	3.75	1	24	1	0.83	3	24.37	3	29.18	3	4.57
Transmission Tower Damage	1	2												
Transmission Line Damage	4	9.95	2	4.8			4	22.13			2	0.57	2	5.9
Rotor Rim Failure														
Coils connector circuit failure							1	1						
Coil internal Short circuit														
Ventilation fan failure			1	3										
Loosing of Breakshoes	1	1.6												
Stator coil failure			1	11										
power device failure	2	3	2	3	2	1	1	0.5	2	1	1	0.5	2	1
PCB card	1	14			0	0	1	1.82	0	0				
Battery Damage					1	4								
Relay fails									1	0.5				

ANNEX-II

Maintenance Data of BSHP-I Unit-I

Table: Maintenance Data of BSHP-I Unit-II

Fiscal Year	075-076 unit 1		074-075 unit 1		073-074 unit 1		072-073 unit 1		071-072 unit 1		070-071 unit 1		069-070 unit 1	
Basic Event	No of failure	Total time of failure (hrs)	No of failure	Total time of failure (hrs)	No of failure	Total time of failure (hrs)	No of failure	Total time of failure (hrs)	No of failure	Total time of failure (hrs)	No of failure	Total time of failure (hrs)	No of failure	Total time of failure (hrs)
Thrasrack clean	2	1.2	1	0.2	2	0.4	3	1.6	3	2.4	3	2	2	2.3
Overhauling														
Switchyard/Transmission equipment	2	3.7			1	2.5	1	0.87	1	0.67	1	8.33	2	1.45
canal and penstock inspection														
Insufficent flow	4	1071.12	2	155.35	6	1592	6	226.06	8	136.89	4	142.53	4	128.78
system failure			2	6.4	1	3.76	0	0	1	7.25	1	7.38	1	15.73
flood							4	77.44	4	37.19	2	19.85	2	14.17
LDC instruction														
Transmission line and station maintenance	4	142.5	1	1			1	11			1	0.63	1	6.77
Intake gate/flushing gate/cooling system	5	22	3	36	4	52	3	76	8	165	12	120	14	98
Broken guide vane shear key			0	0										
oil pressure decrease			1	2.7									1	1.43
leakage in pressure pipe					1	6.67	1	18.23			2	4.38		
Hydraulic system output signal malfunction			0	0	1	3.76							1	2.23
Interruption of governor power problem in the pump														
The broken linkage between shaft and runner			0	0										
Runner problem	1	2							1	10.36				

Contd..

Faulty Component in shaft bearing fails	1	360												
Pump fail	1	74												
motor damage			1	2										
Power interruption														
Steel core damage					1	8								
Insulation part fails					1	8								
Conductive part fails					1	8								
Coil fails														
Paper elements fail														
Cooling system fails											1	9.05		
oil level gauge fails to initiates trip									1	2				
Oil temperature indicator fails to initiate the trip														
Tap selector switch fails	1	1.6												
control Device fails	1	1.6												
Drive mechanism fails														
Tank Rapture														
Insulator Failure			2	64.4										
Isolation Switch Gear failure	1	14.5	1	1.5							1	1.93		
SF6 Degarding of Pressure									1	2.58	1	1.85	1	15.88
Potential and Current Transformer Abnormal			1	3.75	1	24	1	0.83	3	24.37	3	29.18	3	4.57
Transmission Tower Damage	1	2												
Transmission Line Damage	4	9.95	2	4.8			4	22.13			2	0.57	2	5.9
Rotor Rim Failure														
Coils connector circuit failure							1	15.32						
Ventilation fan failure			0	0										
Loosing of Breakshoes	1	1.6												
Steel Core failure														
Insulation failure														
Stator coil failure														
power device failure	1	1	1	0.5	3	1	1	0.5	2	79.72	1	0.5	1	0.5
PCB card	1	5			1	5.98			0	0				
Battery Damage					1	4								
Relay fails											1	0.5		

ANNEX-III

Fault tree of BSHP-I

ANNEX IV

Publications

1. **Authors:** Rajan Sharma, Dr Nawraj Bhattarai

   Title: Reliability-Based Maintenance in Hydropower: A case study of Bijaypur-I Small Hydropower Plant

   Publication: A peer-reviewed journal of INNOVATIONS IN ENGINEERING EDUCATION, volume-3, Issue-1, March 2020

   Publisher: IOE, Thapathali Campus

   ISSN-2594-343x

2. **Authors:** Rajan Sharma, Dr Nawraj Bhattarai

   Title: Strategy Selection for Reliability-Based Maintenance in Hydropower Plant: A case study on Bijaypur-I small Hydropower Plant

   Publication: IOE Graduate Conference, 2020-Summer

   Publisher: Tribhuvan University, Institute of Engineering

Rajan_Sharma_II.pdf

ORIGINALITY REPORT

12%	6%	5%	10%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to Institute of Engineering, Pulchock Campus, Tribhuvan University Student Paper	1%
2	Submitted to Asia e University Student Paper	1%
3	www.intechopen.com Internet Source	<1%
4	Submitted to Asian Institute of Technology Student Paper	<1%
5	Submitted to University of Canterbury Student Paper	<1%
6	Hoang Pham. "System Software Reliability", Springer Science and Business Media LLC, 2006 Publication	<1%
7	indico.cern.ch Internet Source	<1%
8	Submitted to University of Southern Queensland Student Paper	<1%