



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

School of Mechanical and Industrial Engineering Department

Electromechanical System Failure Analysis in Hydropower Plant

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Thermal Engineering

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Advisor: Dr-ing Edessa Diribsa

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Declaration

I, the undersigned declare that this thesis is my original work and has not been presented in any university, and that all the source of materials used for the thesis has been duly acknowledged.

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Acronyms and Abbreviations

FTA – Fault Tree Analysis

FMEA-Failure Modes and Effects Analysis

FMECA - Failure mode Effects and Criticality Analysis

RBD- A Reliability Block Diagram

PMRM- Partitioning Multi-objective Risk Method

PRA- Probabilistic Risk Assessment

AFTH- Fault Tree Handbook with Aerospace Applications

BDD- Binary Decision Diagram

DFTs - Dynamic Fault Trees

CFD- Computational Fluid Dynamics

UGB- Upper guide bearing

LGB- Lower guide bearing

TGB- Turbine guide bearing

THB- Thrust bearing

HVDC-High-voltage direct-current

MTBF- Mean Time before Failure

MTTR- Mean time to Repair

RCM- Reliability-Centered Maintenance

BN- Bayesian Networks

Abstract

In this thesis, assess electromechanical components of hydropower plant condition by using fault tree analysis. Show the failure occurrences of Gilgel gibe II hydropower plant generation units.

Also developed and constructed the model of fault tree of electromechanical components of hydropower plant system based on Gilgel Gibe II hydropower plant in Ethiopia.

The causes are deductively identified as the event causing every possible hazard by constructing a fault tree. The fault tree is constructed in a hierarchical structure with a single top event. The qualitative results help in focusing attention on main apparatus of electromechanical components that contributed to the unreliability of the system. Through qualitative fault tree analysis of electromechanical components Disabled turbine sub-system contain 26 single-basic-event minimal cut sets with occurrence probabilities 0.026; this indicates that disabled turbine sub-system is the highest ranking in qualitative structure importance which means the disabled turbine sub-system is the weakness point in the electromechanical system. The Turbine generator unit failure sub-system contain 14 single basic events and 12 two basic events of minimal cut sets with occurrence probabilities 0.014012, this indicates that The Turbine generator unit failure subsystem is the strongest point of electromechanical system.

Quantitative analysis is performed to estimate the probability of the top event occurrence and sub top event occurrences or unreliability of the electromechanical components hydropower plant system. The quantitative fault tree analysis resulted the rankings of quantitative contribution of sub-systems to the occurrence of top event are obtained as Disabled Turbine with occurrences of 0.0256776, Malfunction Generator with occurrences of 0.0158806 and Turbine-Generator unit failure with occurrences of 0.0139212 respectively. This means that utmost care should be taken to prevent the occurrence of the most contribute sub-system of electromechanical system failure. Turbine Failure is the most contribute sub-system of electromechanical system failure, so it takes care to prevent the electromechanical system. And finally propose maintenance policy for the common component or system failure (cooling and lubrication system) under root causes.

Keywords: Fault tree analysis, electromechanical components of hydro power plant (Turbine, Generator and Governor and Control system)

CHAPTER ONE

1 INTRODUCTION

1.1 Background

Hydroelectricity is the term referring to electricity generated by hydropower; the production of electrical power through the use of the gravitational force of falling or flowing water.

Hydro power contributes around 16.6% of the world electricity generation. [1] As a renewable energy source it has become more important economical resource compared to other renewable sources.

Hydro power produces no direct waste that affect the environment and contribution to CO₂, green house gases compared to fossil fuel plants. Global installed capacity of Hydropower generation (electrical) is approximately 1212GW (3870TWh/year). [2] It is around 88% of the renewable energy sources. [2]

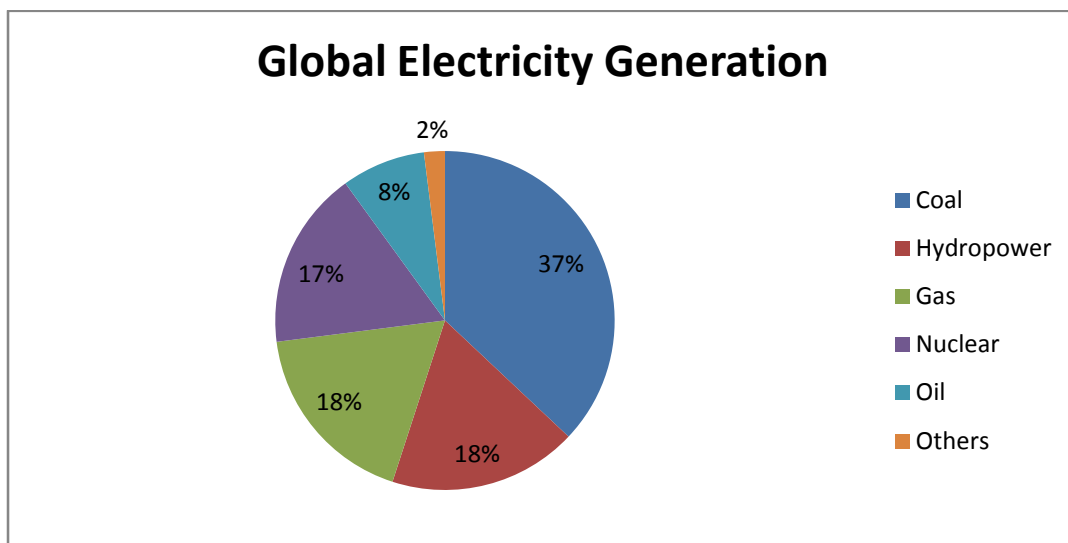


Figure 1-1 Global Electricity Generation in World

In Ethiopia about 94% of electricity is generated by hydropower [3].

- System installed capacity ~ 4422 MW
 - Hydropower (94%)
 - Wind and Geothermal (4%)
 - Solar (2%)

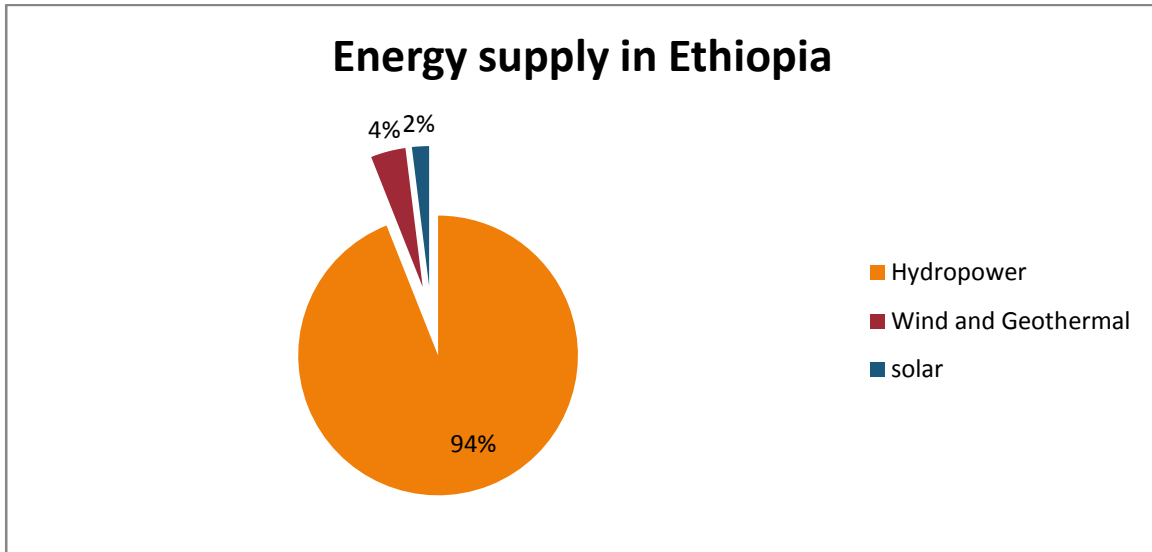


Figure 1-2 Energy supply in Ethiopia

1.1.1 List of Hydropower Stations in Ethiopia

Table 1-1 list of hydropower plant in Ethiopia In service [4]

No.	Hydroelectric station	Type	Capacity (MW)	Year completed	Name of reservoir	River
1	Tis Abay I Power Station	Reservoir	12	1953	Lake Tana	Abay River
2	koka Power Station	Reservoir	43	1960	Lake Gelila	Awash River
3	Awash II Power Station	Reservoir	32	1966	Lake Gelila	Awash River
4	Awash III Power Station	Reservoir	32	1971	Lake Gelila	Awash River
5	Fincha Power Station	Reservoir	134	1973		
6	Melka Wakena Power Station	Reservoir	150	1989		
7	Sor Power Station	Reservoir	5	1990		

Electromechanical System Failure Analysis In Hydropower Plant

No.	Hydroelectric station	Type	Capacity (MW)	Year completed	Name of reservoir	River
8	Tis Abay II Power Station	Reservoir	73	2001	Lake Tana	Abay River
9	Gilgel Gibe I Power Station	Reservoir	184	2004	Gilgel Gibe Reservoir	Omo River
10	Tekeze Power Station	Reservoir	300	2009	Tekeze Reservoir	Tekeze River
11	Gilgel Gibe II Power Station	Run of river	420	2009	Gilgel Gibe Reservoir	Omo River
12	Beles Power Station	Reservoir	460	2010		Lake Tana/Beles River

Table 1-2 list of hydropower plant in Ethiopia Under construction or Proposed [4]

Hydroelectric station	Type	Capacity (MW)	Year completed	Name of reservoir	River
Fincha Amerti Neshe	Reservoir	100	2013		
Gilgel Gibe IV	Reservoir	1472	2014		Omo River
Gilgel Gibe V	Reservoir	660			Omo River
Grand Ethiopian Renaissance	Reservoir	6000	2018		Blue Nile River
Halele Worabesa	Reservoir	440	2015		Omo River
Chemoga Yeda	Reservoir	278	2015		

1.2 Statement of the Problems

Hydroelectric power fails due to damage of hydro electric power station or its connections. Every generating station trips from time to time due to minor defects components of the and can usually be restarted when the defect has been remedied. Various protections are built into the stations to cause shutdown before major damage is caused. Some hydroelectric power station failures may go beyond the immediate loss of generation capacity, including destruction of the turbine itself, reservoir breach and significant destruction of national grid infrastructure downstream. These can take years to remedy in some cases.

Every failure has a major effect on economy due to loss of productive hours and man hour losses. Therefore for losses in production corrective and preventive action should be taken. In order of this, hazard identification can play an important role. In order to reduce the probability, frequency and duration of failure events and reduce its effect, it is necessary to perform financial investments in direction to increase the system reliability. Fault tree analysis has been successfully applied in many kinds of technical processes to improve operation reliability and safety. So the statement of the problems is reducing these problems by analyzing system faults that happen in electromechanical components of hydropower plant by using Fault-Tree Analyzing methods.

1.3 Objective

1.3.1 General Objective

The main objective of this thesis is to analyze reliability of hydropower plant system by fault tree analysis. This thesis demonstrates the application of fault tree analysis method to hydropower plant assessment of Gilgel Gibe I, II and III hydropower plant in Ethiopia. The reliability assessment of electromechanical components of hydropower plant system shows in qualitative and quantitative fault tree analysis.

The purpose of this thesis is to develop applicable qualitative and quantitative method for identifying critical and root causes of electromechanical components failure of hydropower plant.

1.3.2 Specific Objective

The specific objective of this paper describes the analysis of major failure of electromechanical components of hydropower plants, Such as hydro turbine, generator and governor and control system which is unable to deliver power. Fault Tree Analysis is used as one method of analyzing the reliability of these complex systems.

So the specific objectives are:-

- ✓ Able to construct fault tree to the hydro turbine failure.
- ✓ Able to construct fault tree to the hydro generator failure.
- ✓ Able to construct fault tree to the governor and control system failure.
- ✓ Able to Analysis qualitatively to results in minimal cut sets and qualitative importance of electromechanical system.
- ✓ Able to Analysis qualitatively to helps in focusing attention on main apparatus of hydropower plant that contributed to the unreliability of the system.
- ✓ Able to analysis quantitatively to estimate the top event occurrence and sub top event occurrences or unreliability of the hydropower electromechanical system failure.
- ✓ Able to analysis quantitatively to result the rankings of quantitative contribution of subsystems to the occurrence of top event.

1.4 Goal and Contribution of the Thesis

Monitoring and diagnostic methods of hydropower plant system have been developed since the invention of this equipment in power system. There are a variety of tools available to evaluate the condition of hydropower plant system, yet there is an increasing need for better diagnostic and monitoring tools to assess the condition of hydropower plant electromechanical system.

In this thesis, proposes an approach in order to assess hydropower plant of electromechanical condition by using fault tree analysis. We have aimed to develop the fault tree analysis of electromechanical components of hydropower plant system by using fault tree.

Motivations to conduct the research can be considered as an attempt to provide a practical approach to solve of electromechanical system assessment in hydropower plant system of Ethiopia. This method has been used and refined over the ensuing years, is attractive because it does not require extensive theoretical work and it is a practical tool that any engineer can learn to use easily. This analysis will document the cause and effect relationship between failures at various subsystem levels, to identify the most important failures and weakness points in the hydropower plant systems.

Finally conclusion and recommendation are proposed in order to contribute for resolving the reliability problem assessment of practical hydropower electromechanical systems to ensure the safety operation and distribution of Ethiopian hydropower plant systems.

1.5 Material and Method

Fault Tree Analysis is a systematic deductive procedure used to identify the basic causes of a fault event. The method is deductive because it starts from a single fault at the top of a flow chart and expands out and downward to identify many contributing causes to that single top fault. Thus the method proceeds from one event to many events. Many fault

conditions would be identified and then these conditions would be evaluated to find how they might connect to generate an undesired event. Fault trees are the model which is developed with the help of logic gates and the effect and cause relationship. Fault Tree Analysis has cut sets which help the actual cause of failure. This technique is applied on turbine, generator and governor and control system of power generating plant and hence finds the probability of failure.

FTA is often used to generate:

- 1) Qualitative description of potential problems.
- 2) Quantitative estimates of failure occurrence.
- 3) Suggested actions to reduce risk.
- 4) Quantitative evaluations of recommendation effectiveness.

So from these problems or failures, the failures in the generator, turbine and governor and control system are analyzed by making Fault Tree Analysis. Fault Tree Analysis is a useful technique to define root causes of a fault event such as failure of critical components of the system.

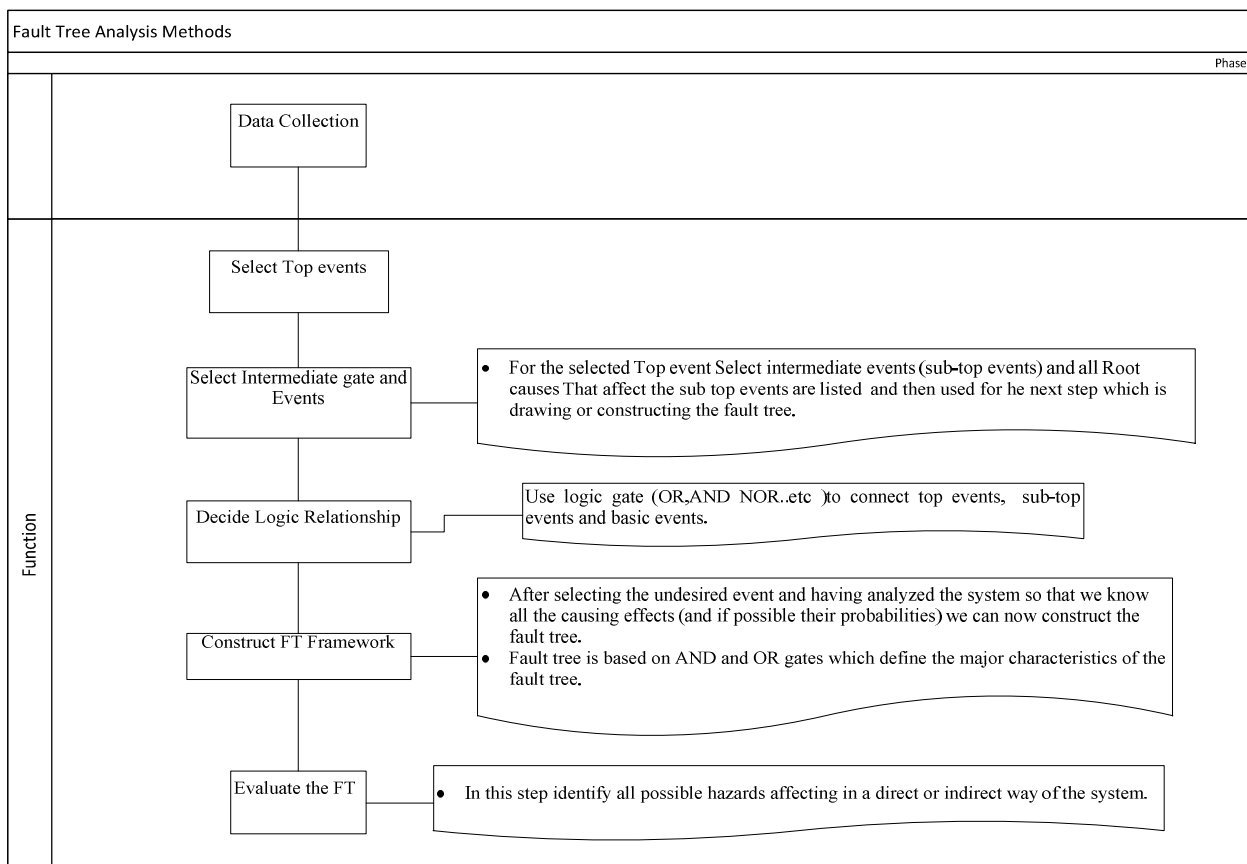
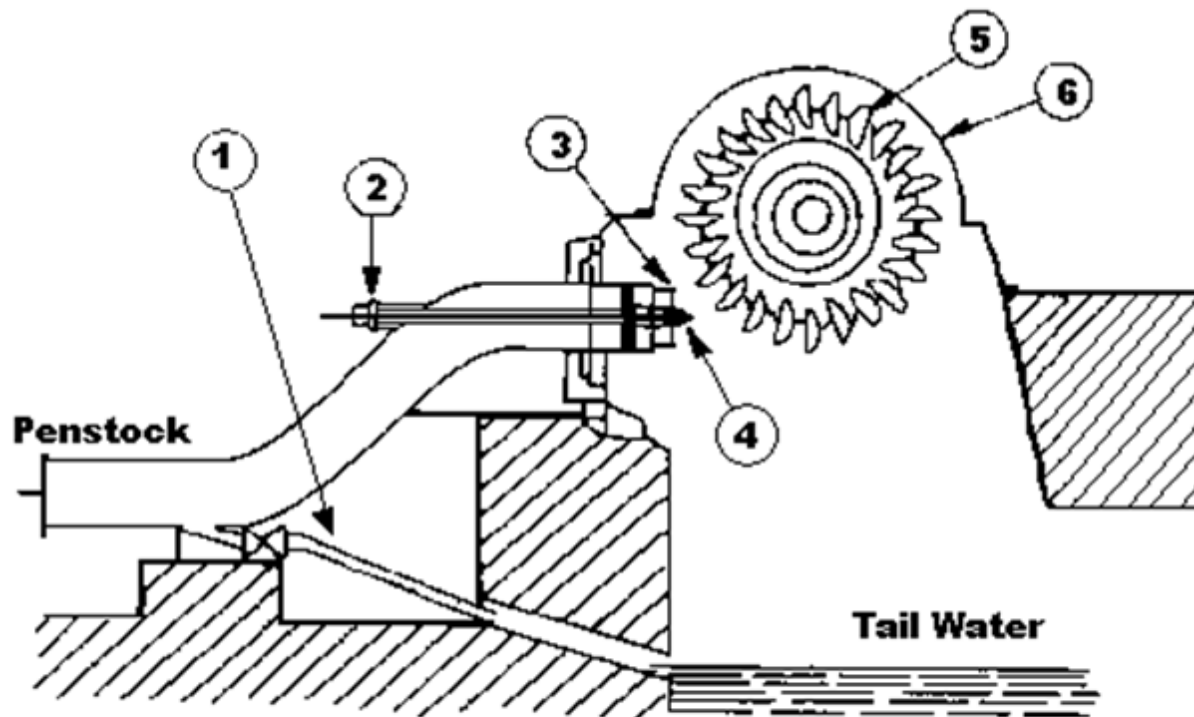


Figure 1-3 Methodology of FTA

1.6 Working Principle of Hydropower Plant

The Pelton turbine as shown in figure is used where there is a small water discharge with a large available water head on the turbines. It is similar to the water wheels used in the past. Pelton turbines constitute a series of runners/buckets aligned around the rim of the shaft. Water from the dam is fed through the nozzles at high speed, hitting the blades of the turbine, converts potential energy of the water in mechanical energy (shaft rotation), which is ultimately transformed into electrical energy through generator.



- 1) Penstock Drain Line
- 2) Hydraulic Needle Valve Control Cylinder
- 3) Water Nozzle
- 4) Needle Valve
- 5) Turbine Bucket
- 6) Case

Figure 1-4 Hydro Electric Flow Chart [5]

There are also some feedback loops, shown with dotted arrows. Solid arrows represent power, while dotted arrows represent "signals". For example, the turbine sends a signal about how fast it's turning to a gadget called a "speed governor". If the turbine starts turning too fast or too slow, this gadget reduces or increases the flow of water to the turbine. There's a similar feedback loop involving the generator.

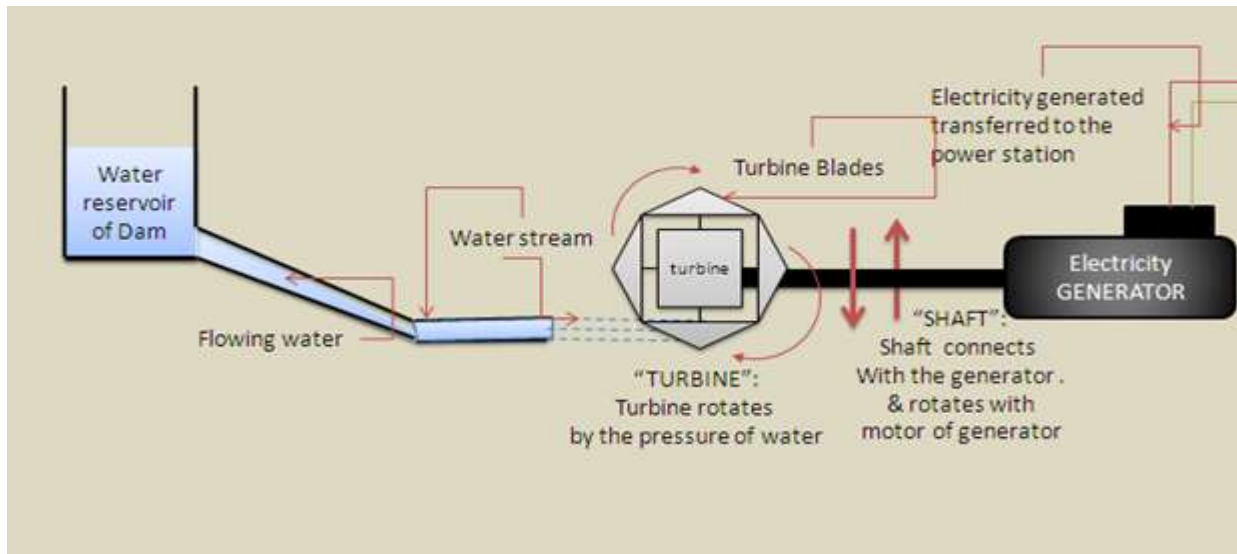


Figure 1-5 How Hydropower Plant Works [6]

The main components are:

- ✓ Penstock
- ✓ Turbine inlet valve system
- ✓ Turbine inlet valve bypass valve
- ✓ Guide vane
- ✓ Turbine runner
- ✓ Governor hydraulic system
- ✓ Generator

The penstock feeds the turbine with water from the dam with a head of 50 meters. The energy from the water is used for turning the turbine runner, which then turns the generator.

The turbine inlet valve is situated in the penstock just before the turbine; its main function is to isolate the water flow to the turbine when the turbine is shutdown or under emergency conditions. The system is designed with a static counter weight to ensure that the valve will close should the control of hydraulic systems fail.

The turbine inlet valve bypass valve is required to equalize the pressure across the main inlet valve before the inlet valve is opened. This is required to relieve the stress on the main valve during opening.

The guide vanes are placed in a ring formation around the spiral casing of the runner, and consist of 16 individual blades. The purpose of the guide vanes is to control the water flow

through the turbine. By varying the position of the guide vanes the water flow is altered and the speed of the machine can then be controlled.

The guide vanes are controlled by a hydraulic servo motor connected to the guide vane ring. The position of the servo motor is controlled by a hydraulic proportional position control valve. The proportional control valve receives its set point from the control system, and then positions the servo motor accordingly, altering the position of the guide vanes and thus changing the speed of the machine. [7]

1.7 Structure of the Thesis

The thesis is organized as follows.

Chapter 2 shows literature review on electromechanical components of hydropower plant failure studies. Also introduce the FTA methods and compare and contrast with other failure analysis methods, reviews documents write about FTA and FTA software.

Chapter 3 shows the process of developing and constructing the model of fault tree of electromechanical components of hydropower plant system. Furthermore this chapter conducts the qualitative fault tree analysis of electromechanical components of hydropower plant. By qualitative analysis of the FTA, we found the weakness of electromechanical systems of hydropower plant. Also presents quantitative FTA in assessing the reliability of electromechanical systems of hydropower plant.

Chapter 4 shows results and discussions about the most important failures that in three electromechanical systems (turbine, Generator and control and governors systems) and propos maintenance policy to reduce the risk.

Chapter 5 presents a brief summary of the research carried out in this thesis, conclusion and recommendation and proposes some potential future research topics.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Introduction

This section, reviews the literature on Problems and solutions of hydroelectricity and it's production, A risk analysis of hydro power (HP) plants and Common Types of Failure in Hydroelectric Power Plants.

It Suggests some actions we need to take during the formulation phase of any new program development effort. A few simple steps can increase our chances for preventing failures in our future launches and projects.

In our work, we tend to focus on ways to make things "go right." This confident optimism is an important characteristic that helps us pursue the challenges of invention and exploration. However, to make things "go right," we also need to understand and control the things that can "go wrong." This beneficial pessimism is sometimes a bit more difficult to apply to our own creations, but is needed to increase the likelihood of future successes. Therefore, asks that to put more effort into analyzing "what can go wrong."

There are a number of engineering tools and techniques that can help us understand the vulnerabilities to our systems. These include the bottom-up analytical approach, known as the Failure Modes and Effects Analysis (FMEA), and the top-down approach, known as the Fault Tree Analysis. A third assessment, the Probabilistic Risk Assessment, integrates information from these two approaches and other sources to assess the potential for failure and help find ways to reduce risk. These analyses constitute a three-pronged approach to help program/project managers assess and mitigate risk and to increase the likelihood for safe and successful missions.

Fault Tree Analysis is not a new method. The Boeing Corporation first applied it in 1964 to analyze "what could go wrong" with the Minuteman ICBM. It remains, however, one of the best methods for systematically identifying and graphically displaying the many ways something can go wrong. It is "best" in the sense that it is the easiest to use and can be used by anyone, not just safety or reliability experts. It is the easiest in that one begins with a top-level undesired event and works down to identify the subordinate events that could cause such an unwanted outcome. Moreover, in most cases, quantification is not needed to obtain valuable insight into the weaknesses of a design. [8]

At NASA, a Fault Tree Analysis is a methodical review of a system's hardware and software that begins by envisioning an undesired end state, such as mission failure or loss of crew or

vehicle. The project team identifies, in a logical manner, the sequences and combinations of events that could lead to the undesired event. [8]

Fault Tree Analysis is most cost-effective when performed early in a project and updated as the project develops.

2.2 Risk Assessment

Risk assessment is used for estimating the likelihood and the outcome of risks to human health, safety and the environment and for enlightening decisions about how to deal with those risks. Risk assessments are tools that used for preparing a scientific basis to reduce the risk. The tools were selected as recommended by risk assessment method for hazard analysis because the wide applicability and success in making decisions such as Failure Mode Effects and Criticality Analysis (FMECA), Failure Mode and Effect Analysis (FMEA) and A Reliability Block Diagram (RBD).

2.2.1 Failure Mode Effects and Criticality Analysis (FMECA)

Failure Mode Effects and Criticality Analysis (FMECA), a semi-quantitative analysis, is also widely applied in fault diagnosis. Furthermore, several quantitative probability analysis models were developed for risk and fault diagnosis, such as statistical deduction, reliability analysis and model simulation. For statistical deduction, common techniques used are the relative frequency method and BN.

The advantages of FMECA are similar to those of FMEA:

- An FMECA offers a systematic review of all components, assemblies and sub-systems, in order to identify failure modes, causes and effects of such failures, ranked according to criticality.
- The output of an FMECA acts as input to other reliability and safety analyses such as Hazard Analysis, Fault Tree, Event Tree, Reliability Block Diagram, etc.
- An FMECA should assist evaluation of design requirements related to redundancy, failure detection systems, fail-safe characteristics, automatic and manual override and test planning.

The analysis is limited at single failures and is time-consuming. [9].

2.2.2 Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) was one of the first systematic techniques for failure analysis. It was developed by reliability engineers in the 1950s to study problems that may arise from malfunction of military systems. FMEA is an inductive method or a bottom-up approach. Induction involves reasoning from individual cases to a general conclusion. An

FMEA is often the first step in a system reliability study. It connects given initiating causes to their end results or consequences. These consequences are often failure of a system or component. It involves reviewing all components, assemblies and sub-systems if possible, in order to identify failure modes, causes and effects of such failures. For each component, the failure modes and their resulting effects on the rest of the system are recorded in a specific FMEA worksheet. If, in the consideration of a certain system, a particular fault or initiating condition is postulated and an attempt is made to ascertain the effect of that fault or condition on system operation, an inductive system analysis is being conducted. It starts from failure initiators and basic event initiators, and then proceeds upwards to determine the resulting system effects of a given initiator. A set of possible causes are analysed for their effects. There are several standards and procedures providing guidelines for this method, such as older military standard.

Advantages of FMEA

An FMEA offers a systematic review of all components, assemblies and subsystems if possible, in order to identify failure modes and the causes and effects of such failures. It connects single failures with their effects and identifies the causes of those failures. The output of an FMEA is input to other reliability analyses such as Fault Tree, Event Tree, Reliability Block Diagram, etc.

Limitations of FMEA

The analysis is limited to single failures and is time-consuming. [9]

2.2.3 Reliability Block Diagram (RBD)

A Reliability Block Diagram (RBD) is a success-oriented network describing the function of the system. RBD is an inductive model wherein a system is divided into blocks that represent distinct elements such as components or subsystems. These elemental blocks are then combined according to system-success pathways. As RBDs are generally used to represent active elements in a system, in a manner that allows an exhaustive search for and identification of all pathways for success. Dependencies among elements can be explicitly addressed. Initially developed top-level RBDs can be successively decomposed until the desired level of detail is obtained. Alternately, series components representing system trains in detailed RBDs can be logically combined, either directly or through the use of Fault Trees, into a super component that is then linked to other super-components to form a summary model of a system. Such a representation can sometimes result in a more transparent analysis. Separate blocks representing each system element (such as for example fuel supply, block valves, control valves On System Safety and Reliability Methods in Early Design Phases and motor) are structurally combined to represent both potential flow paths through the system.

The model is solved by enumerating the different success paths through the system and then using the rules of Boolean algebra to continue the blocks into an overall representation of system success. When an element is represented by a block it usually means that the element is functioning (as in Figure). Each element has also a probabilistic model of performance, such as Weibull, for example. If the system has more than one function, each function must be considered individually [9].

Some of the advantages of using RBD are:

- Often constructed almost directly from the system functional diagram; this has the further advantage of reducing constructional errors and/or systematic depiction of functional paths relevant to system reliability.
- Deals with most types of system configuration including parallel, redundant, standby and alternative functional paths.
- Capable of complete analysis of variations and trade-offs with regard to changes in system performance parameters.
- Provides (in the two-state application) for fairly easy manipulation of functional (or non functional) paths to give minimal logical models (e.g. by using Boolean algebra).
- Capable of sensitivity analysis to indicate the items dominantly contributing to overall system reliability.
- Capable of setting up models for the evaluation of overall system reliability and availability in probabilistic terms.
- Results in compact and concise diagrams for a total system.

Some of the limitations using RBD are:

- Does not, in itself, provide for a specific fault analysis, i.e. the cause-effect(s) paths or the effect-cause(s) paths are not specifically highlighted.
- Requires a probabilistic model of performance for each element in the diagram.
- Will not show spurious or unintended outputs unless the analyst takes deliberate steps to this end.
- Is primarily directed towards success analysis and does not deal effectively with complex repair and maintenance strategies or general availability analysis.
- Is in general limited to non-repairable systems.
- The analysis is limited to single failures and is time-consuming.

Reliability analysis makes use of probability density function (PDF) to deduce the requirement and the probability for the system to stay within safety margin. Monitoring data over the years are used to determine parameters for the model. Nevertheless, limited maintenance data can be collected during the life cycle of the dam facilities. The life time of

the dam facilities is generally much longer than that of electronic facilities and rarely maintenance data are collected for the fault diagnosis. Because of that, some semi quantitative analysis methods were proposed for the system diagnosis, such as FTA.

Therefore, Fault tree analyses have been successfully applied in many kinds of technical processes to improve operation reliability and safety.

2.2.4 Discussion

There are many approaches for hazards analysis on operating facilities or new projects. The different approaches have various applications and advantages, and they need different level of effort and resources.

Based on the literature review it can be seen that the risk assessment method have been applied in many areas. In offshore the methods that currently used for hazard analysis are HAZOP, FMEA, FTA and ETA as described in Table

Table 2-1 Comparison of Hazard Analysis

No	APIRP14J	Hazard and Operability(HAZ OP)	Failure Modes and Effects Analysis(FMEA)	Fault Tree Analysis(FTA)	Even Tree Analysis(ETA)
1	Level of effort / complexity	Medium to High	Medium to High	High	High
2	Level of Expertise Required for Analysis Teams	Medium	Medium	Medium to High	Medium to High
3	Qualitative Accident Descriptions	✓	✓	✓	✓
4	Quantitative Risk Characterizations	-	✓	✓	✓
5	Relative Importance of Accident Contributors	-	✓	✓	✓
6	Types of Activities or Systems	All types of process/plants/facilities	All, in the design phase, facility modifications and operation	All, in the design phase, facility modifications and operation	All, in the design phase, facility modifications and operation
7	Utilizing Data	A complete set of process flow diagrams, P&IDs,	The technique requires at least two analysts who are familiar with	P&IDs, equipment drawings and specifications,	P&IDs, equipment drawings and specifications,

Electromechanical System Failure Analysis In Hydropower Plant

		plot plans, equipment layouts and operating procedures	the process and the equipment.	operating procedures, knowledge of failure modes	operating procedures, knowledge of failure modes
8	Results	A list of problem areas that lead to potential hazards / operability problems, and a list of recommended changes, suggestions or actions to improve safety/operability.	A tabulation of facility equipment items, their potential failure modes and the effects of these failures on the equipment or facility.	A set of logic diagrams that illustrates how certain combinations of failures and/or errors can result in specific accidents.	A set of logic diagrams that illustrates sequence of events of specific accidents.

Typically HAZOP is used to perform safety related studies, while FMEA Identification of single point failures and their mode and effect. The FTA is visually models the logical relationship between equipment failures, human errors, and external events that can combine to cause specific accidents. The ETA is technique that logically develops visual models of the possible outcomes of an initiating event. Each methods of hazard analysis have their own limitations; therefore a lot of researchers combine each method with another method. Focusing the four methods of hazard analysis HAZOP, FMEA, FTA and ETA the limitations of each method can be seen in Table

Table 2-2 Limitations of hazard risk analysis methods

No	Hazard Risk Analysis Methods	Limitations	Tendency to Type of Decision Analysis
1	Failure Modes and Effects Analysis (FMEA)	<ul style="list-style-type: none"> - Examination of human error is limited - Focus is on single event initiators of problems - Examination of external influences is limited - Results are dependent on the mode of operation 	<ul style="list-style-type: none"> - Highly structured assessment relying on evaluation of component failure modes and team experience - Uses frequently as the basis for optimizing planned
2	Hazard and Operability (HAZOP) Analysis	<ul style="list-style-type: none"> - Requires a well defined system or activity - Time consuming - Focuses on one event causes of deviations 	Used to review procedures and sequential operations
3	Fault Tree Analysis (FTA)	<ul style="list-style-type: none"> - Narrow focus - Art as well as science - Quantification requires significant 	Assessments generates relative importance of various failure and

		expertise	contributing events
4	Fault Tree Analysis (FTA)	- Limited to one initiating event - Can overlook subtle system dependencies	Analysis technique generates failure sequences and contributing events

2.3 Risk Assessment of Power System Catastrophic Failures and Hidden Failure Monitoring & Control System

2.3.1 Risk of Power System Catastrophic Failures

Most complex systems involve minimizing costs, maximizing benefits, and minimizing risks of various kinds. A power system is a complex system that involves minimizing risks of load flow infeasibility, thermal overload, steady-state instability, transient instability, and dynamic instability.

Partitioning Multi-objective Risk Method (PMRM) separates extreme events from other non-catastrophic events, thereby providing decision-makers with additional valuable information. In addition to using traditional expected values, the PMRM generates a number of conditional expected-value functions, termed risk functions, which represent the risk, given that the damage falls within specific probability ranges (or impact ranges).

In the risk assessment of power systems, the disturbance events may be partitioned into three impact ranges: high probability of minor events that have slight consequences; medium probability of average events that have some impact; and low probability of extreme events with catastrophic implications. Accordingly, the impact axis may be partitioned into three impact ranges. [10]

2.3.2 A Risk Analysis of Hydro Power (HP) Plants

In open literature of Hydro turbine failure, by **Ugyen Dorji, Reza Ghomashchi School of Mechanical Engineering, The University of Adelaide, SA 5005, Australia**, study the turbine failure and its subsequent impact on the power house structure and the threat it may impose to the operational and maintenance crews needs due attention to improve the performance of the turbines and safeguard the power plant. This can only be achieved through understanding of the turbine failure mechanisms, and particularly identify turbine parts that are most susceptible to specific type of failure. Four types of failure, namely cavitation, erosion, fatigue and materials failure due to improper installation procedure have been identified as the main cause of failure for most turbines. [11]

Attempts were also made to highlight the relationship between the type of turbine (Pelton, Francis and Kaplan) and the most vulnerable part of the turbine to a specific failure. Also some suggestions were made to mitigate turbine failure. [11]

Hydro-power systems in Taiwan utilize the operation, maintenance and surveillance manuals as the basis for maintenance and inspection. In practice, a periodic interval (i.e., week, month, season, or year) is selected for the inspection and the regular maintenance, based on the system types, component characteristics and operational environments [12]. Since facilities are only regularly maintained or replaced, the desire of early fault prevention cannot be achieved without prior diagnosis of the faulty states and fragile conditions. That may lead to unnecessary waste of manpower and resources in maintenance.

Since 1990, risk and fault diagnosis evaluation have been included in dam safety assessment and hydro-power system management programs around the world. US Federal Energy Regulatory Commission (FERC) implemented Potential Failure-Mode Analysis by adopting core-group discussion to conduct qualitative evaluation [13]. Failure Mode Effects and Criticality Analysis (FMECA), a semi-quantitative analysis, is also widely applied in fault diagnosis. Furthermore, several quantitative probability analysis models were developed for risk and fault diagnosis, such as statistical deduction, reliability analysis and model simulation. For statistical deduction, common techniques used are the relative frequency method and BN [14]. Reliability analysis makes use of probability density function (PDF) to deduce the requirement and the probability for the system to stay within safety margin. Monitoring data over the years are used to determine parameters for the model. Nevertheless, limited maintenance data can be collected during the life cycle of the dam facilities. The life time of the dam facilities is generally much longer than that of electronic facilities and rarely maintenance data are collected for the fault diagnosis. Because of that, some semi quantitative analysis methods were proposed for the system diagnosis, such as FTA [15, 16, 17, 18].

FTA assumes an event to be either fault or normal state (i.e., two states). In FTA two logic gates are commonly used to link the events in hierarchy and they are “OR Gate” and “AND Gate,

2.3.3 Common Types of Failure in Hydroelectric Power Plants

The following types of failure (not ranked in order) which can cause costly damage and power outages are responsible for the most frequent losses in hydroelectric power plants:

- ✓ Failure in the stator winding of the generator
- ✓ Failure in switch control room and set of electrical tracks and cable fire
- ✓ Failure in control equipment
- ✓ Disappearance of auxiliary and power supply
- ✓ Failure in transformers
- ✓ Cracks and breakage in shovels and other turbine failures
- ✓ Failure in bearings with lubrication and cooling systems
- ✓ Flooding of machine hall and other room for machinery equipment
- ✓ Fire in the machine hall or other engine rooms
- ✓ Fault on Guide vane
- ✓ Waterway cannot supply flow
- ✓ Disabled cooling system
- ✓ Disabled turbine
- ✓ Malfunction generator
- ✓ Transmission system unable to deliver power
- ✓ Faulty on governor and control system
- ✓ Tailrace cannot discharge flow

Dam Failure

Hydroelectric power is produced mostly from the potential energy of dammed water driving a water turbine and generator. Water is delivered by a huge pipe or “penstock” to the turbine. The power drawn from the water is related to its volume and the “head” or height range between the water source and its outflow.

Dams can fail for one or a combination of the following reasons:

- ✓ Overtopping caused by floods that exceed the capacity of the dam
- ✓ Deliberate acts of sabotage
- ✓ Structural failure of materials used in dam construction

- ✓ Movement and/or failure of the foundation supporting the dam
- ✓ Settlement and cracking of concrete or embankment dams
- ✓ Piping and internal erosion of soil in embankment dams
- ✓ Inadequate maintenance and upkeep

In this research constructing FTA model of electromechanical system of hydropower plant and analysis in both qualitatively to decide root causes and quantitatively to decide failures occurrence and contribution of failure.

2.4 Fault Tree Analysis

Fault tree analysis (FTA) is a top down, deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events. This analysis method is mainly used in the fields of safety engineering and reliability engineering to understand how systems can fail, to identify the best ways to reduce risk or to determine (or get a feeling for) event rates of a safety accident or a particular system level (functional) failure. The basic symbols used in FTA are grouped as events, gates, and transfer symbols represented in Appendix 2.

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

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

2.4.1 Quantitative Fault Tree Analysis

Quantitative results include the top event unavailability, unreliability or failure rate. The top event parameters are defines as follows:

- Unavailability: $A(t)$ the probability that the system failure mode exists at time t .
- Unreliability: $R(t)$ the probability that the system failure occurs at least once from time t to time t .
- Failure rate: the rate at which the system failure mode occurs.

All of these quantities can be used to judge the acceptability of the system performance.

To perform quantitative fault tree analysis, firstly a failure rate must be obtained and entered in the calculation properties for each lowest-level event in the fault tree. When quantitative fault tree are calculated, the unreliability of the system can be computed. These measures, rather than reliability, are computed because fault tree's are organized around failures rather than successes.

When fault tree calculations are performed, first determines whether the fault tree is static or dynamic. Any fault tree that includes a dynamic gate is considered a dynamic fault tree. Dynamic fault tree are broken down into corresponding modules, and each module is individually analyzed as a static or dynamic entity. To generate exact calculated results, the static entities are computed using standard combinatorial techniques, which consider conditional event and gate probabilities in the same manner as BDD's. The dynamic entities are transformed into equivalent Markov models. The results for these various entities are then brought together for generalized fault tree analysis to produce exact calculation.

Quantification of the fault tree static gates

To calculate the probability of occurrence of top event in fault tree, it is necessary to understand the relation among the top, intermediate, and basic events. To quantify the probability of the top event of the fault tree, a probability for each basic event in the fault tree must be provided. These basic event probabilities are then propagate upward to the top event using the Boolean relationship for the fault tree. Commonly used Boolean operators are, namely, AND and OR gates.

Alternatively, the minimal cut set can be generated from the fault tree and then used to quantify the top event. The minimal cut set generation approach is used by most software because of the additional, important information provided by the minimal cut sets.

Since the top event is expressed as the union of the minimal cut sets, the probability of the top event can be approximated as the sum of the individual minimal cut set probabilities, provided these probabilities are small. Since the minimal cut set is an intersection of basic event's, the probability of a minimal cut set is simply the product of the individual basic event probabilities. Thus, the probability of the top event is expressible as the sum of the products of individual basic event probabilities. This expression is called the sum of products approximation.

In term of symbols the sum of products expression is given as:

$$P (TE) = P (MCS_i) \dots\dots\dots Eq 1$$

$$P (MCS_i) = P (BE_1) P (BE_2) \dots\dots\dots P (BE_k) \dots\dots\dots Eq 2$$

Where:

$P()$ = the probability of the enclosed event

TE = s the top event

MCS_i = a particular minimal cut set

BE_j = basic event j

k = the number of basic events in a minimal cut set

2.4.2 Failure probabilities

Events in a fault tree are associated with statistical probabilities. For example, component failures may typically occur at some constant failure rate λ (a constant hazard function). In this simplest case, failure probability depends on the rate λ and the exposure time t:

$$P = 1 - \exp(-\lambda t) \dots \dots \dots \text{Eq 3}$$

$$P \approx \lambda t, \lambda t < 0.1$$

A fault tree is often normalized to a given time interval, such as a flight hour or an average mission time. Event probabilities depend on the relationship of the event hazard function to this interval.

Unlike conventional logic gate diagrams in which inputs and outputs hold the binary values of TRUE (1) or FALSE (0), the gates in fault tree output probabilities related to the set operations of Boolean logic. The probability of a gate's output event depends on the input event probabilities.

An AND gate represents a combination of independent events. That is, the probability of any input event to an AND gate is unaffected by any other input event to the same gate. In set theoretic terms, this is equivalent to the intersection of the input event sets, and the probability of the AND gate output is given by:

$$P(A \text{ and } B) = P(A \cap B) = P(A) * P(B) \dots \dots \dots \text{Eq 4}$$

An OR gate, on the other hand, corresponds to set union:

$$P(A \text{ or } B) = P(A \cup B) = P(A) + P(B) - P(A \cap B) \dots \dots \dots \text{Eq 5}$$

Since failure probabilities on fault trees tend to be small (less than .01), $P(A \cap B)$ usually become a very small error term and the output of an OR gate may be conservatively approximated by using an assumption that the inputs are mutually exclusive events:

$$P(A \text{ or } B) \approx P(A) + P(B), P(A \cap B) \approx 0 \dots \dots \dots \text{Eq 6}$$

An exclusive OR gate with two inputs represents the probability that one or the other input, but not both, occurs:

$$P(A \text{ xor } B) = P(A) + P(B) - 2P(A \cap B) \dots \dots \dots \text{Eq 7}$$

Again, since $P(A \cap B)$ usually becomes a very small error term, the exclusive OR gate has limited value in a fault tree.

The Unreliability, $F(t)$, is defined as the probability that the component or system experiences the first failure or has failed one or more times during the time interval zero to time t , given that it was operating or repaired as good as new at time zero.

$$R(t) + F(t) = 1 \text{ or Unreliability } F(t) = 1 - R(t)$$

$$R(t) = e^{-\lambda t}, \text{ where: } \lambda = \text{the failure probability per unit time and } t = \text{time } t$$

2.4.3 Top Event FTA professional 2016 software

Top Event FTA 2016 is interactive software for Qualitative and Quantitative Fault Tree Analysis. It supports both coherent and non-coherent fault trees. Top Event FTA 2016 incorporates two Fault Tree evaluation methods: The Classical Minimal Cut Sets Method (Classical MCSs Method) and the Binary Decision Diagram Method (BDD Method).

You can easily create complex Fault Trees with the Top Event FTA 2016 Fault Tree Editor. The Fault Tree Editor includes two Views: the standard Fault Tree Diagram View and the Tree List View. These Views provide a full overview of the Fault Tree. Top Event FTA allows you to create both coherent and non-coherent fault trees.

The symbols and description represents on appendix 2.

With Top Event FTA 2016, you can quickly evaluate complex Fault Trees with millions of Minimal Cut Sets. The Qualitative Fault Tree Evaluation can be obtained via the Classical Minimal Cut Sets Method (Classical MCSs Method) or the Binary Decision Diagram Method (BDD Method). Top Event FTA 2016 supports cut-off thresholds based on the maximum order of the Minimal Cut Sets (Order cut-off) and the minimum probability of the Minimal Cut Sets (Probability cut-off).

Top Event FTA 2016 can calculate the exact values of the Unavailability and Importance Factors. The Quantitative Fault Tree Evaluation can be obtained via the Classical Minimal Cut Sets Method or the Binary Decision Diagram Method. The BDD Method provides the exact

values of the Unavailability and Importance Factors, and the Classical Method provides a rare event approximation of the probabilities.

Top Event FTA 2016 provides methods for calculating:

- Unavailability
- Minimal Cut Sets
- Risk Achievement Worth
- Risk Reduction Worth
- Diagnostic Importance Factor

CHAPTER THREE

3 METHODOLOGY

3.1 Introduction

Aiming to run the applicability of the methodology proposed in this paper, it is necessary to define a hydroelectric plant that will be taken as the basis of analysis in order to complete characterize their systems, allowing the application of Faulty Tree Analysis, which forms the basis for a future implementation of RCM based maintenance policies and asset management techniques.

The hydro power plant in analysis is located in gilgel Gibe II hydro power plant each one equipped with pelton turbine and presenting 420 MW nominal outputs with in 4 generating unit.

Figures 3.1 illustrate the main components of a hydroelectric generating unit. The generating unit may have its shaft oriented in a vertical, horizontal, or inclined direction depending on the physical conditions of the site and the type of turbine applied.

3.2 Functional tree analysis

Initially, in Figure 3.2, the functional diagram has been proposed for the plant. It is proposed that the plant be subdivided into systems: dam, water intake, auxiliary services of alternating current and direct current, synchronization system, other auxiliary equipment and generating units.

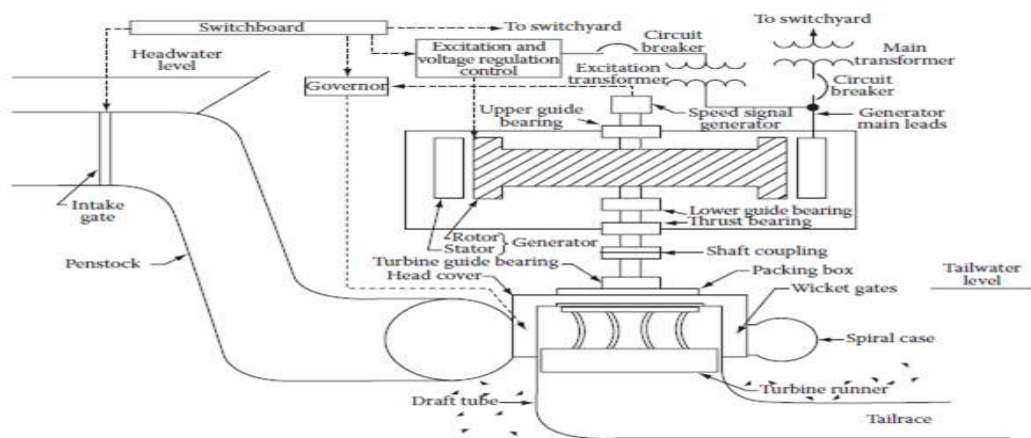


Figure 3-1 Typical Vertical Shaft Francis Turbine Unit [7]

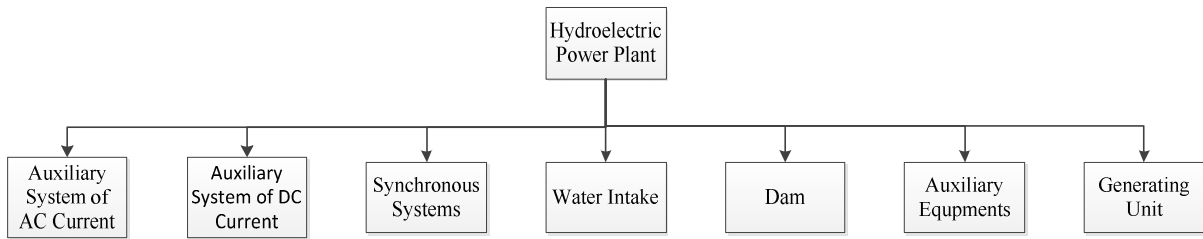


Figure 3-2 Hydroelectric Power Plant Functional Tree [19]

Figure 3.3 shows the functional diagram of a generating unit. This piece of equipment is divided into eight subsystems, which are: turbine, generator, thrust and guide bearings, draft tube and suction, power substation, and control/monitoring system.

Throughout the study functional trees of each of subsystems were developed. In Figure 3.4 is shown as the turbine functional tree. According to the diagram, the turbine system is composed of several components having primary function of transforming the kinetic energy of fluid flow into mechanical energy.

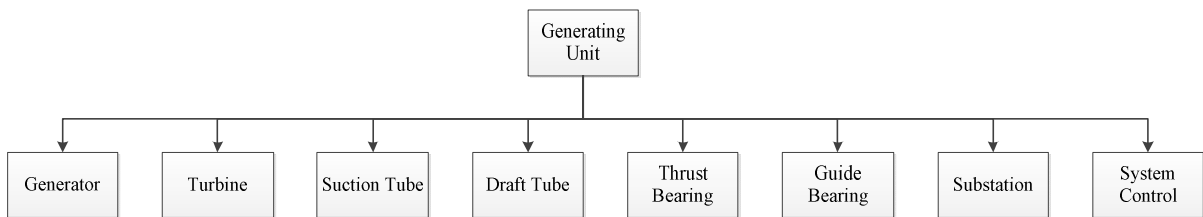


Figure 3-3 Generating Unit Functional Tree [19]

Therefore the turbine must have a control system, which maintains the frequency of its rotation, regardless of the magnitude of energy transformed, and must have components that act directly on the transformation and transmission of energy to the generator, such as the rotor, axis, the guide bearing and shaft coupling. Additionally, this system has components that support its operation, but do not act directly in the main function, such as the shaft seal, the aeration system, monitoring and protection equipment.

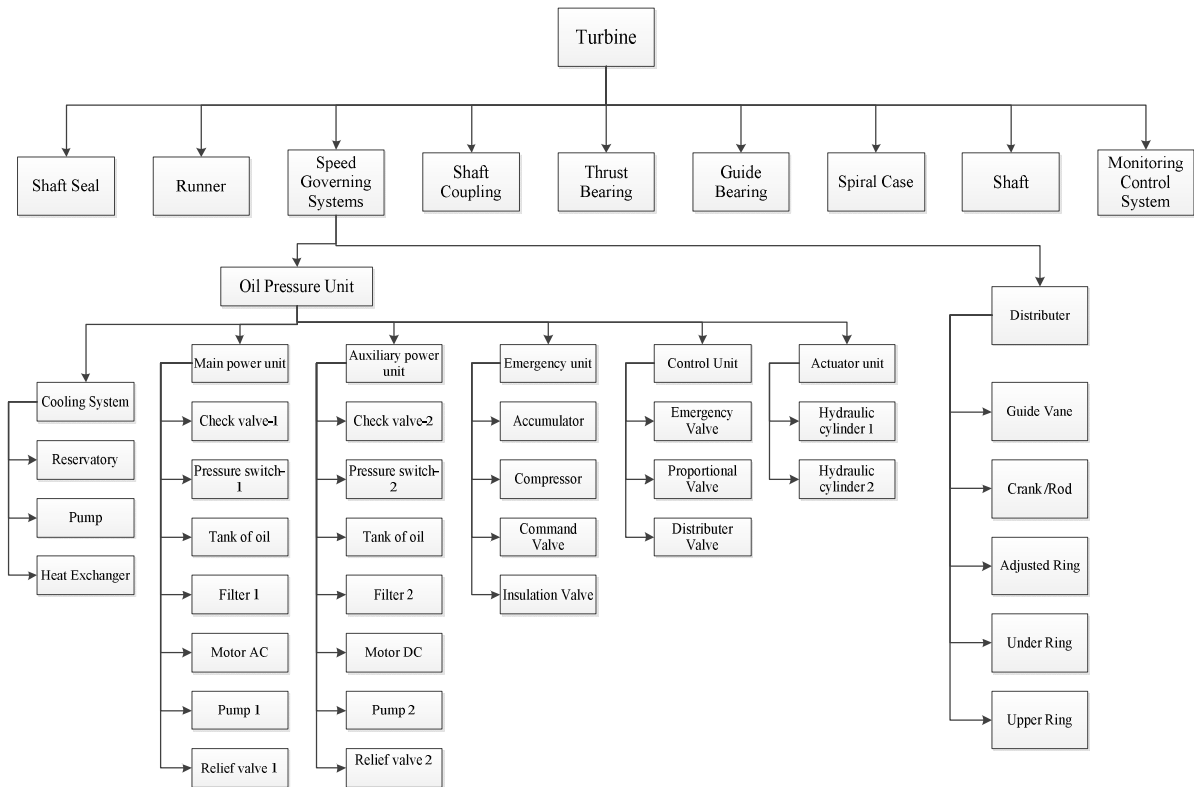


Figure 3-4 Hydro Turbine Functional Tree [19]

The generating unit depends on some systems for monitoring and controlling its operation that includes monitoring of both active and reactive power, voltage in the generator, and temperature in some parts of the machinery, such as winding insulation and heat exchangers fluid temperature.

Finally, the output of the generating unit is coupled to a substation, which connects the unit with the transmission line, having transformers that fit with the generated voltage required by the transmission line, and has a protective system which aims to protect the generating unit against faults that could occur in the transmission line.

3.3 Availability and Reliability analysis

For a generating unit of the hydroelectric plant, an availability analysis employing the block diagram shown in Figure 3.5 is carried out. From the failure data collected, it was possible to characterize the reliability of the subsystems shown in Figure 3.5.

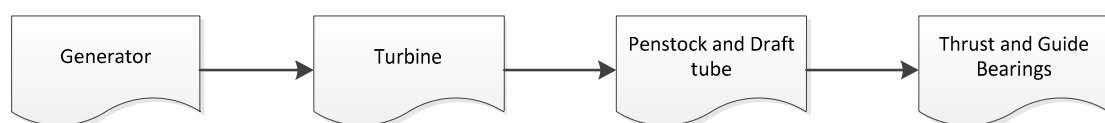


Figure 3-5 Simplified Block diagram of Hydroelectric

The operational data for the generating units were registered aiming at defining the failures that cause equipment unavailability.

The operational registered data are presented in Table 3.1. The generating units states present in that table are represented from appendix 4. The ‘in service hours’ represents the number of hours that a unit is in service state. The Miscellaneous outages (MO): outages resulting from shortage of water, silt content, etc normally external reasons not attributable to the power plant. The ‘forced outage hours’ represent the number of hours that an unit is unavailable due to the occurrence of a component failure that causes immediate removal from service. The ‘basic planned outage’ represents the number of hours that the unit is unavailable due to the execution of programmed maintenance activities. Table 3.2 shows the number of failures (forced outage) associated with the basic generating unit which will be used as for reliability analysis.

Table 3-1 Operational data of generating units

Distribution of Hours	Generating Unit	Operational Data
In Service Hours (hrs)	UG-1	8070.83
	UG-2	7767.08
	UG-3	8122.067
	UG-4	7827.4
Forced Outage Hours (hrs)	UG-1	28.933
	UG-2	36.45
	UG-3	30.82
	UG-4	121.67
Basic Planned Outage (hrs)	UG-1	296.667
	UG-2	415.38
	UG-3	118.3
	UG-4	512.95
Miscellaneous outages (hrs)	UG-1	387.567

	UG-2	565.73
	UG-3	512.82
	UG-4	321.98
Number of Failures that cause Forced Outage	UG-1	8
	UG-2	7
	UG-3	3
	UG-4	12

The generating unit failure rate is defined as the sum of the subsystems failure rates and also presented in Table 3.2. Generating unit 4 presents the greater failure rate and generating unit 3 smallest failure rate. According to the power plant generation data units 1 and 3 are preferentially used to attend the power generation demand while units 2 and 4 are used to complement generation in case of higher demand.

Table 3-2 Failures Rate Estimate for Generating Units

Generating Unit	Number of Failures	In Service Hours (h)	Generating Unit Failure rate (1/h)
UG-1	8	8070.83	0.000991224
UG-2	7	7767.08	0.0009012396
UG-3	3	8122.067	0.0003693641
UG-4	12	7827.4	0.0015331

Based on the plant operator report most of the turbine subsystem failures are associated with control guide vanes failures, including breakage of mechanical actuators, failure on runner, vibration on shaft and speed governor hydraulic system failures. Regarding generator subsystem failures, most of them are caused by exciter components failures including 125 DC system failures, rotor and stator failure. The penstock and draft tube subsystem failures are associated with butterfly inlet valve failures caused by hydraulic system failures.

Key Terminology

Reliability – The probability that an entity experiences no failures under given conditions for a given time interval.

Availability – The probability that an entity is operating under given conditions at a given instant of time.

Mean Time between Failure (MTBF) – The average operating time between failures.

Mean Time To Recover (MTTR) – The average time to restore or recover

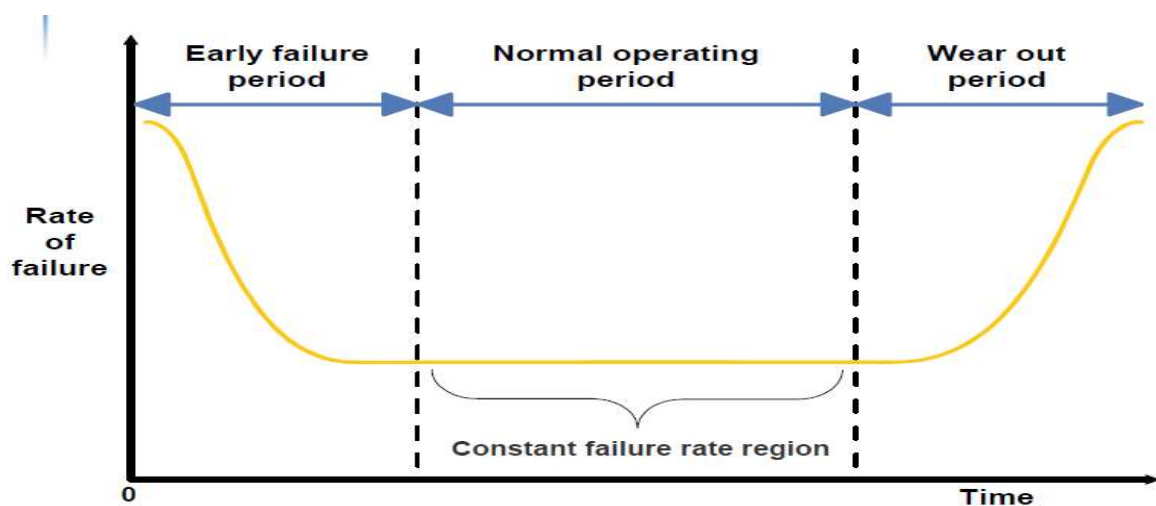
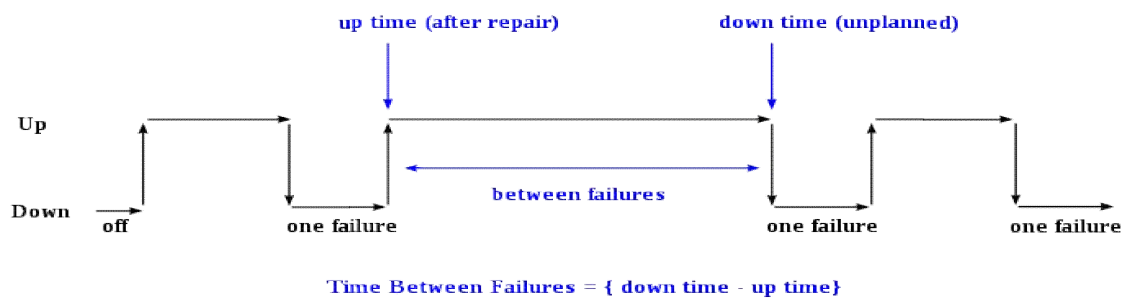
Failure Rate (λ) – The inverse of MTBF or

$$\lambda = \frac{1}{MTBF} = \frac{1}{MTTF}$$

Recovery Rate (μ) – The inverse of MTTR or

$$\mu = \frac{1}{MTTR}$$

Source: Reliability Engineering Handbook



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

Reliability - $R = R = e^{-\lambda t}$

$$A = \frac{MTBF}{(MTBF + MTTR)}$$

The failure availability in one operational year (8760 operational hours) is calculated by the above formula. The results are summarized in Table 3.3. It shows that a greater in service hours, UG-3 availability is greater than others generating units and also low failure rate and great reliability. This fact is associated with the lack of planned maintenance of UG-3. In similar way the generating unit UG-4 is low availability and with low service hours but it have greater planned maintenance.

Table 3-3 The availability of Gilgel gibe II for one operational year (8760 operational hours)

Generating Unit	MTTF	Failure rate (λ)	MTTR	Recovery rate (μ)	Reliability ($R = e^{-\lambda t}$)
UG-1	984.14	0.001	8.4354	0.11855	$1.56885 \cdot 10^{-4}$
$\text{Availability} = \frac{\mu}{\mu + \lambda} = \frac{0.11855}{0.001 + 0.11855} = 0.99164$					
UG-2	906.5	0.0011	6.0405	0.16555	$6.533 \cdot 10^{-5}$
$\text{Availability} = \frac{\mu}{\mu + \lambda} = \frac{0.16555}{0.0011 + 0.16555} = 0.99339$					
UG-3	1542.041	$6.485 \cdot 10^{-4}$	4.1667	0.23999	$3.41 \cdot 10^{-3}$
$\text{Availability} = \frac{\mu}{\mu + \lambda} = \frac{6.485 \cdot 10^{-4}}{6.485 \cdot 10^{-4} + 0.23999} = 0.997$					
UG-4	528.05	0.0019	7.9236	0.12621	$5.91 \cdot 10^{-8}$
$\text{Availability} = \frac{\mu}{\mu + \lambda} = \frac{0.12621}{0.0019 + 0.12621} = 0.9852$					

Table 3-4 System Availability and Reliability of Gilgel Gibe II hydropower plant in 2007

Generating Unit	Availability	Reliability
UG-1	0.99164	1.56885×10^{-4}
UG-2	0.99339	6.533×10^{-5}
UG-3	0.997	3.41×10^{-3}
UG-4	0.9852	5.91×10^{-8}

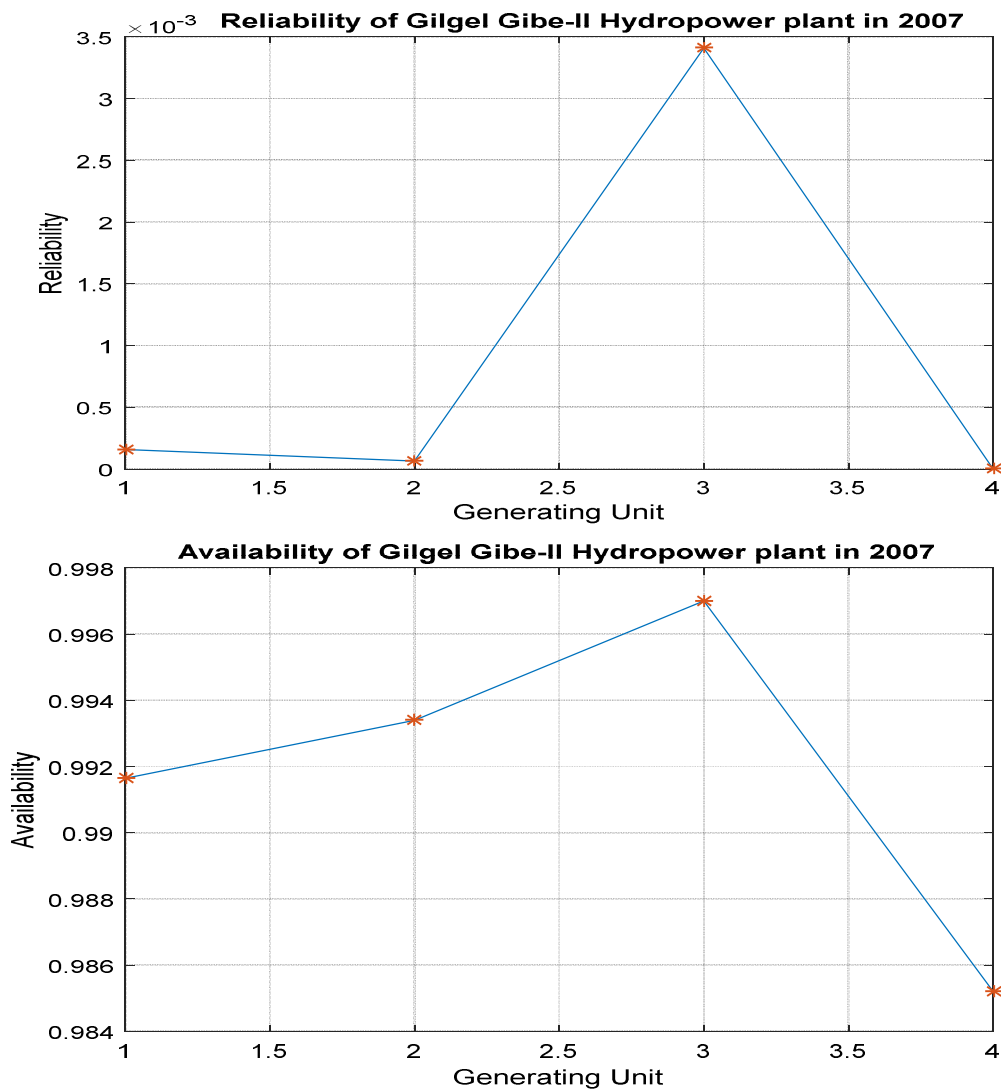


Figure 3-6 Availability & Reliability of Gigel Gibe II hydropower plant in 2007 to 2008

Due to the data of Gilgel gibe II hydropower plant the generating units, generating unit 3 is the most available and generating unit 4 is the least one from 8-July 2015 to 7 July 2016 for one years. Table 3.5 shows the four generating unit and its available hours with in one years.

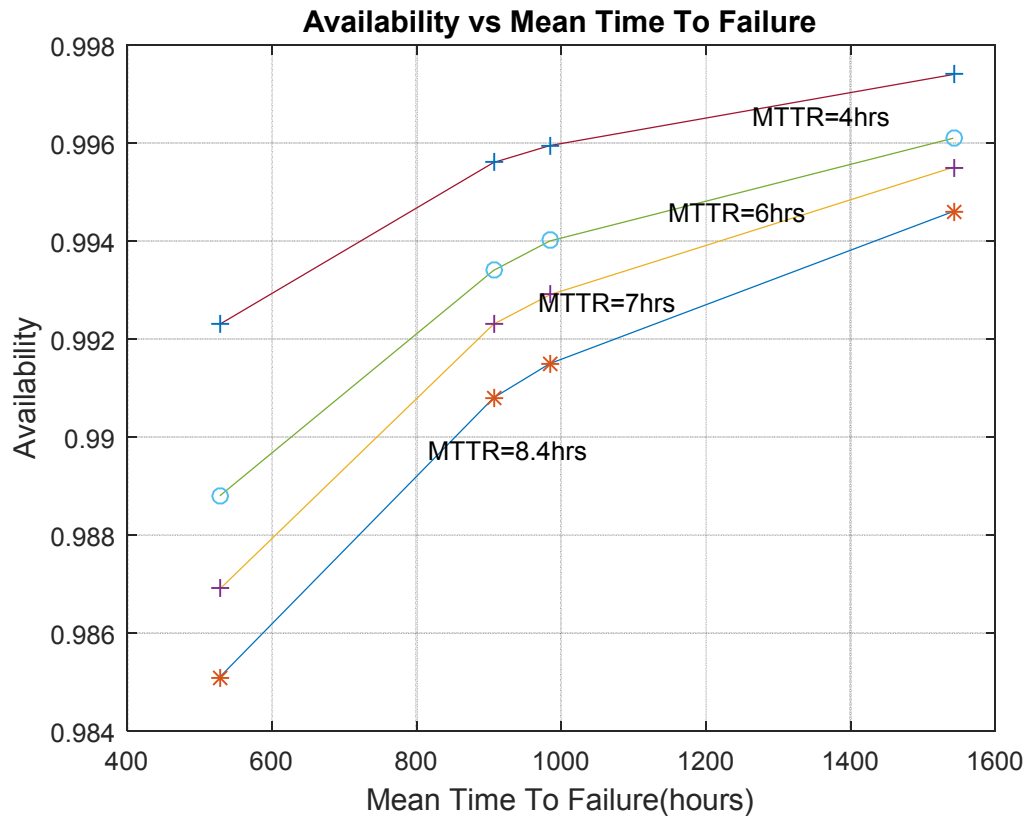
The availability for one operational year (8760 operational hours) is calculated. The results are summarized in Table 3.5. It is clear that even for a greater in service hours, UG-3 available in system is better than others generating units because of low failure rate. This fact is associated with the planned maintenance of UG-3. In similar way the generating unit 2 and 4 are have the least available in a system because of high failure rate and least service hours but it have greater planned maintenance.

Table 3-5 Gilgel gibe II Generating Units Available Hours in a Year

Generating unit	Available hours in a years	Availability percentage
UG-1	8458:24	96.56%
UG-2	8332:49	95.125%
UG-3	8634:53	98.646%
UG-4	8157:32	93.125%

Therefore Gilgel gibe II available for 8395:45 in a given time intervals. This indicates the availability was around 0.9584. So it was not generate expected value of power for 364:05 hours that means around for 15 days.

Not: - This thesis not show the availability and reliability of Gilgel Gibe II hydropower plant because in this thesis analysis by using one year data. Therefore there is lack of data. It shows the relationship between availability and failures time, and how to increase the availability.



In the figure above shows the availability, MTTR and MTTF relationships. Availability depends on the value of MTTR and MTTF. When the MTTR times increase the availability value will be decreases and vice versa. So to maximize the operating time and minimize MTTR (Mean Time to Repair) must analysis the failure of hydropower plant systems. In the table 3.1 the value of MTTR 4 to 8 hours, it's not mach but when the system be complex it takes mach time. To minimize this MTTR time must address the problems location, however to address the location of failure components take mach time, so to take over this failure location use failure analysis method. The most important and preferable failure analysis is Fault Tree Analysis (FTA).

3.4 Fault Tree Analysis of Electromechanical System Failure

The analysis was performed using as initial event a failure mode of a hydro generator component. The analysis allows the study of the propagation of the failure in other subsystems or hydro generator systems, aiming at defining the loss of performance caused by the initial failure. The failure propagation effects analyses are considered in subsystems with which the component has operational relationship in accordance with the functional tree. In other words considers the propagation in the subsystems located in the higher levels of the functional tree.

FTA analysis supports the selection of the mechanical failures that cause immediate shutdown of the hydro Power plant, which are:

- i) Failure in the turbine or generator shaft, represented by the cross section rupture due to the presence of excessive permanent deformation (due to overloads), varying its straightness, or due to crack growth associated to variable loading;
- ii) Failure in the turbine rotor, involving the rupture of the rotor blade due to fatigue mechanism and
- iii) Failure in the bearings structures, involving the rupture or permanent deformation.
- iv) Failures in the governor systems.
- v) Failure in generator rotors and stators.

Recent developments in technology have led to an increase in the complexity of systems. The failures within these systems can cause disruption to the operational functionality. Fault location has therefore become a first objective in engineering applications. Several techniques have focused on identifying faults. Obviously, effective diagnostic approaches can decrease downtime and consequently enhance operational functionality.

Framework for fault diagnosis was proposed in, which divided fault diagnosis approaches into qualitative analysis approaches and quantitative analysis approaches. The former which is very suitable for diagnosing complex system is automatic, independent on mass failure data and can make full use of some quantitative data and structural information performed within the system design phase.

3.4.1 The Framework for Fault Diagnosis

The method for fault diagnosis uses system fault tree model. All minimal cut sets are generated using qualitative analysis of fault tree, while DIF is calculated via quantitative analysis. DIF is the corner stone of our methodology and provides an accurate measure of components' relevance from a diagnosis perspective [20]. The DIF is defined conceptually as the probability that an event has occurred given the top event has also occurred.

Due to the different complexity of components their test costs are different. A balance is needed between the DIF and test costs. Therefore, Ref. [9] proposed a new measure of importance called the cost and diagnostics importance measure (CDIF). This measure is simply the DIF per unit cost. The CDIF measure appears in (9).

Based on above analysis, a framework for fault diagnosis method is presented in Fig. 1. It uses fault tree model which can come from the system design phase for reliability analysis. We generate all minimal cut sets using qualitative analysis of fault tree and calculate DIF of components. Meanwhile we update the sum of all minimal cut sets and the components' posterior failure probability based on the evidence data from sensors. Also, based on these results we design an efficient diagnostic decision algorithm and generate efficient DDT, which reduces dependence on engineering expertise.

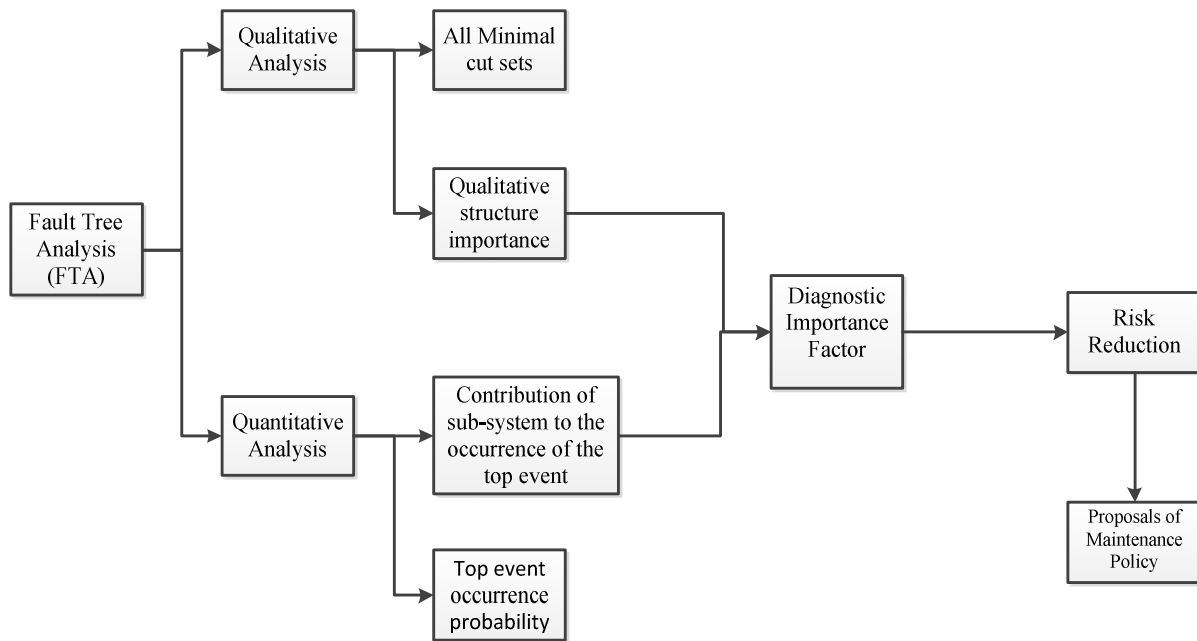


Figure 3-7 The Framework for Proposed Fault Diagnosis Method

3.4.2 Root Cause Analysis of Hydropower plant Failure

The key for effective problem prevention is detecting the causes of a problem, followed by a structured investigation of the problem to identify which underlying causes need to be fixed. Root cause analysis (RCA) is a method that is used to address a problem or non-conformance, in order to find the root cause of the problem. It is used to correct or eliminate the cause, and prevent the problem from recurring.

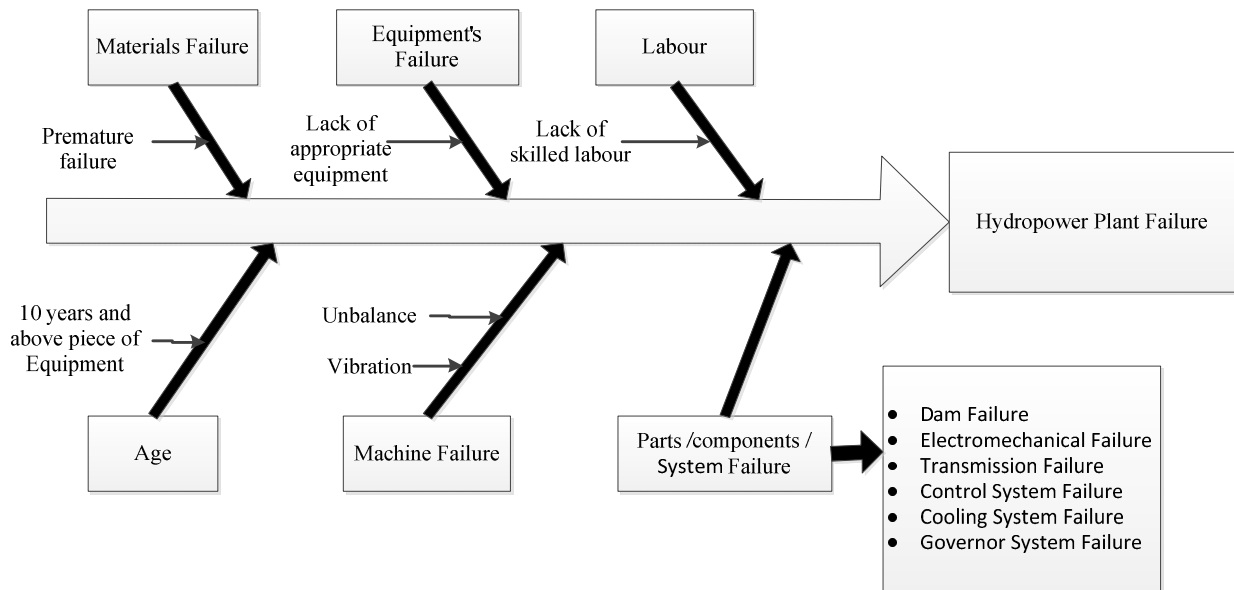


Figure 3-8 General Cause and Effect Diagram

3.4.3 Uses of Fault Tree Analysis Methods in electromechanical components failure

The basic idea of the proposed electromechanical components condition assessment analysis is using Fault Tree Analysis (FTA) to obtain the probability of component failure leading to an electromechanical components failure. A fault tree analysis is a logic diagram that shows potential events affecting system performance and the relationship between potential events.

- This method will assess electromechanical components condition to determine a policy of maintenance and operation.
- Fault Tree Analysis is a tool with which protection engineers can easily compare the reliability of proposed protection of electromechanical parts of hydropower plant systems.
- FTA can be used to identify the system weakness and evaluate possible upgrades.
- Fault tree analysis can also be used to monitor and predict behaviour.
- Furthermore, fault tree analysis can be used to diagnose causes and give potential corrective measures for an observed system failure.

In assessing the condition of hydropower plant by using fault tree analysis, the first step is to model the system and failures sequences with a fault tree. Using minimal cut sets method, we can make qualitative evaluation of the model. This analysis will document the cause and effect relationship between failures at various subsystem levels, and identify the most important failures and weakness points in the systems. These characteristic helps to provide an appropriate maintenance to extend life service and increase the reliability of hydropower plant systems.

The purpose of this chapter is to analysis reliability of electromechanical systems in hydropower plant by using qualitative fault tree. The first step is to model the system and constructing a fault tree of hydropower plant based on its function and structure of main components. Then a top event was defined and the other events in the fault tree were identified stepwise by a deductive method.

Top event in this study is “Electromechanical parts of hydropower plant failure that not generate electricity”. Failure of the top event is made up of the failure of the two main apparatus (defined as the sub-top events). Then qualitative fault-tree analysis consists of determining the minimal cut sets and qualitative importance.

3.4.4 Fault Tree Construction of Electromechanical Components Failure

Fault tree analysis is very powerful as a systematic methodology for identifying root causes, plus it also provides a visual communication model that most individuals can readily understand and follow with a little knowledge of the tool, the system design or the accident situation. This visual model displays the logical relationship in the chain of events leading to a failure in hydropower plant electromechanical system.

One of the strengths of fault tree is that it provides an approach to organize failure speculation in a structured graphical manner. Every parts, faults, cuts, conditions and relationships are displayed in standardize graphical notation that is very easy to understand and follow. The model can be easily modified as more data and information becomes available or any redundant equipment added to the system.

A fault tree is constructed for disabled Turbine Malfunction Generator and Turbine-Generator unit failure (sub systems) of hydropower electromechanical systems. The failure properties of these sub systems are lumped together by the fault tree to indicate the failure of the hydropower electromechanical systems. The first step in constructing FTA is to determine the single top event to be assessed and by deductive methods to expanding to sub system until no more gates to be expanded. The final fault tree for the failure of the electromechanical systems of hydropower plant has a top event which cause is given by the failure of any of sub systems (dam failure, disabled turbine, malfunction generator and transmission unable to deliver power but this thesis analysis the failure of electromechanical systems of hydropower plant system).

Every sub system expanded based on its hardware parts and its function of every single component in the whole systems. The expanding of fault tree is stopped when no more components needed to develop nor more sufficient data exists. After the fault tree are completed all sub system are transferred into minimal cut sets.

Top event of fault tree

The top event of fault tree is “Electromechanical parts of hydropower plant failure that not generate electricity”. This top event related to the main function of hydropower plant. Any failure of the main apparatus (subsystems) will lead to the top event, such as disabled Turbine malfunction generator and turbine generator unit failures,

The Figure below shows that one of the sub-systems of electromechanical components failure affects the Top events crated by Top event professional FTA 2016 software.

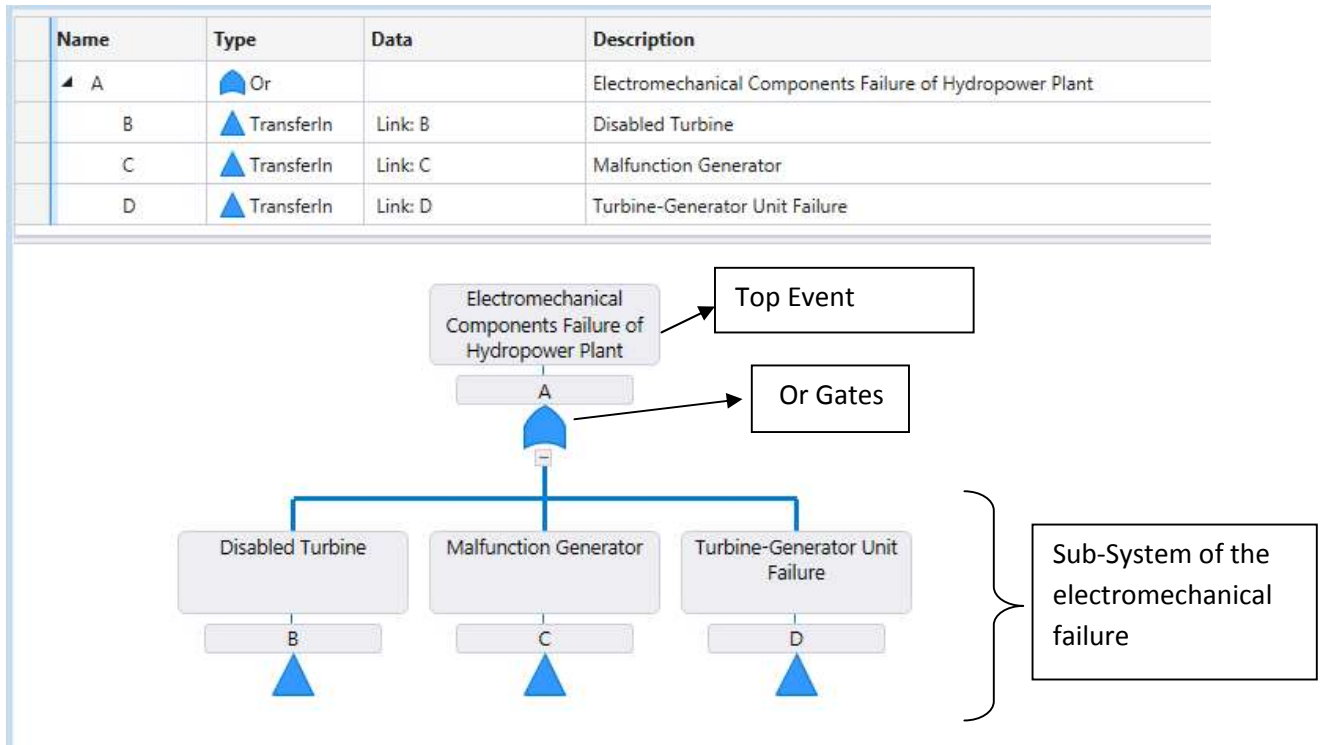


Figure 3-9 Top event of Electromechanical parts of hydropower plant fault tree

Sub systems of the fault tree

The lower levels of fault tree were identified stepwise by a deductive method. The sub system of tree contains with three main apparatus of electromechanical systems (Disabled turbine Malfunction of Generator and Turbine-Generator unit Failure). On the tree, all events are basically correlated with a Boolean logic operator AND gate and OR gate for static fault tree and for dynamic fault tree correlated by Priority AND gate. In this study, causes for a particular event is searched based on a survey, literature or expert knowledge, and regarded as the event on the next hierarchical level. Then a cause for next event is searched, and this procedure is repeated until the basic events in the lowest hierarchical level of the tree are identified.

Disabled turbine

Turbine failure not only increases the plant down-time and brings about revenue losses but also poses a serious threat to the life of the operational and maintenance personnel especially when the power house is underground. There are basically four main failure modes identified in open literature. The current article presents an overview of these four hydro turbine failure modes based on an extensive literature review. [11]

Four types of failures are:-

1. Cavitation,
2. Erosion,
3. Fatigue and
4. Material Defects

Moreover, the above literature of the four types of failure affects the components of turbine. It also attempts to elucidate some recommended methods to prevent/mitigate against these failure modes.

Some of the major problems encountered in the hydro turbines components are:-

- Damage in Runners due to erosion, cracking and cavitation due pressure pulsation in draft tube, instability of operation at partial gate opening.
- Failure of Turbine bearings, leakages of water through of turbine guide bearings, leakage of water through guide vane seals and turbine gland seals.
- Failure of Guide Vane
- Turbine Blades
- Excessive Shaft Vibration
- Spiral Case Clogging(sometimes not always)

Name	Type	Data	Description
└ B	Or		Disabled Turbine
Event1	Basic	Model1 = Constant(q=0.001)	Spiral Case Clogging
B1	TransferIn	Link: B1	Faulty Guide Vane
B2	TransferIn	Link: B2	Excessive Shaft Vibration
B3	TransferIn	Link: B3	Runner Not Pick Speed

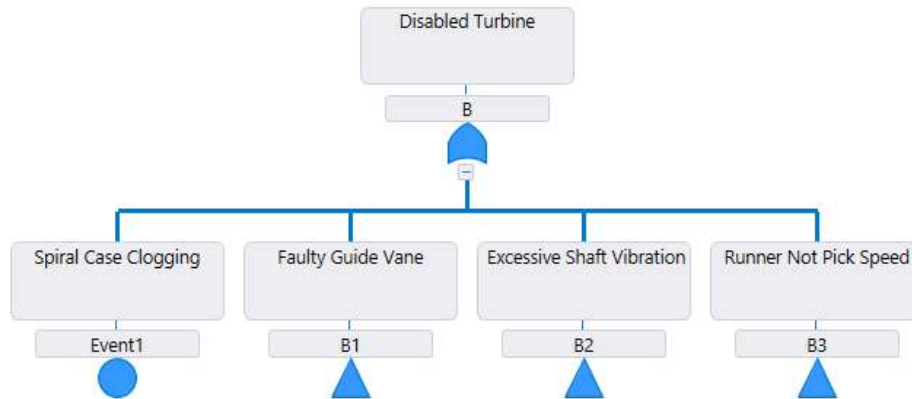


Figure 3-10 Sub System of Disabled Turbine Fault Tree

Spiral Case Clogging

Spiral case is casting welding part, equipped with fixed guide vane in it. Spiral case shall make the water become number of swirl of water flow and guide water to flow regularly into guide vane apparatus and runner along circumference. It is equipped with an air relieve valve on the top of spiral case to exhaust air when filling water initially. Sometimes the spiral case clog by unwanted element like stone, that affect turbine functions.

Faulty Guide Vane

It consists of guide vane lever, shaft sleeve, front cover, back cover, etc. It can form or change number of swirls of water flow to adjust turbine discharge according to variation of load. It is also used to normal and emergency shutdown. The control ring is welded by steel plate as a whole. Circular guiding rail and wiring plate with lubricating performance are located on the bottom surface of the control ring. The control ring has enough strength and rigidity, won't occur excessive bending due to unbalance stress of servomotor. The guide vanes consist of number of blades that can be adjusted in order to increase or reduce the flow rate through the turbine. The vanes are arranged between two parallel covers normal to the turbine shaft.

Figure 3-11 Guide Vane System Failure List

Name	Type	Data	Description
▲ B1	Or		Faulty Guide Vane
▲ B5	Or		Hydraulic system can not operate guide vane
Event5	Basic	Model5 = Constant(q=0.001)	Pump Fail
Event6	Basic	Model6 = Constant(q=0.001)	Oil Leakage from Pipes
Event7	Basic	Model7 = Constant(q=0.001)	Motor Fail
Event2	Basic	Model2 = Constant(q=0.001)	Broken guide vane shear key
▲ B6	Or		Faulty governor
▲ B7	Or		Hydraulic system output signal malfunction
Event8	Basic	Model8 = Constant(q=0.001)	Oil Filter Damage
Event9	Basic	Model9 = Constant(q=0.001)	Throttle valve Damage
▲ B8	Or		Interruption of governor power speed
Event10	Basic	Model10 = Constant(q=0.001)	Leakage of Oil Through Pipe lines
Event11	Basic	Model11 = Constant(q=0.001)	Oil Pressure Too Low
Event3	Basic	Model3 = Constant(q=0.001)	Guide Vane Bushes Wornout
Event4	Basic	Model4 = Constant(q=0.001)	Servomotor Seals Wornout

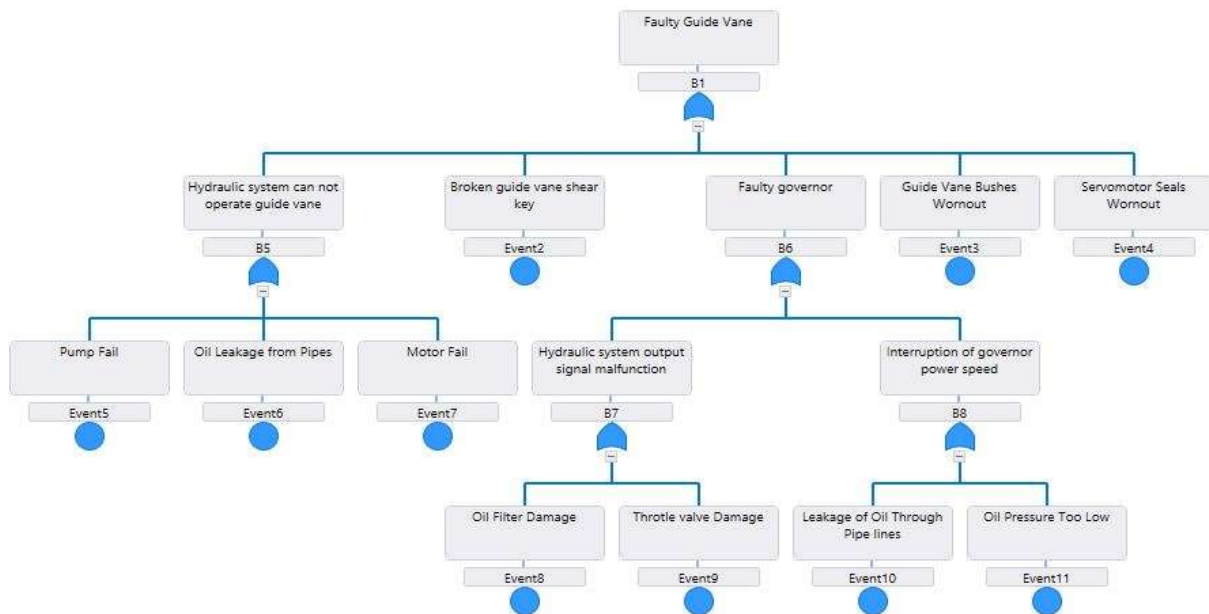


Figure 3-12 Faulty Guide Vane Fault Tree

Runner Failure

Runner is cast and welded as a whole, crown, band and blade is made of stainless steel ZG06Cr13Ni4Mo which has perfect performance of anti-cavitation, anti- corrosion and weldable. The runner is subject to static balance testing after machining. Ten $\Phi 24$ holes are located on runner crown in order to reduce the pressure applied on runner by the water.

Electromechanical System Failure Analysis In Hydropower Plant

Name	Type	Data	Description
▲ B3	Or		Runner Not Pick Speed
Event18	Basic	Model1 = Constant(q=0.001)	Stone or Other Soild in Casing
▲ B11	Or		Runner Vibrates
Event1	Basic	Model4 = Constant(q=0.001)	Blade Damage
▲ B12	Or		Shaft Failure
Ev	Basic	Model6 = Constant(q=0.001)	Shaft Bent
Ev	Basic	Model7 = Constant(q=0.001)	Shaft Wornout
Event1	Basic	Model5 = Constant(q=0.001)	Runner Hab Damage
▲ B13	Or		Bearing Loose
Ev	Basic	Model9 = Constant(q=0.001)	Lack of Lubrication
Ev	Basic	Model10 = Constant(q=0.001)	Bearing House Bolts Loose
Event19	Basic	Model2 = Constant(q=0.001)	Casing Deformed
Event20	Basic	Model3 = Constant(q=0.001)	Runner Touch the side of Casing

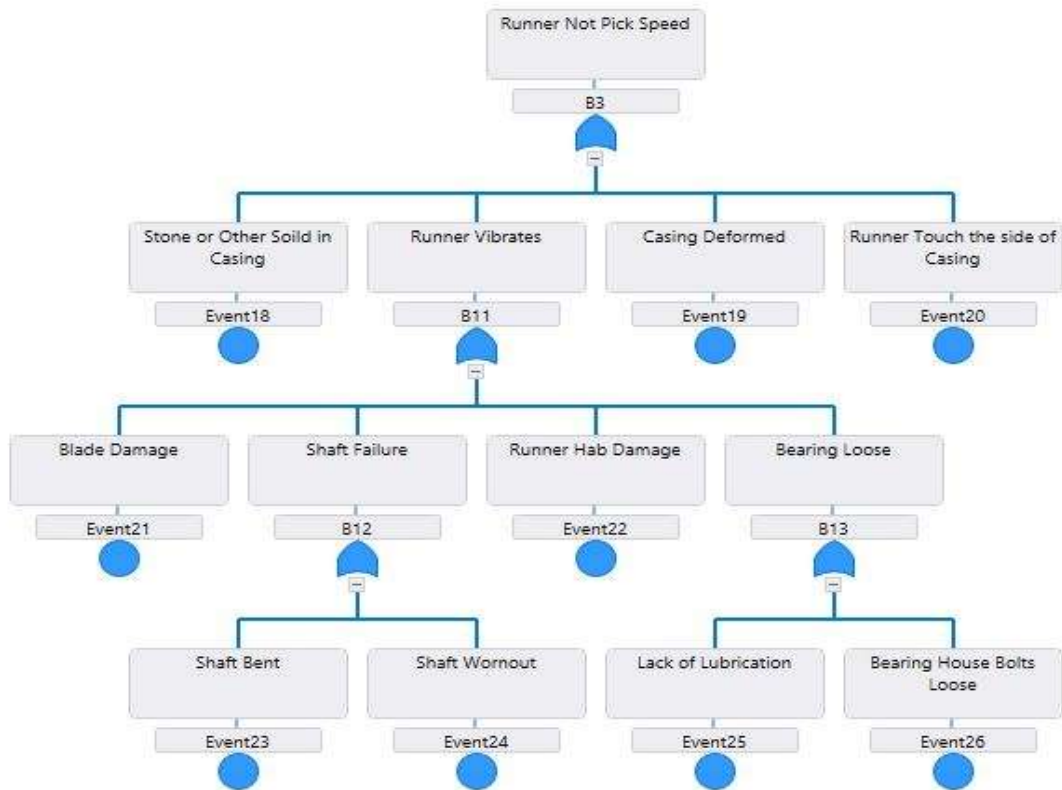


Figure 3-13 Runner Failure Fault Tree

Shaft Failure

Name	Type	Data	Description
▲ B2	Or		Excessive Shaft Vibration
Event12	Basic	Model12 = Constant(q=0.001)	Broken linkage b/n shaft and Runner
▲ B9	Or		Faulty shaft Bearing
Event14	Basic	Model14 = Constant(q=0.001)	Faulty components
▲ B10	Or		Faulty lubrication system
Event15	Basic	Model15 = Constant(q=0.001)	Pump fail
Event16	Basic	Model16 = Constant(q=0.001)	Motor damage
Event17	Basic	Model17 = Constant(q=0.001)	Power interruption
Event13	Basic	Model13 = Constant(q=0.001)	Runner jammed by drift wood

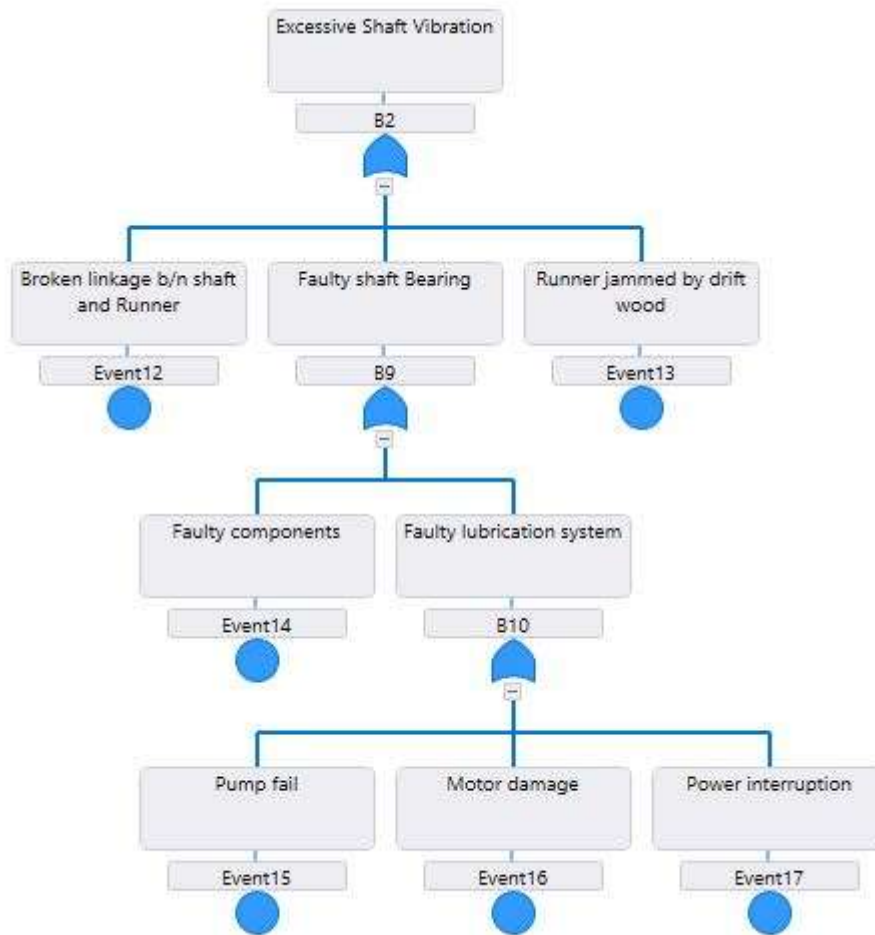


Figure 3-14 Stator Failure Fault Tree

Generator Failure

The electric generator converts the mechanical energy of the turbine into electrical energy. The two major components of the generator are the rotor and the stator. The rotor is the rotating assembly to which the mechanical torque of the turbine shaft is applied. By magnetizing or “exciting” the rotor, a voltage is induced in the stationary component, the stator. The principal control mechanism of the generator is the exciter-regulator which sets and stabilizes the output voltage. The speed of the generator is determined by the turbine selection, except when geared with a speed increaser. In general, for a fixed value of power, a decrease in speed will increase the physical size and cost of the generator.

Conventional cooling a generator is accomplished by passing air through the stator and rotor coils. Fan blades on the rotating rotor assist in the air flow. For larger generator (above 5 MVA capacity) and depending on the temperature rise limitations of the winding insulation of the machine, the cooling is assisted by passing air through surface air coolers, which have circulated water as the cooling medium.

Hydraulic turbines driven generators for hydro plant above 5 MW are salient pole synchronous alternating current machines. Large salient pole generators are relatively slow speed machines in the range 80-375 rpm with large number of rotor poles.

These salient pole hydro generators interconnected with large grids have undergone considerable changes over time which has resulted in reducing size of hydro generators considerably from the electrical and mechanical point of view.

Development in the following areas is most prominent.

- a) Insulation system for stator and rotor winding
- b) Improved material
- c) Ventilation and cooling system
- d) Advanced manufacturing technology
- e) Formation of large grids requires special design consideration for operation and stability.

Hydroelectric generators are key components in the power train at hydroelectric power plants and are appropriate for analysis under a condition assessment program. Unexpected generator failure can have a significant economic impact due to the high cost of emergency repairs and lost revenues during an extended forced outage.

Determining the condition of a generator types is an essential step in analyzing the risk of failure. This part provides a process for arriving at a Generator Condition which may be

used to develop a business case addressing risk of failure, economic consequences, and other factors.

Main sub-systems failures that affect generator function:-

1. Stator Failure
2. Rotor Failure
3. Insulation failure
4. Lubrication failure

Name	Type	Data	Description
▲ C	Or		Malfunction Generator
C1	▲ TransferIn	Link: C1	Rotor Failure
C2	▲ TransferIn	Link: C2	Stator Failure

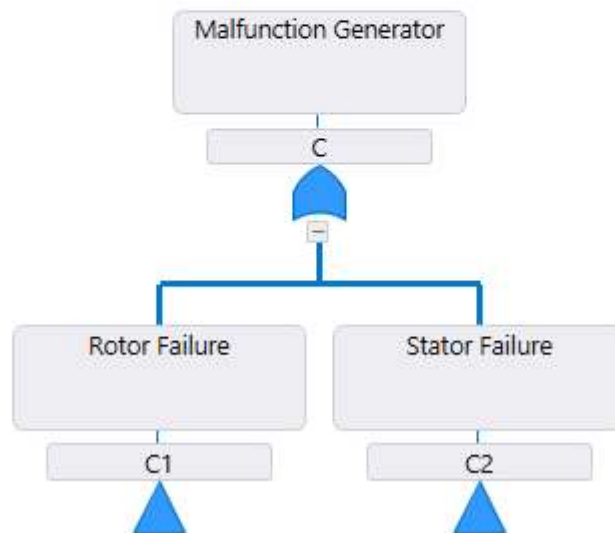


Figure 3-15 Main sub system of Generator Failure Fault Tree

Rotor Failure

A rotor dynamic analysis of the entire shaft system should be performed. This analysis should include the prime mover, generator, and any other rotating components. This analysis should include lateral and torsional shaft system response to the various excitations that are possible within the operational duties allowed by the standards. When the turbine generator is purchased as a set, it would be typical that the manufacturer should perform this analysis. When shaft components are purchased from different manufacturers, the purchaser should arrange to have this analysis. Critical speeds of the generator rotor assembly should not cause unsatisfactory operation within the speed range.

Several types of problems that affect generator rotor components are:-

- ✓ Overheating,
- ✓ Loose and vibrating components,
- ✓ impact damage, and
- ✓ Contamination.

The following components failures should be the root causes of rotor failure

- Rotor hub, radial arms, and rotor rim failures;
- Field poles, keys, collars, and pole faces failure;
- Field windings and inter pole connections failures;
- Field winding leads failures;
- Rim-mounted fan blades failures and Brake ring failure.

Name	Type	Data	Description
▲ C1	Or		Rotor Failure
Event31	Basic	Model2 = Constant(q=0.001)	Rotor Rim Failure
▲ C4	Or		Rotor Pols Failure
Event33	Basic	Model3 = Constant(q=0.001)	Coil's connector circuit Failure
Event34	Basic	Model4 = Constant(q=0.001)	Coil internal short circuit
Event32	Basic	Model5 = Constant(q=0.001)	Ventilation Fans Failure
▲ C5	Or		Break Ring failure
Event35	Basic	Model6 = Constant(q=0.001)	Loosening of break shoe
Event36	Basic	Model7 = Constant(q=0.001)	Mechanical Failure

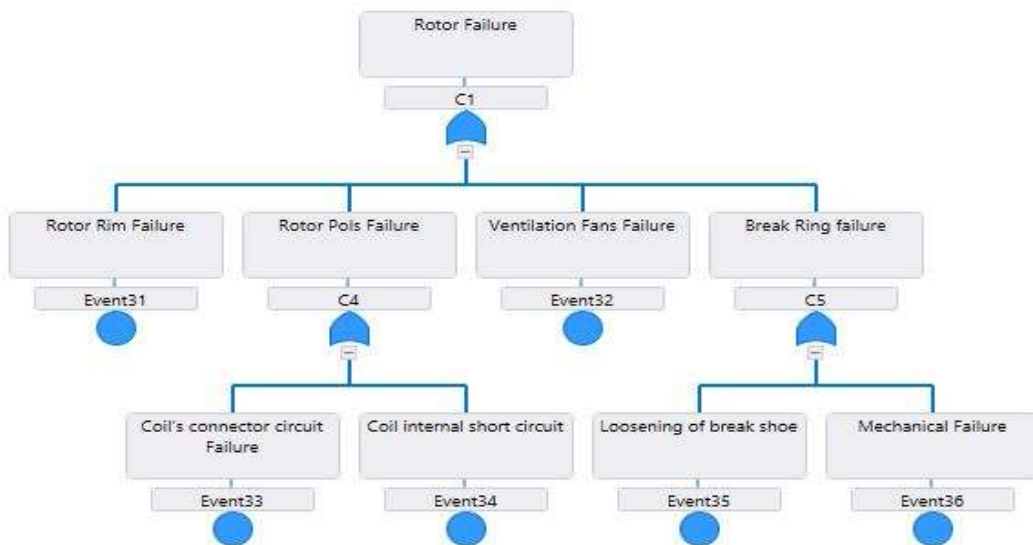


Figure 3-16 Rotor Failure Fault Tree

Stator Failure

The stator frame is designed for rigidity and strength to allow it to support the clamping forces needed to retain the stator punching in the correct core geometry. Strength is needed for the core to resist deformation under fault conditions and system disturbances. Also, the core is subjected to magnetic forces that tend to deform it as the rotor field rotates. In some large size machines, this flexing has been known to cause the core to contact the rotor during operation. In one instance, the core deformed and contacted the rotor, the machine was tripped by a ground fault, and intense heating caused local stator tooth iron melting, which damaged the stator winding ground insulation.

In machines with split phase windings where the split phase currents are monitored for machine protection, the variation in the air gap causes a corresponding variation in the split phase currents. If the variations are significant, the machine will trip by differential relay action, or the differential relays will have to be desensitized to prevent tripping. Desensitizing the relays will work, but it reduces their effectiveness in protecting the machine from internal faults.

Several types of stator winding problems are:-

- ✓ Insulation cracks,
- ✓ Bulging or puffy coils,
- ✓ Surface corona,
- ✓ Contamination,
- ✓ Carbon tracks,
- ✓ Winding movement,
- ✓ Loose bracing and blocking, and
- ✓ Loose wedges or slot fillers.

The above problems also affect the following areas

- Stator winding;
- Stator winding wedges, packing, blocking, and bracing;
- Circuit ring bus;
- Main and neutral leads.

Name	Type	Data	Description
▲ C2	Or		Stator Failure
Event37	Basic	Model8 = Constant(q=0.001)	Stator Frame Failure
▲ C6	Or		Stator Core Failure
Event39	Basic	Model10 = Constant(q=0.001)	Steel Core Failure
Event40	Basic	Model11 = Constant(q=0.001)	Insulation Failure
Event38	Basic	Model9 = Constant(q=0.001)	Stator Coil Failure

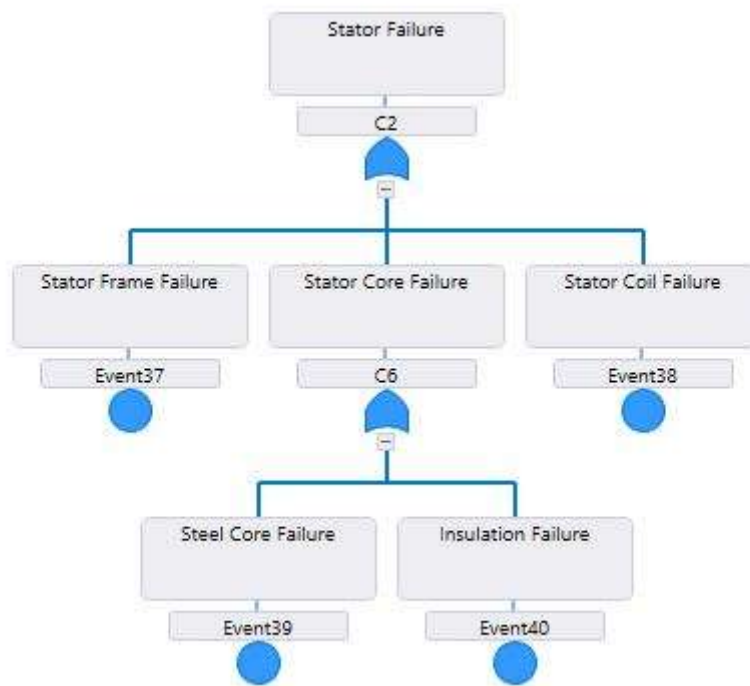


Figure 3-17 Stator Failure Fault Tree

Insulation Failure Mechanisms of Power Generators

Several statistics have been published dealing with failure causes of high voltage rotating machines in general and power generators in particular. Some of these statistics only specify the part of the machine which failed without giving any deeper insight in the failure mechanism. Other publications distinguish between the damage which caused the machine to fail and the root cause which affected the damage.

Hydro generators failed machines showed insulation damage, other major types being mechanical, thermal and bearing damages (Figure 3.13). Root causes which led to these damages are subdivided into 7 different groups (Figure 3.14).

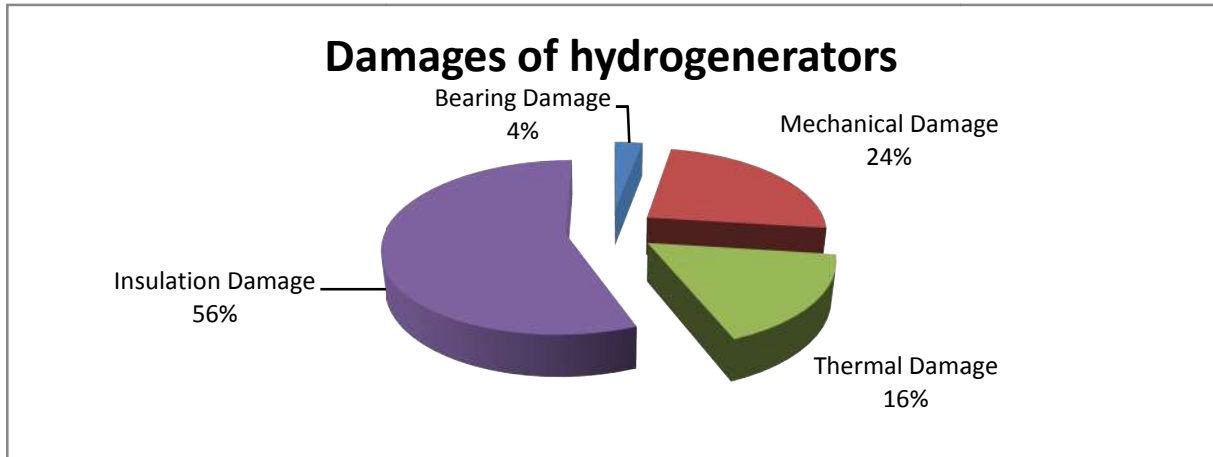


Figure 3-18 Hydro Generator Failure Percentage

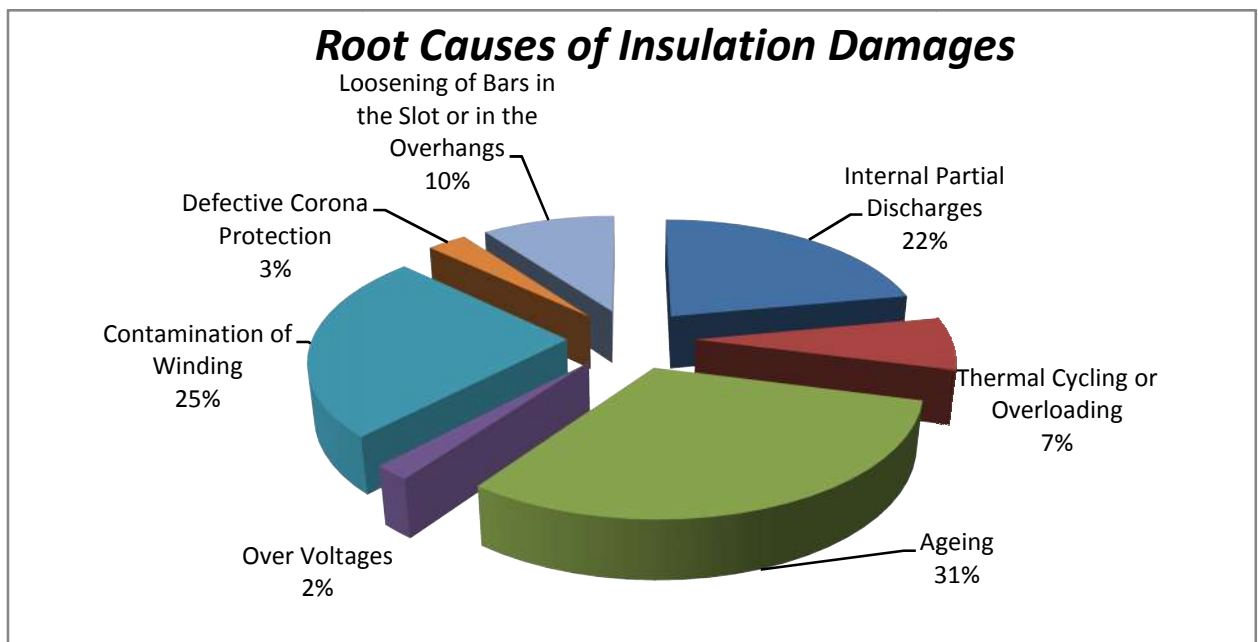


Figure 3-19 root causes of insulation damages

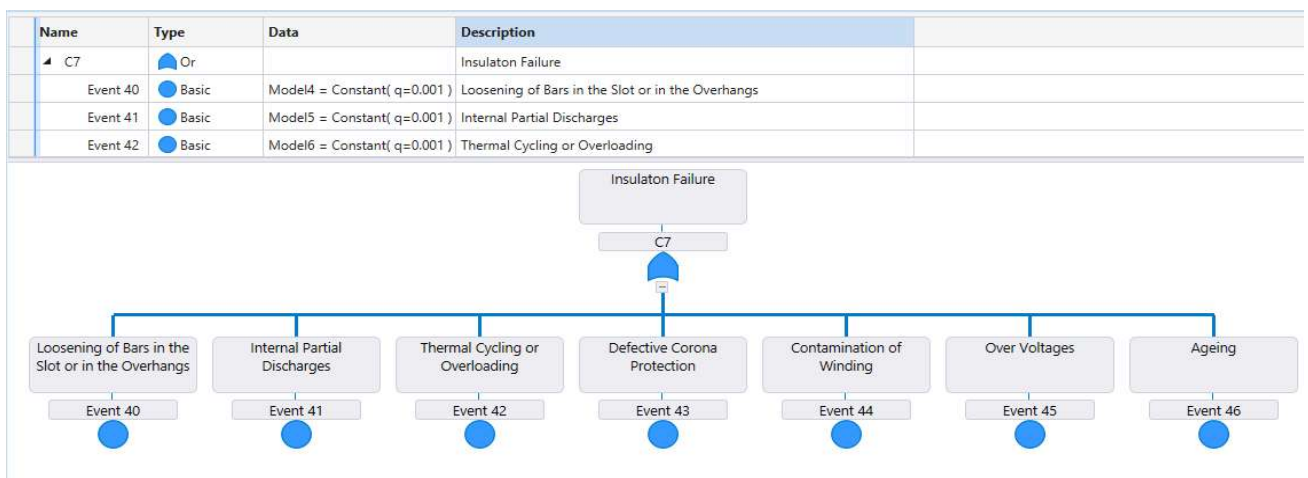


Figure 3-20 Insulation Failure Fault Tree

Turbine – Generator unit Failure

Turbine – Generator unit Failure is a combination of turbine and generator components that affect the electromechanical system. Bearing failure and Governor and control system failure affects the turbine – Generator unit.

Name	Type	Data	Description
└ D	Or		Turbine-Generator unit Failure
D1	TransferIn	Link: D1	Bearing Failure
D2	TransferIn	Link: D2	Governor and Control Failure

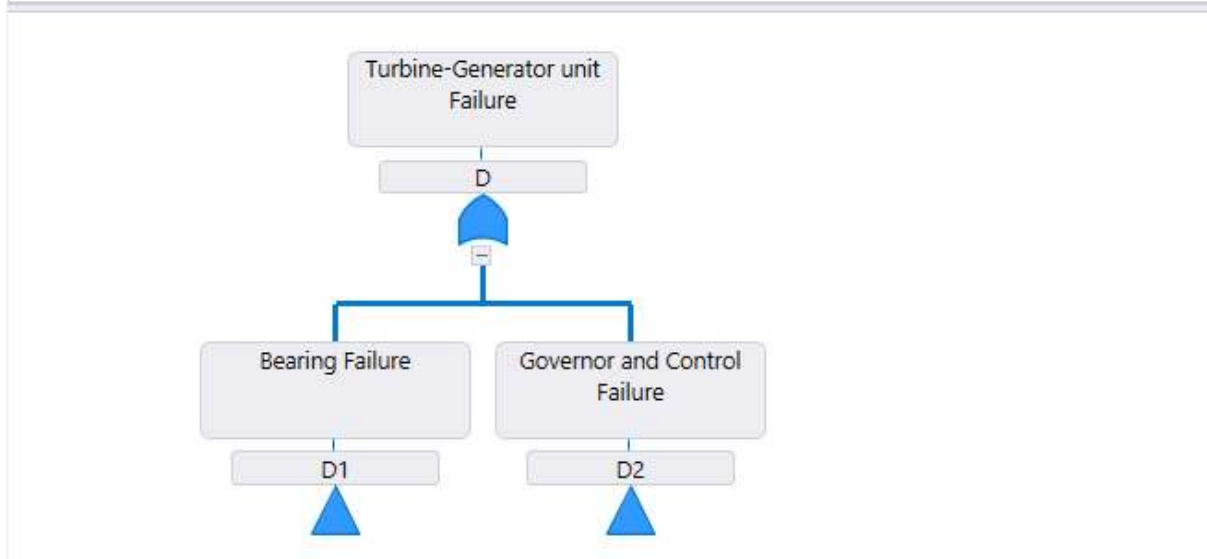


Figure 3-21 Turbine-Generator unit Failure Fault Tree

Bearing Failures

Bearing failures account for almost 4 percent of the failures of hydroelectric generators. A principal cause of failures of generator guide bearings is the occurrence of radial forces due to

- ✓ Misalignment between rotor and stator,
- ✓ Rotor imbalance, or
- ✓ Disturbance from the turbine
- ✓ Pad misalignment.

The usual way to measure bearing load is to install load sensors behind the bearing pads. However, because the cost to reconstruct the bearings to install the sensors is relatively high, a majority of generators are not instrumented for bearing load measurement.

Typical arrangement of the bearings in a vertical shaft generator-turbine unit of a hydropower plant

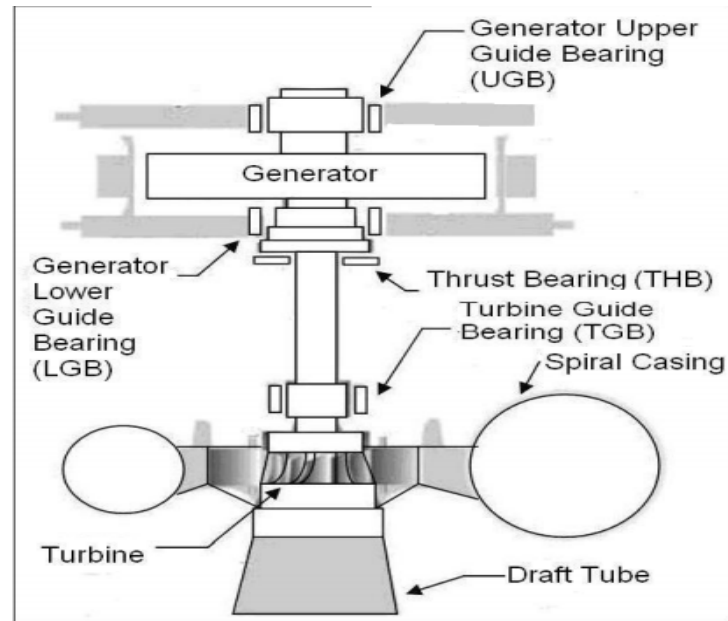


Figure 3-22 Turbine-Generator Bearing Arrangements [16]

- Upper guide bearing UGB,
- Lower guide bearing LGB,
- Turbine guide bearing TGB,
- Thrust bearing THB)

One of the most heavy duty applications of thrust bearings is in hydroelectric power stations for support of the shaft, carrying hydraulic turbine and electric generator. [16]

White metal bearing alloy is the preferred choice as the facing material in those applications because of its outstanding embeddability, conformability, wear and corrosion resistance. On the other hand, white metal falls rapidly with temperature rise and its limitation factor is low fatigue strength.

The causes of bearing failure are

- ✓ Oil circulation system failure, which will serve the three bearings of one unit.
- ✓ Irregular oil sample monitoring.
- ✓ Improper sealing of bearing in order to keep oil clean.
- ✓ Improper alignment of bearing pads.
- ✓ Cooling system copper tubes failures,

Bearing damage is concentrated on the outer part of the pad, suggesting that the outer edge was higher than it should be and was in 'metal to metal' contact with runner. Temperature in the contact area reached white metal melting point and the lining material melted.

In fact, the outer part of the pad was overloaded and in combination with overheating experienced cracking and loss of area of lining by propagation of cracks, which is fatigue failure.

Wear of bearing surface is caused by sliding. Bearing failure we belittle cavitation and corrosion wear mechanism. Wear pattern does not correspond to cavitation wear marks.

Name	Type	Data	Description
▲ D1	Or		Bearing Failure
Event 47	Basic	Model1 = Constant(q=0.001)	Generator Top Guide Bearing Failure
▲ D3	Or		Thurst Bearing Failure
Event	Basic	Model4 = Constant(q=0.001)	Oil Leak Due to Broken Pipe
Event	Basic	Model5 = Constant(q=0.001)	High pressure Lifting Pump
Event 48	Basic	Model2 = Constant(q=0.001)	Generator Bottom Guide Bearing Failure
▲ D4	Or		Turbine Guide Bearing Failure
Event	Basic	Model3 = Constant(q=0.001)	Oil level Too Low
Event	Basic	Model6 = Constant(q=0.001)	Bearing Temperature Too High
Event	Basic	Model7 = Constant(q=0.001)	Oil Leakage from Bearing Housing

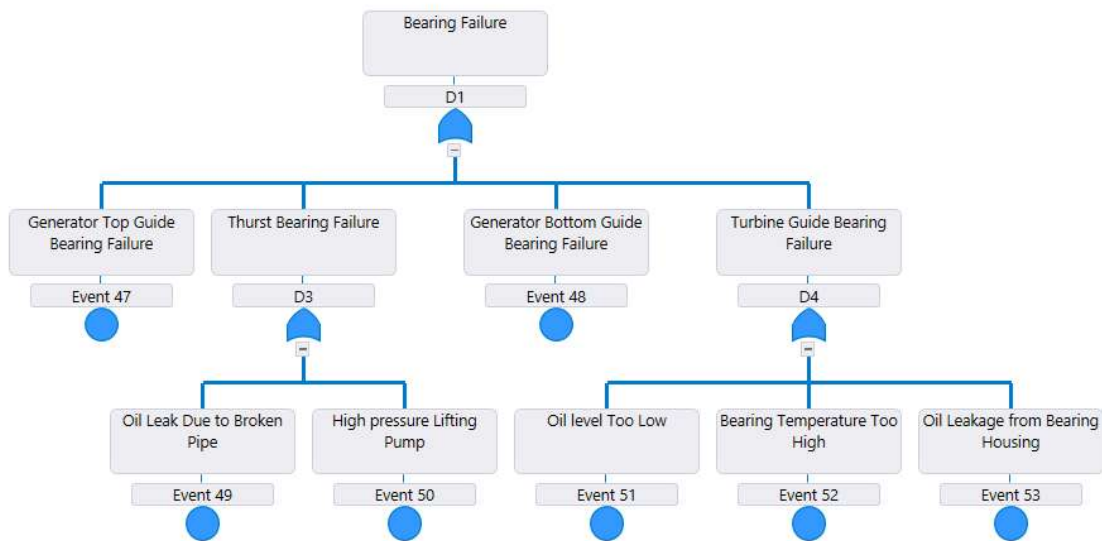


Figure 3-23 Bearing Failure Fault Tree

Control and Governor System Failure

Governing system or governor is the main controller of the hydraulic turbine. The governor varies the water flow through the turbine to control its speed or power output. Generating units speed and system frequency may be adjusted by the governor.

Governing system includes following

- a) Speed sensing elements
- b) Governor control actuators
- c) Hydraulic pressure supply system
- d) Turbine control servomotors-these are normally supplied as part of turbine

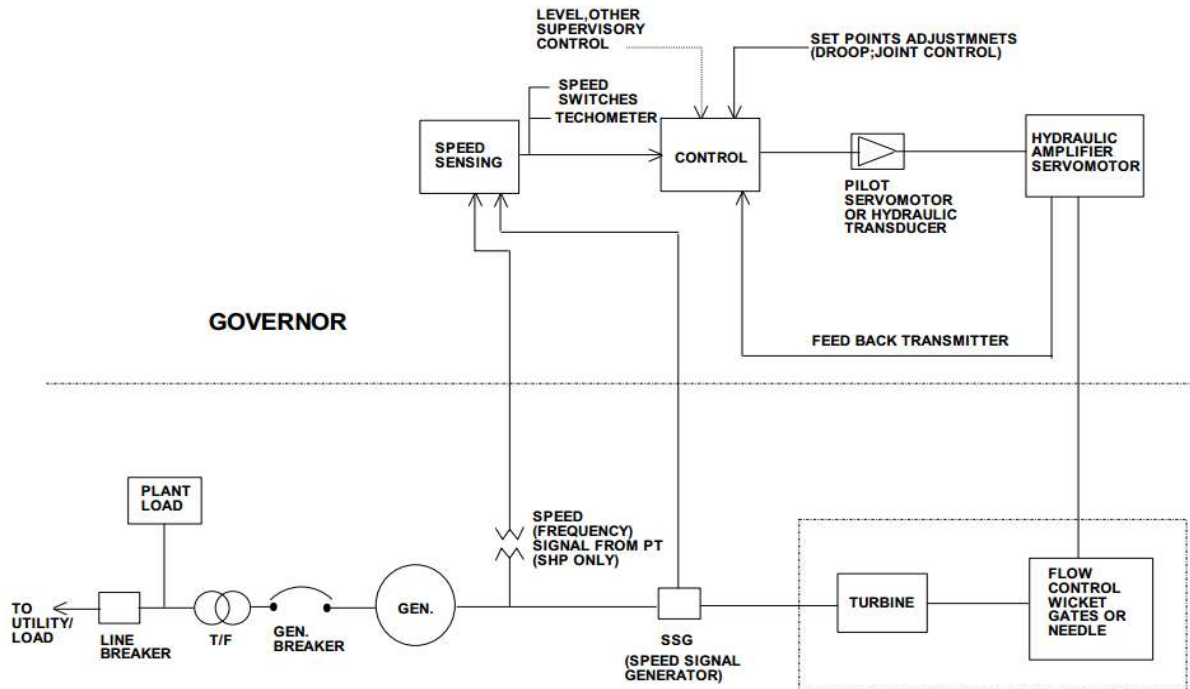


Figure 3-24 Governing System – Block Diagram [21]

The primary functions of the hydraulic turbine governor are as follows:

- I. To start, maintain and adjust unit speed for synchronizing with the running units/grid.
- II. To maintain system frequency after synchronization by adjusting turbine output to load changes.
- III. To share load changes with the other units in a planned manner in response to system frequency error.
- IV. To adjust output of the unit in response to operator or other supervisory commands.
- V. To perform normal shut down or emergency over speed shut down for protection.

Basic Control System

Governor control system for Hydro Turbines is basically a feed back control system which senses the speed and power of the generating unit or the water level of the forebay of the hydroelectric installation etc. and takes control action for operating the discharge/load

controlling devices in accordance with the deviation of actual set point from the reference point.

Governor control system of all units controls the speed and power output of the hydroelectric turbine. Water level controlled power output controllers can be used for grid connected units. Governing system comprises of following sections (figure 6.2).

- a) Control section
- b) Mechanical hydraulic Actuation section

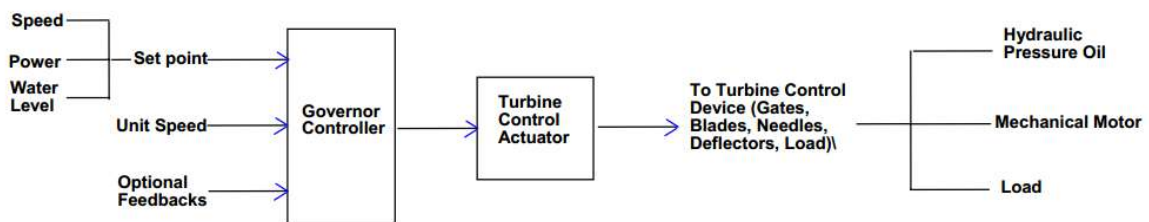


Figure 3-25 Basic Governor Control System [21]

Governor Mechanical Cabinet failure:

- i. Filter and throttle damage
- ii. Leakage of oil through pipe line joints and valves.
- iii. Auto rod setting disturbance.
- iv. Misalignment of feed back wire rope pulleys.

Governor:

- i. Worn out of OPU pumps. Bushes, bearings etc.
- ii. Defects on pump motors.
- iii. Cleaning OPU sump and pressure accumulator and refill with filtered oil.
- iv. Leakages of oil pipeline flanges and valves.
- v. Leakages of Governor Mechanical cabinet, loose of links.

Different types of governors are in use in different hydro power stations:

- a) Mechanical governor can be classified as follows
 - i. Fly ball type
 - ii. Accelerometric type
- b) Governor employing magnetic amplifier.
- c) Governor employing electro hydraulic amplifier.

The governor may require maintenance because of the following reasons:

- I. Chocking of oil parts and throttles
- II. Wearing out of throttles due to which oil leakage becomes more and readjustment of governor becomes essential.

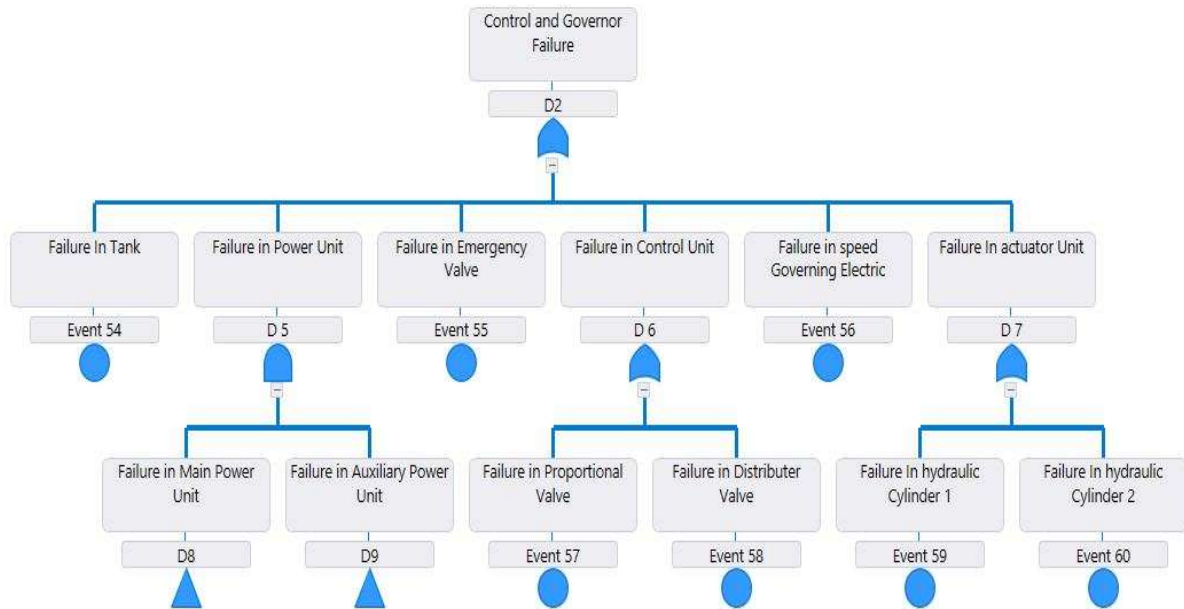


Figure 3-26 Governor and Control Failure Fault Tree

Name	Type	Data	Description
▲ D8	Or		Failure in Main Power Unit
Event 61	Basic	Model15 = Constant(q=0.001)	Failure in Filter
Event 62	Basic	Model16 = Constant(q=0.001)	Failure in Pump
Event 63	Basic	Model17 = Constant(q=0.001)	Failure in Motor AC

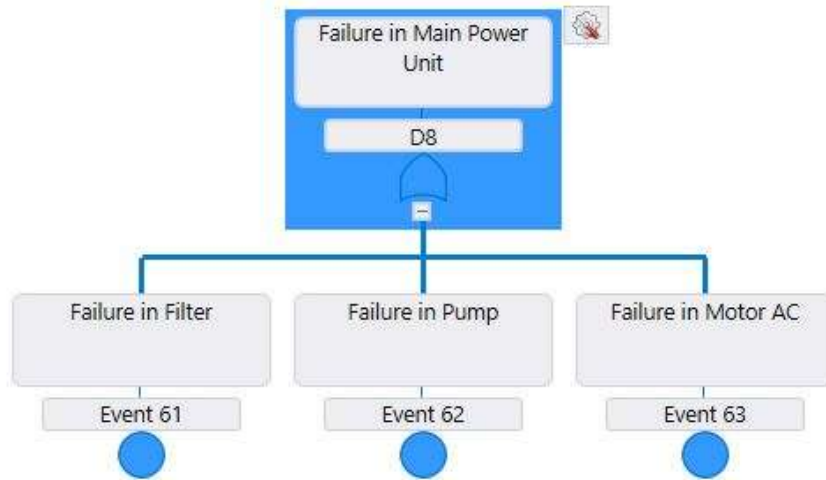


Figure 3-27 Main Power Unit Failure Fault Tree

Name	Type	Data	Description
▲ D9	Or		Failure in Auxiliary Power Unit
Event 64	Basic	Model18 = Constant(q=0.001)	Failure in Filter 2
Event 65	Basic	Model19 = Constant(q=0.001)	Failure in Pump 2
Event 66	Basic	Model20 = Constant(q=0.001)	Failure in Pressure Switch
Event 67	Basic	Model21 = Constant(q=0.001)	Failure in Motor DC

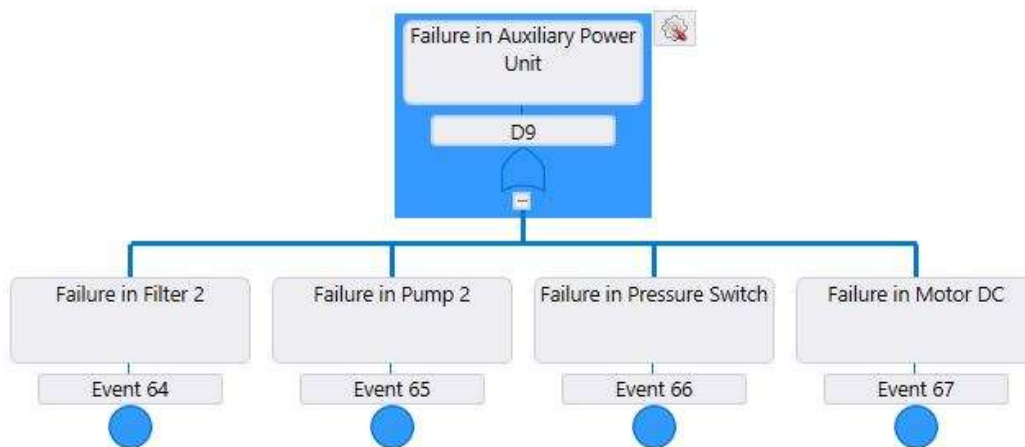


Figure 3-28 Auxiliary Power Failure Fault Tree

Cooling and Lubrication System of combined bearing Failure

Hydropower Facility → Powerhouse → Power Train Equipment → Balance of Plant/Auxiliary Components → Lubrication System

Lubrication System Components

Bearing lubrication systems are critical to unit operation. There are a number of different types of lubrication systems such as pressure, gravity, and submersion.

The reliability related components of lubrication systems include

- The lubricant/oil,
- The filter sub-system,
- The cooling sub-system,
- The oil pumps,
- The vessel and piping,
- The console/skid, and
- The instrumentation/alarm

Lubricant/Oil: The functions of the lubricant/oil are to:

- Minimize friction and wear in hydro machinery
- Maintain internal cleanliness by suspending contaminants or keeping contaminants from adhering to components.
- Cool moving elements, absorb heat from the contact surface area, and transport it to a location in which it can be safely dissipated.
- Dampen shock (cushion the blow of mechanical shock). A lubricant film can absorb and disperse these energy spikes over a broader contact area.
- Prevent corrosion or minimize internal component corrosion. This can be accomplished either by chemically neutralizing the corrosive products or by setting up a barrier between the components and the corrosive material.
- Transfer energy. A lubricant may be required to act as an energy transfer medium as in the case of hydraulic equipment.

Filter Sub-System:

The function of the filter sub-system is to continuously provide clean auxiliary fluid (oil) to the critical equipment. A typical filtration specification for auxiliary system is 10 absolute particle sizes meaning the greatest size of any solid particle in the oil film should be 10 micron. There are two types of filtration systems: “inline” and “offline” filtration.

The inline filter sub-system consists of a transfer valve, which allows transfer from one bank of components to the stand-by bank of components without significant pressure pulsations being introduced into the system, filters, differential pressure indication, and alarm.

The Offline filtration, often call Kidney Loop filtration, functions independently of the designed lubrication system of the unit.

Cooling Sub-System:

The function of this sub-system is to continuously provide cool auxiliary fluid (oil) at the required temperature to the critical equipment. Most coolers in use in hydropower plants are of a shell and tube heat exchange design since cooling water is readily available. As with filter sub-systems, they consist of a transfer valve, as well as twin heat exchangers and a temperature transmitter and alarm.

Oil Pumps:

The function of the oil pumps is to continuously supply the system fluid at the required flow rate. This means it must be capable of interrupted operation for the same period as the turbine it is servicing.

Vessel and Piping:

The vessel functions as the oil reservoir for the system. The correct sizing is critical for the hydro equipment that the lubrication system is servicing. Size will be a function of system flow and subsequently the amount of flow the hydro equipment (main guide bearings, thrust bearings) will actually pass. The function of the piping is to connect the console/skid auxiliary equipment (pumps, vessel, etc.) to the hydro units it services. The typical oil velocities are on the order of 4 to 6 feet per second.

Console/Skid:

The function of the console/skid is to house most of the lubrication system components (pumps, vessel, etc.). Since auxiliary equipment must be maintained and calibrated during operation, it is important for the console/skid to be sized with ample space for maintenance personal.

Instrumentation/Alarms:

The function of the instrumentation is to measure and regulate the process variables of the auxiliary fluid (oil) such as flow, temperature, level, and pressure. Pressure indicators,

temperature indicators, and differential pressure transmitters are examples of key instrumentation.

Cooling system failures

1. Fan blades and radiators failures
2. Fans and controls (check fan rotation)
3. Oil pumps failure
4. Pump bearings (vibration, sound, and temperature)

Chapter Four

4 Results and Discussion

4.1 Introduction

Taking as a basis the results of the FTA analysis, suggestions are presented for the maintenance practices for critical equipment of the hydro power plant under study, which are defined according to the consequences of failure on the hydro generator operational condition.

4.1.1 Qualitative Fault Tree Analysis of Electromechanical Components of Hydropower plant

Minimal Cut Sets

The cut set simply any sets of basic events that cause the top event, and the minimal cut sets imply only the least-needed cut sets events. The minimal cut sets thus highlight the most significant failure combinations and show where design changes can eliminate or reduce undesirable combinations. Minimal cut sets also support fault tree validation which specific minimal cut sets can be checked to determine whether they indeed cause the top event. Minimal cut sets can furthermore be reviewed for dependencies and susceptibilities to CCF (common cause failure) potentials. The minimal cut sets thus provide valuable, qualitative information as well as quantitative information.

Table 4-1 Minimal Cut Set of Disabled Turbine

Fault Tree: B		Fault Tree Node: B		Search...	
	Minimal Cut Set	Order	Unavailability	Contribution	
1	Event1	1	0.001	0.0344828	
2	Event5	1	0.001	0.0344828	
3	Event6	1	0.001	0.0344828	
4	Event7	1	0.001	0.0344828	
5	Event2	1	0.001	0.0344828	
6	Event8	1	0.001	0.0344828	
7	Event9	1	0.001	0.0344828	
8	Event10	1	0.001	0.0344828	
9	Event11	1	0.001	0.0344828	
10	Event3	1	0.001	0.0344828	
11	Event4	1	0.001	0.0344828	
12	Event12	1	0.001	0.0344828	

Table 4-2 Minimal Cut Set of Malfunction Generator

	Minimal Cut Set	Order	Unavailability	Contribution
1	Event26	1	0.001	0.0666667
2	Event27	1	0.001	0.0666667
3	Event29	1	0.001	0.0666667
4	Event30	1	0.001	0.0666667
5	Event28	1	0.001	0.0666667
6	Event31	1	0.001	0.0666667
7	Event32	1	0.001	0.0666667
8	Event37	1	0.001	0.0666667
9	Event39	1	0.001	0.0666667
10	Event40	1	0.001	0.0666667
11	Event38	1	0.001	0.0666667
12	Event33	1	0.001	0.0666667
13	Event35	1	0.001	0.0666667
14	Event36	1	0.001	0.0666667
15	Event34	1	0.001	0.0666667

Table 4-3 Minimal Cut Set of Turbine – Generator Unit Failure

	Minimal Cut Set	Order	Unavailability	Contribution
5	Event 51	1	0.001	0.0713674
6	Event 52	1	0.001	0.0713674
7	Event 53	1	0.001	0.0713674
8	Event 54	1	0.001	0.0713674
9	Event 55	1	0.001	0.0713674
10	Event 57	1	0.001	0.0713674
11	Event 58	1	0.001	0.0713674
12	Event 56	1	0.001	0.0713674
13	Event 59	1	0.001	0.0713674
14	Event 60	1	0.001	0.0713674
15	Event 61-Event 64	2	1E-06	7.13674E-05
16	Event 61-Event 65	2	1E-06	7.13674E-05
17	Event 61-Event 66	2	1E-06	7.13674E-05
18	Event 61-Event 67	2	1E-06	7.13674E-05

CutSet Order		Count
1		14
2		12
Total:		26

A minimal cut set gives a necessary condition for electromechanical components failure to occur. The minimal cut sets are given in Table 3.2 shows 26 minimal cut sets with one basic event for disabled of turbine, Table 3.3 shows 16 minimal cut sets with one basic event for malfunction of generator and Table 3.4 shows 26 minimal cut sets with 7 one basic event for

both bearing failure and control and governor failure (14 one basic events) and 12 two basic events of control and governor failure.

The electromechanical component has many possibility of the occurrence of basic events failure which lead to the occurrence of the top event. Any occurrence of the minimal cut sets will directly correspond to the occurrence of the top event.

Qualitative Structure Importance

In qualitative structure importance evaluation, the more basic events are included in a minimal cut set, the less the minimal cut sets contributes to the occurrence of the top event and vice versa. Qualitative importance gives a qualitative ranking on each sub system with regard to its contribution to system failure. Table below shows the qualitative importance of electromechanical components. Assuming that basic event occurrence probabilities are the same and less than 0.001, the rankings of qualitative importance of fault tree is obtained as: disabled turbine sub-system (26 single basic events with occurrence probabilities 0.026), malfunction Generator sub system (16 single basic events with occurrence probabilities 0.016), Turbine generator unit failure sub-system (14 single basic events and 12 two basic events with occurrence probabilities 0.014 and 1.2e-5 for single basic events and two basic events respectively, there for occurrence probabilities of Turbine generator unit failure sub-system 0.014012),

Disabled turbine sub-system contain 26 single-basic-event minimal cut sets with occurrence probabilities 0.026, this indicates that disabled turbine sub-system is the highest ranking in qualitative structure importance which means the disabled turbine sub-system is the weakness point in the electromechanical system. The Turbine generator unit failure sub-system contain 14 single basic events and 12 two basic events of minimal cut sets with occurrence probabilities 0.014012, this indicates that The Turbine generator unit failure subsystem is the strongest point of electromechanical system.

Assuming every component is independent, the ranking of qualitative component importance is given in table below. The more single-basic-event of minimal cut sets are included in a component, the more significant contribution to the occurrence of the top event.

Based on this result, it is important to focusing attention on disabled turbine sub-system that the most contributed to the unreliability of the electromechanical system.

Table 4-4 Minimal Cut Set (MCS) of Electromechanical system of Hydropower Plant

No	Sub-System	Components Name	No of Cut Sets	Occurrence Probability
1	Disabled Turbine	Spiral Case Clogging	0	0.001
		Faulty Guide Vane	10	0.00995512
		Excessive Shaft Vibration	6	0.00598502

		Runner not Pick Speed	9	0.00896408
2	Malfunction Generator	Rotor Failure	6	0.00598502
		Stator Failure	4	0.00995512
3	Turbine-Generator Unit Failure	Bearing failure	7 one basic events	0.00697903
		Governor and Control Failure	7 one basic Events and 12 two basic events	0.00699092

4.1.2 Quantitative Fault Tree Analysis of electromechanical components of hydropower plant

The principal electro mechanical components of a hydro plant are the turbine, generator and Turbine – Generator Unit (Bearing and Governor and control system).

In recently years, there are many methods to assess the reliability of hydropower plant, several monitoring techniques are used and under investigations. The purpose of this chapter is to assess the reliability of electromechanical components of Gilgel Gibe II using quantitative fault tree.

The first step in the quantitative evaluation of a fault tree is to find the structural representation of the top event in terms of the basic events. In previous work, proposed the qualitative fault tree analysis of electromechanical components of hydropower plant as a base for the quantitative analysis.

If the rate of occurrence and fault duration for all basic events are known and the statistical dependency of each basic event is known (or assumed), then the statistical expectation or probability of top event can be determined. The purpose of quantitative analysis of a fault tree usually is to determine the probability occurrence of the top event (system failure).

Note: - for quantitative fault tree analysis the rate of occurrence of basic events that represent in qualitative FTA analysis will be known (or assumed). However it is difficult to know the rate of occurrence of basic event. So in this dissertation the basic event occurrence rate uses by assumption. Assume that the basic events occur within 45 days, that changes in hours become 1080hrs. So the rate of occurrence for each basic events will be 0.0009 its approximately 0.001.

The basic idea of the proposed electromechanical system condition assessment analysis is quantitative fault tree analysis to obtain the probability of electromechanical component failure leading to a hydropower plant failure. A fault tree analysis is a logic diagram that shows potential events affecting system performance and the relationship among potential events.

4.1.2.1 Electromechanical components of hydropower plant Model

The principal electromechanical components of a micro hydro plant are the turbine and generator. This paper depends on Gilgel Gibes II hydropower plant. Gilgel Gibe’s hydropower plants have Francis turbine and Synchronous generator. So this paper deals about Francis turbine and synchronous generator.

4.1.2.2 Top Event Occurrence Possibilities

The probability of occurrence of the top event , i.e., failure of the Electromechanical System of Hydropower plant is obtained by FTA software on the probability occurrence of top event and subsystem at time t =0 until time t = 1000 Results given in Table 3.5. This result shows representation of future behaviour of the system in terms failure and success of Electromechanical System of Hydropower plant.

Disabled turbine (B) connected with spiral case clogging (event 1), faulty guide vane (B1), Excessive shaft vibration (B2) and runner not pick speed (B3) by OR gates. There for the occurrence probability of Disabled turbine (P_B) calculates as

$$P(A \text{ or } B) = P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

$$P_B = P_{\text{event1}} + P_{B1} + P_{B2} + P_{B3} - [P_{\text{event1}} * P_{B1} + P_{\text{event1}} * P_{B2} + P_{\text{event1}} * P_{B3} + P_{B1} * P_{B2} + P_{B1} * P_{B3} + P_{B2} * P_{B3} + (P_{\text{event1}} P_{B1} P_{B2} P_{B3})]$$

$$= 0.0256776$$

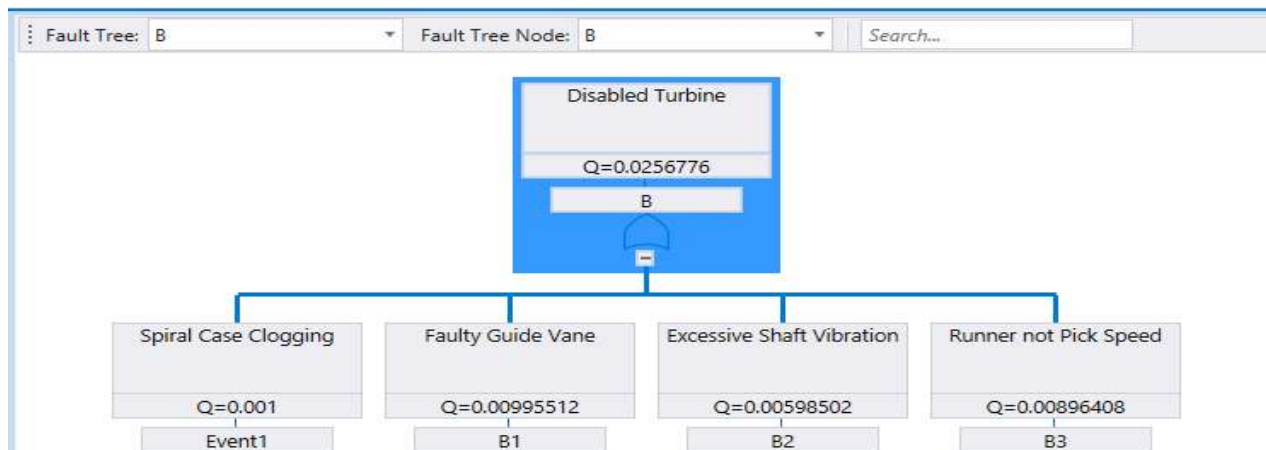


Figure 4-1 Occurrence probability of Disabled Turbine

The intermediate gates connected to the top event through OR gates, this means that any occurrence of the intermediate gate will leading to the occurrence of the top event. Table 3.5 also shows the quantitative contribution to the occurrence of top event is obtained as: Disabled Turbine sub-system, Malfunction Generator sub-system and Turbine-Generator Unit Failure sub-system.

Malfunction Generator (C) connected with stator failure (C1) and rotor failure (C2) by OR gates. There for the occurrence probability of the Malfunction Generator (P_c) calculates as

$$P(A \text{ or } B) = P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

$$P_c = P_{C1} + P_{C2} - (P_{C1} * P_{C2})$$

$$= 0.00598502 + 0.00995512 - (0.00598502 * 0.00995512)$$

$$= 0.0158805584076976$$

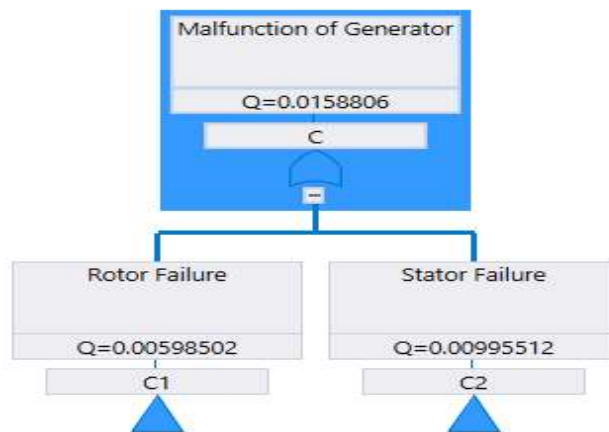


Figure 4-2 Occurrence probability of Malfunction Generator

Turbine – Generator unit failure (D) connects with Bearing failure and control and governor failure by OR gates. There for the occurrence of probability of turbine generator unit failure (P_D) calculates as

$$P_D = P_{D1} + P_{D2} - [P_{D1} * P_{D2}]$$

$$= 0.00697903 + 0.00699092 - [0.00697903 * 0.00699092]$$

$$= 0.0139211601595924$$

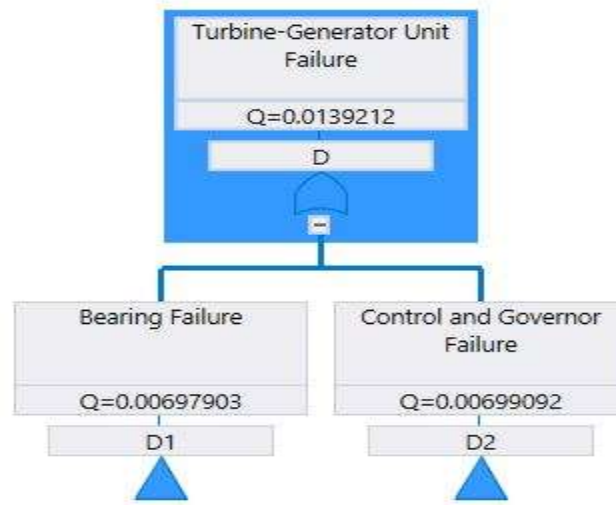


Figure 4-3 Occurrence Probability of Turbine Generator unit failure

Note: - Assume At time $t = 1000$ hours each basic event have the probability of the occurrence 0.001.

The probability of the occurrence of the top event (Electromechanical components Failure of Hydropower plant) and intermediate events is given in figure 4.4. Table 3.5 shows the probability occurrence and percentage contribution of failure probability every sub system and the occurrence of the top event at any time t . At any time during operation time of Electromechanical System of Hydropower plant, we can obtain the probabilities occurrence of every gates and top event. It means the behaviour of the system can be predicted in order to improve reliability services and better maintenance.

Electromechanical components failure of hydropower Plant (A) connects with Disabled turbine (P_B), Malfunction generator (P_C) and Turbine-generator unit failure (P_D) by OR gates. There for the occurrence of probability of electromechanical components failure (P_A) calculates as

$$P(A \text{ or } B) = P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

$$\begin{aligned} P_A &= P_B + P_C + P_D - [P_B * P_C + P_B * P_D + P_C * P_D] \\ &= 0.0256776 + 0.0158806 + 0.0139212 - [0.0256776 * 0.0158806 + 0.0256776 * 0.0139212 + 0.0158806 * 0.0139212] \\ &= 0.0544930842916 \end{aligned}$$

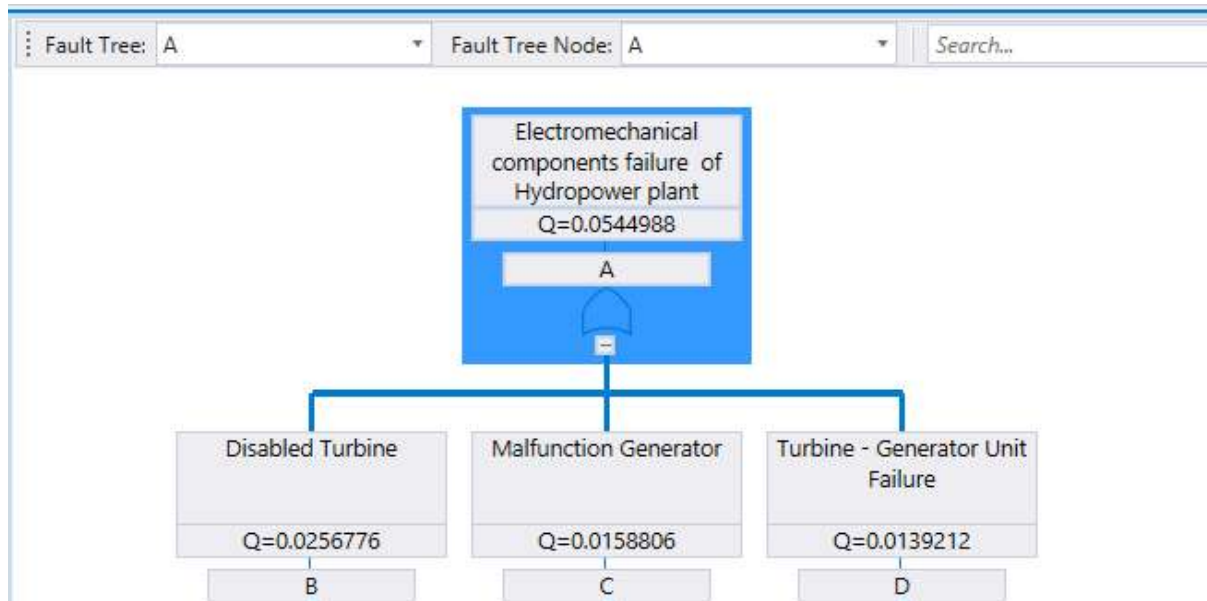


Figure 4-4 Occurrence probability of Electromechanical components Failure of Hydropower plant

The top event represents the electromechanical components of Hydropower plant failure or unreliability. The three sub system (intermediate gates) representing Electromechanical System of Hydropower plant failure are Disabled Turbine that turbine failed by spiral case clogging, faulty in guide vane, excessive shaft vibration and Runner not pick speed with a occurrence probability of 0.0256776 represented in figure 4.1, Generators malfunction by Rotor failure and stator failure with occurrence probability of 0.0158806 represented in figure 4.2 and Turbine-Generator Unit Failed by bearing failure and control and governor failure with occurrence probability of 0.0139212 represented in figure 4.3. Each sub-system also have its own sub-system that represents on qualitative analysis in chapter 3.

By this result The Disabled Turbine sub-system is the most contribute to the occurrence of the top event in any time, this indicates that Disabled Turbine subsystem is the weakness point in the Electromechanical components of Hydropower plant. The Turbine- generator unit sub-system is the strongest point of Electromechanical components of Hydropower plant. Based on this result, it is important to focusing attention on Disabled Turbine sub system that the most contributed to the unreliability of the electromechanical components of Hydropower plant.

When we see the FTA analysis of electromechanical system failure and Gilgel Gibe II hydro power plant report data high oil temperature, cooling and lubrication systems plays a major role to affect the power system. From data presented in APPENDEX 4 it is interesting to observe that the generating units presented oil temperature. It is also interesting to observe the great number of failures associated with the generator subsystem.

The FTA analysis indicates that guides vanes, runner, excessive shaft vibration, rotor ventilation systems and bearings failure can cause hydro generator shutdown because of loss of oil pressure or increase of oil temperature.

Those problems are caused by cooling and lubrication oil systems components failures. The same failures for the speed governor hydraulic system will also cause the hydro generator shutdown. The failure of the refrigeration system used by the hydraulic systems and also by the generator can cause machine shutdown. Another type of failure that implies in machine shutdown is the deterioration of rotor and stator winding insulation, which operational condition must be verified over time.

Therefore High oil temperature affects turbine, generator and governors systems. That means it affect all electromechanical system of hydropower plant. So it takes mach consideration to reduce the risk happen in power plants.

4.2 Proposals of Maintenance Policy

In accordance with RCM concepts, preventive or predictive maintenance practices must be evaluated to components whose failure modes generate consequences with severity greater, in other words, those that degrade the performance or even cause shutdown of hydro generator.

Considering that most of the failures for subsystems turbine and penstock and draft tube are associated with hydraulic systems the faster the maintenance team locates a failed component the smaller will be the forced outage period.

The failure diagnosis can be based on pre-defined faults that can cause interruption of hydraulic system operation. For each fault a tree must be developed to identify the possible components which failures cause the tree top event. Those trees can be developed by engineering and maintenance crew of each power plant.

In Figure 4.9 a tree is presented to indicate the root-cause analysis of increase in hydraulic oil temperature' which causes hydraulic system operational interruption. Those trees can also be used to define monitoring systems that could be able to alert about failures development in hydraulic system basic components aiming at applying predictive maintenance to improve hydro generator reliability.

This methodology can be used to develop analysis of other critical components failure modes aiming at defining monitoring systems to evaluate mechanical components degradation and to support root cause analysis.

The availability analysis indicates that the hydro generator maintenance practices employed by the generation company have proved effective from the point of view of maximizing the availability with reduction of corrective maintenance interventions mainly for hydro generator. The use of maintenance policies selected from the application of the RCM philosophy should increase the availability of machines, minimizing the preventive and corrective interventions.

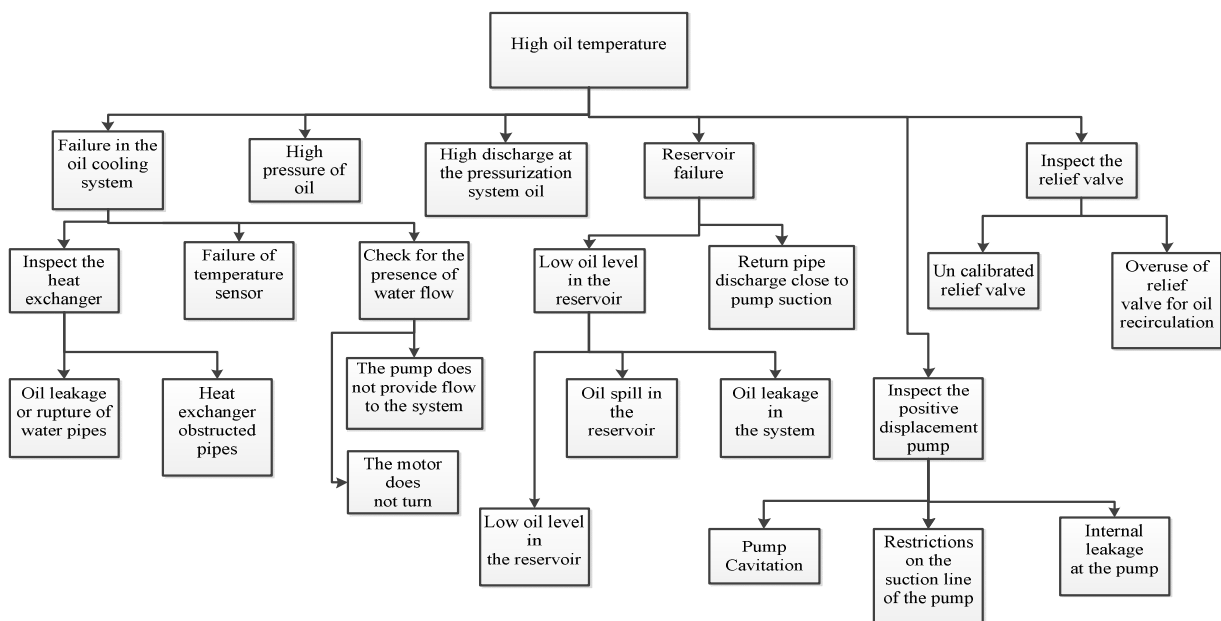


Figure 4-5 Root causes analysis tree for failure Diagnosis [19]

The outcomes of this analysis are:

- i) It is vital the use of an on-line system for monitoring oil temperature used as a lubricating fluid in the bearings of the turbine and generator. The increase of the oil temperature may be an indicator of a failure in the cooling system or bearing failure due to oil film thickness reduction between the shaft and the pads of the bearing. Specifically in the case of monitoring system for the bearings oil temperature, if the oil temperature increases in all bearings simultaneously, there is a clear indication of oil cooling system failure. If the fault is associated with some component of the raw water feeding system an increase in temperature of the air inside the generator can also be detected, based on the indications of air

temperature sensors installed near generator radiators. If the failure is associated with the oil treatment and conditioning system, it won't be observed variation of the air temperature inside the generator;

- ii) The increase of oil temperature in a single bearing is an evidence of failure in cooling system (or pipes). If the failure is associated with an absence of flow of raw water, there will be an indication of water level sensor. Thus, measurement of the oil temperature is an important parameter for determining the performance of hydro-generator and may indicate the occurrence of failures in the cooling system of the hydro-generator;
- iii) The temperature rise of the bearing pad indicated by the temperature sensors may be caused by an increase in oil temperature (which would also be recorded by the oil temperature sensor) or due to an improper contact between the shaft and pads, as function of the shaft vibration. The shaft vibration can be detected by proximity sensors located in the bearings;
- iv) The oil analysis may assist in predicting of the occurrence of wear in the bearing components, which may be associated with a possible contact between shaft and pads, caused by the vibration of the turbine and generator shaft, or by oil contamination due to filtering system failure.
- v) The installation of proximity sensors in the generator to measure air gap is suggested. Such proximity sensors enable the assessment of the orbit of the generator rotor shaft, allowing the assessment of abnormalities in this orbit which characterizes the vibration of the shaft. Moreover, this sensor can monitor the evolution of a failure mode whose effect is the shaft vibration, enabling a maintenance action before a higher degradation of the operational performance of hydro generator.

It should be noted that the monitoring techniques, which support decisions associated with the implementation of predictive maintenance, are basically applied to mechanical components, for failure modes whose time dependency development is clearly defined.

Also for pelton turbine proposal maintenance policy presented in the following table it shows the types of damage, causes and identification /assessments the damages.

Electromechanical System Failure Analysis In Hydropower Plant

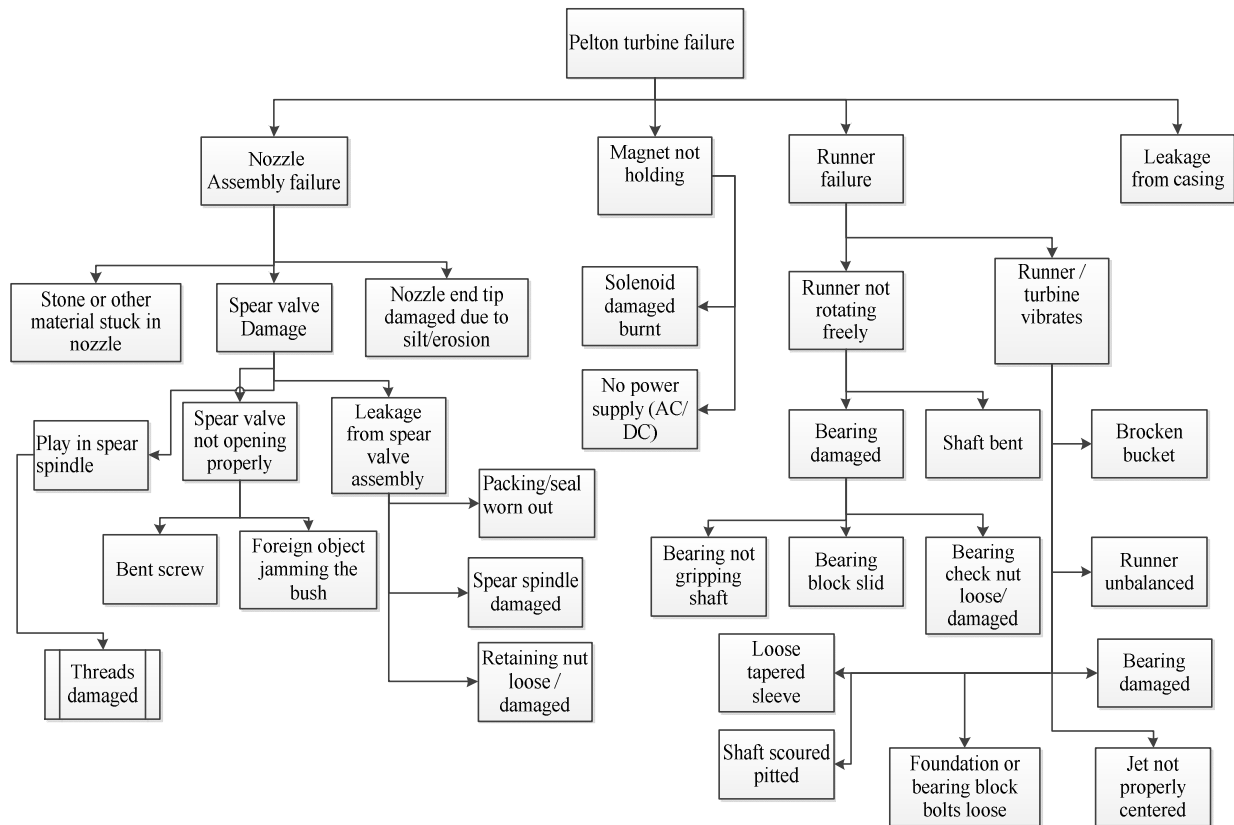


Figure 4-6 Pelton Turbine Failure Maintenance Policy

Type of Damage	Cause	Identification/Assessment
Inadequate flow from nozzle assembly	Stone or other material stuck in nozzle	- Dismantle spear valve assembly and inspect
	Spear valve not opening properly	-
	Bent screw	- Dismantle spear valve assembly and inspect screw - Turn the screw to check bending
Proper jet not forming	Foreign object jamming the bush	- Remove spear spindle from bush and mating surfaces
	- Nozzle end tip damaged due to silt/erosion	- Dismantle nozzle tip measure internal dia. And check roughness
Leakage from spear valve assembly	- Packing/seal worn out - Spear spindle damaged - Retaining nut loose / damaged	- Dismantle spear valve sealing unit - Remove the retaining nut inspect spindle - Check spindle for damage

Electromechanical System Failure Analysis In Hydropower Plant

Play in spear spindle	-Threads damaged	- Dismantle spindle & inspect threads on both surfaces
Jet deflator not functioning properly -	- Cover bent - Deflector plate slipping - Plate/spindle worn out	- Dismantle & inspect for damage
Magnet not holding -	-Solenoid damaged burnt -No power supply (AC/DC)	- Check resistance/continuity using multi meter - Check power supply both input & output of solenoid circuit - Check rectifiers and other components
Runner not rotating freely	- Shaft bent - Bearing damaged - Bearing not gripping shaft • Taper sleeve/neck washer damaged - Bearing block slid - Bearing check nut loose/damaged	- Take out runner and inspect shaft for bending - Take out bearing, clean, rotate and listen to sound, play (worn rollers) - Open check nut, take out washer and inspect - Remove block check for damage (cracking, wear) - Open cover of bearing block and inspect check nut
Runner / turbine vibrates	- Brocken bucket - Runner unbalanced -Bearing damaged - Loose tapered sleeve - Shaft scoured pitted - Foundation or bearing block bolts loose - Jet not properly centered	- Take out runner and inspect - Remove casings cover rotate runner slowly and let it stop normally. If it stops in the same position repeatedly or it rotates backwards than it is unbalanced - Inspect bearing - Remove bearing cover and inspect nut - Check tightness of nuts - Remove and inspect shaft - Check foundation bolts if loose in concrete - Remove top covering and - Measure perpendicular distance between centre of

Electromechanical System Failure Analysis In Hydropower Plant

		nozzle and casing and centre of bucket and casing to see if the two are same
Leakage from casing • At casing joints	- Loose bolts - Gaskets between casing flanges damaged - Casing flange deformed	- Insect bolts - Remove and inspect gaskets - Remove & inspect casing/flange for deformation pitting/cracking
• At shaft entry point	-Sealing system Damaged - Clearance between two discs too large	- Remove turbine cover and inspect the sealing assembly for deformation and damage - Remove sealing component on the shaft - Remove cover and inspect Clearance between two sealing discs.
	Gasket between casing & sealing disc may be damaged	- Remove both sealing discs and inspect gasket

Chapter Five

5 Conclusions and Topics for Future Research

5.1 Conclusion

The qualitative analysis of the fault tree shows in minimal cut sets (MCS's) and in qualitative structure importance. Qualitative analysis is used to identify what combinations of events that affect the top event. It can be performed prior to the entry of failure or repair data in the properties for the events in the fault tree. Based on gate logic, qualitative analysis determines the minimal cut sets for the top event. An important feature of the fault tree analysis is very powerful as a systematic methodology for identifying root causes, it also provides a visual communication model that most individuals can readily understand and follow with a little knowledge of the tool, the system design or the accident situation.

The visual model displays the logical progression in the chain of events leading to failure in electromechanical components of hydropower.

The complete structure of fault tree of electromechanical components failure of hydropower plant is given in Appendix 1.

The qualitative results help in focusing attention on main apparatus of electromechanical components of hydropower that contributed to the unreliability of the system. Through qualitative fault tree analysis of electromechanical components of hydropower can be found that the strongest and the weakest point are disabled turbine sub-system and the Turbine generator unit failure sub-system, respectively.

The quantitative fault tree analysis of electromechanical components of Hydropower plant of is performed. The result of the quantitative fault tree analysis depends on the failure rate of every single-basic-events or components which connected to the gates through static gates. The probability of occurrence of the top event (Electromechanical components failure of Hydropower plant) and every gate are obtained by quantitative methods. Furthermore the quantitative analysis shows the most and the less contributed to the occurrence of the top event.




This means that utmost care should be taken to prevent the occurrence of the most contribute sub-system failure. In this paper the most contribute sub-system is disabled Turbine, so it takes care to prevent the top event.

For the turbine sub system failure high probability of occurrence occurs in Guide vanes and less occurrence in spiral case and Excessive shaft vibrations.

For the generator sub system failure high probability of occurrence occurs in stator and less on exciter and rotor parts.

For turbine-generator sub systems failure probability of occurrence occurs in speed control and governing system greater than bearing failure.

Minimal cut seats and probability of occurrences of electromechanical components of hydropower plants shows below.

Fault Tree: Top		Fault Tree Node: Top		Search...	
	Minimal Cut Set	Order	Unavailability	Contribution ?	
1	B	1	0.0256776	0.462831	
2	C	1	0.0158806	0.286243	
3	D	1	0.0139212	0.250926	

During the execution of this analysis it is clear that regardless of the type of hydro generator analyzed, there are some critical subsystems for ensuring the operational required performance such as the speed governing system, oil cooling system in order to control the bearing lubricating oil temperature (and hence its viscosity) and the stator winding insulation. These subsystems should be the subject to constant attention from maintenance crews which, through application of preventive or predictive tasks, should reduce the probability of unexpected failures of those components.

From the results of the FTA analysis, the critical components or subsystems that can be submitted to predictive maintenance programs are defined, which is the main focus of the RCM philosophy.

Some simple measures can be used as techniques for monitoring the operating condition of the critical components of a hydro generator, such as

- Monitoring the oil temperature inside the bearing and in the speed governing system,
- Monitoring the temperature of the copper conductors in the stator bars,
- Monitoring the air temperature in the core of the generator,
- Monitoring the temperature of bearings pads,
- Checking for the presence of contaminants in the bearing lubricating oil and in the hydraulic unit of the speed governing system.

The monitoring of those data already enables verification of the occurrence of anomalies in the operating condition of hydro generator, and with the aid of the FTA tables may be used to identify possible causes of these anomalies and to predict the need for maintenance tasks before generating unit performance is reduced below a minimum value, requiring the implementation of corrective maintenance.

To calculate the reliability and availability of the generating unit it is necessary to model the reliability and maintainability of its various components. For both analysis a database is needed where the time between failure, repair time and the causes of failure associated to each corrective intervention executed on the component are recorded in a systematic manner.

Operating condition of hydro generator should be continuously recorded to correlate the occurrence of a component failure mode with its operating condition.

This FTA analysis allows the following conclusions:

- i) The system for monitoring the operating temperature of some components of this hydro generator is very well designed, allowing the evaluation of abnormalities which are indicative of the development of some component failure, supporting the application of predictive maintenance techniques;
- ii) The association of this temperature monitoring system database with the effects of component failures on the hydro generator operational performance, presented in the FTA analysis, may help in the process of defining the origin of any abnormal hydro generator operational condition;
- iii) The generator unit has its availability greatly affected by the number of hours employed in preventive tasks and by the required number of operational hours;
- iv) With the increase in efficiency of maintenance tasks, focusing on predictive and preventive activities associated with electromechanical cooling and lubrication systems with the philosophy of RCM, the availability of generating units is expected to increase, affecting the operational performance of the hydroelectric plant.

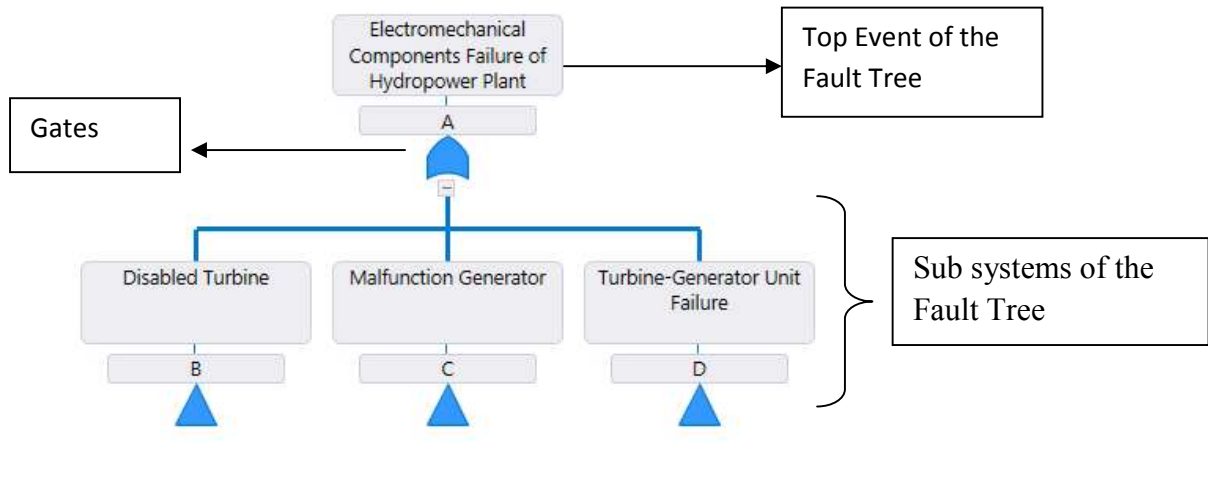
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Appendix 1:- Electromechanical components Failure of Hydropower plant FTA

Name	Type	Data	Description
▲ A	Or		Electromechanical Components Failure of Hydropower Plant
B	TransferIn	Link: B	Disabled Turbine
C	TransferIn	Link: C	Malfunction Generator
D	TransferIn	Link: D	Turbine-Generator Unit Failure



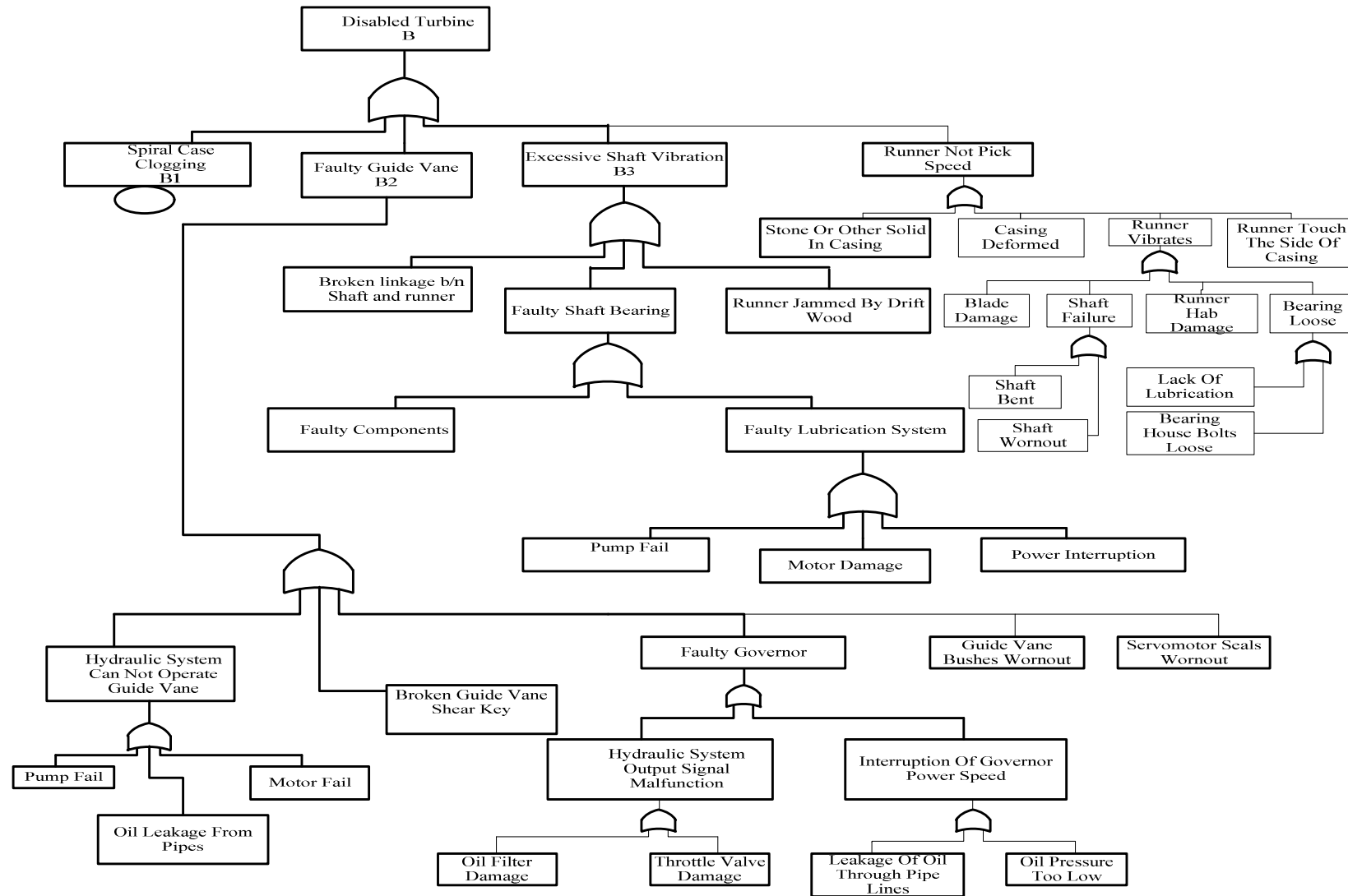
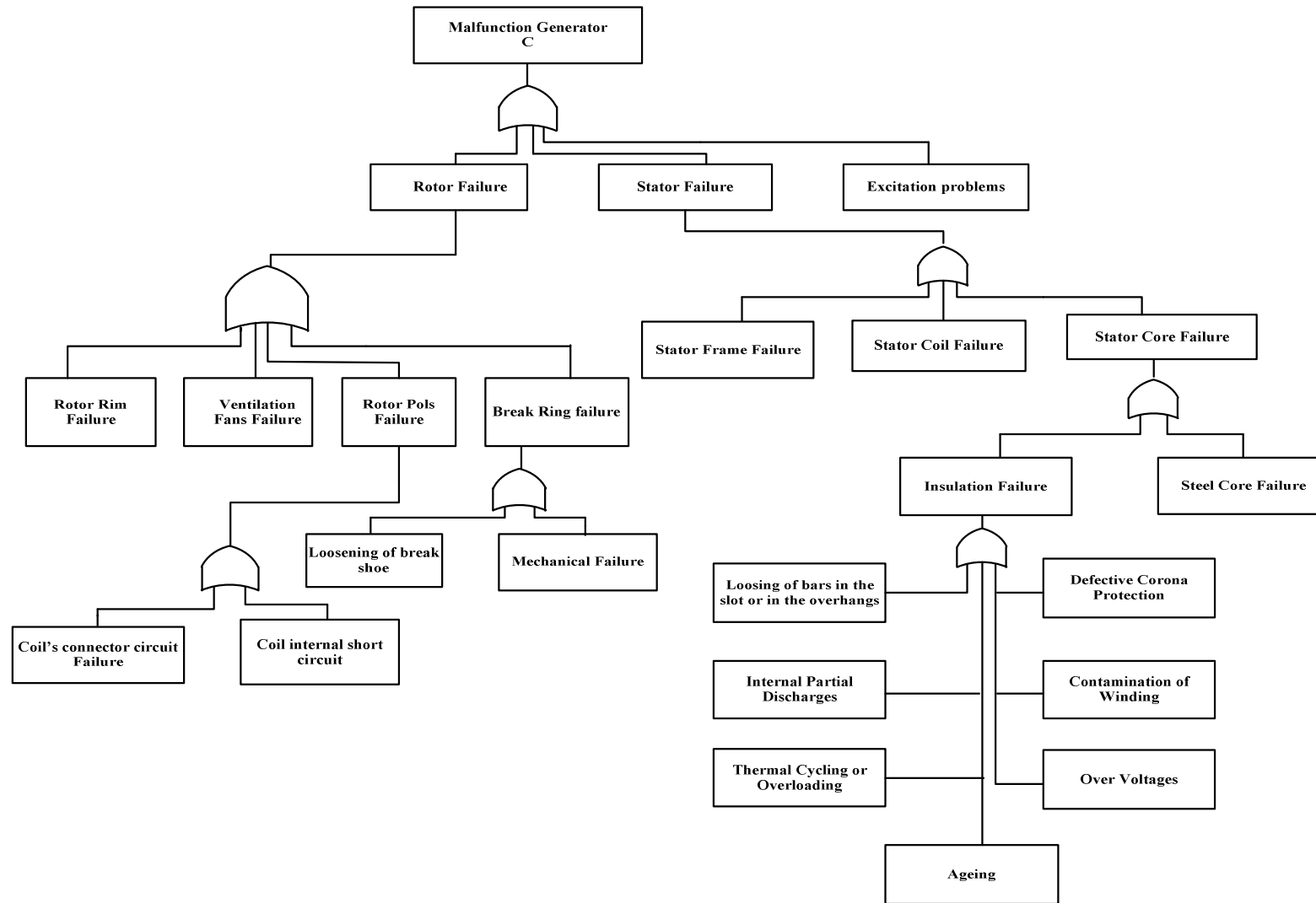
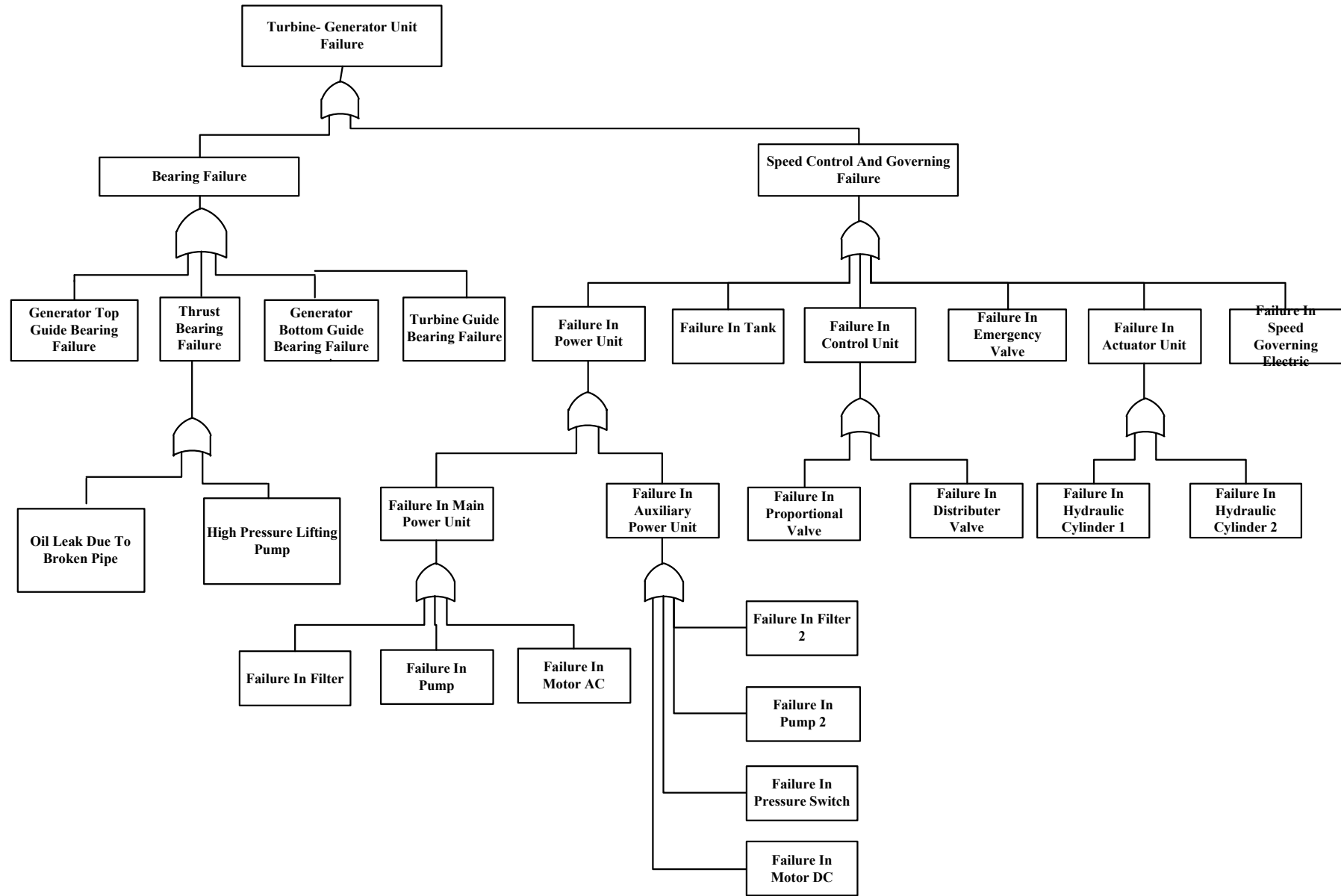


Fig.1; Turbine Fault Tree Analysis



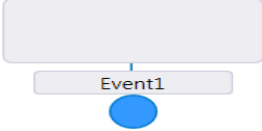
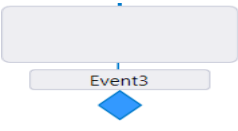
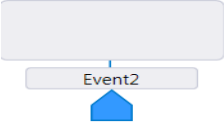
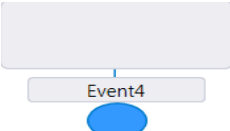










Appendix 2:- Standard for Probabilistic Risk Assessment

1. *Basic event*: an event in a fault tree model that requires no further development, because the appropriate limit of resolution has been reached.
2. *Component*: a basic event in a power transformer fault tree model.
3. *Common cause failure*: multiple component faults that occur at the same time or that occur in a relatively small time window and that are due to a common cause.
4. *Dependency* : requirement external to an item and upon which its function depends and is associated with dependent events that are determined by, influenced by, or correlated to other events or occurrences.
5. *Diagnosis*: examination and evaluation of data to determine either the condition of an structure, systems, components or the cause of the condition.
6. *Event tree*: a logic diagram that begins with an initiating event or condition and progresses through a series of branches that represents expected system or operator performance that either succeeds or fails and arrives at either a successful or failed end state.
7. *Failure*: an unacceptable deviation from the design tolerance or in the anticipated delivered service, an incorrect output, the incapacity to perform the desired function
8. *Fault*: a defect, imperfection, mistake or flaw of varying severity that occurs within some hardware or software component or system. “Fault” is a general term and can range from a minor defect to a failure.
9. *Fault realization or error*: the manifestation of a fault in a system or the information that is processed by the system or a manifestation in the internal system state.
10. *Failure probability*: the likelihood that structures, systems, and components fail to operate upon demand or fail to operate for a specific mission time.
11. *Failure rate*: expected number of failures per unit time, evaluated, for example, by the ratio of the number of failures in a population of components to the total time observed for that population
12. *Fault tree*: a deductive logic diagram that depicts how a particular undesired event can occur as a logical combination of other undesired events.
13. *Minimal cut set*: a smallest combination of basic events whose occurrence results in the occurrence of the top event of a fault tree.
14. *Permanent fault*: a fault with lasting effects. The failed component or system must be replaced.
15. *Safety system*: those systems that are designed to prevent or mitigate a design basis accident.

16. *“State of component” fault*: a fault of a component due to either the failure of the component or the failure of a command to the component.
17. *“State of system” fault*: a fault with a system-level effect and which is not necessarily localized at a given component.
18. *System*: a deterministic entity comprising an interacting collection of discrete elements.
19. *System failure*: termination of the ability of a system to perform any one of its critical design functions.
20. *Top event*: the initial event of a fault tree or success tree. Also it is called an undesired event in the case of a fault tree.
21. *Transient fault*: a fault of limited duration that causes no permanent hardware damage. Transient faults can be caused by excessive heat, power disruptions, timing issues or environmental influences, for example. It is often possible to recover from a transient fault without discarding the affected component or system.
22. *Unavailability*: the fraction of time that a system or component is no capable of supporting its function including, but not limited to, the time it is disabled for test or maintenance.
23. *Unreliability*: the probability that a system or component will not perform its specified function under given conditions upon demand or for a prescribed time.
24. *Undesired event*: the top event of the fault tree.

Appendix 3:- Symbols in Fault Tree

A. Primary Events Symbols	
	<p>BASIC EVENT- A basic event initiating fault requiring no further development</p>
	<p>UNDEVELOPMENT EVENT- AN event which is not further development either because it is of insufficient consequence or because information is unavailable</p>
	<p>HOUSE EVENT- An event which is normally expected to occur</p>
	<p>CONDITIONING EVENT- Specific conditions or restriction that apply to any logic gate (used primary with PRIORITY AND and INHIBIT gates)</p>
B. Gates Symbols	
	<p>AND- Output fault occurs the input faults occur</p>
	<p>OR- Output fault occurs if atleast one of the input faults occur</p>
	<p>COMBINATION-Output fault occurs if n of the input faults occur</p>
	<p>EXCLUSIVE OR- Output fault occurs if exactly one of the input faults occur</p>
	<p>PRIORITY AND- Outp urs if all of the input faults occur in a specific sequence (the sequence represented by a conditioning event drawn to the right of the gate)</p>
	<p>INHIBIT- output fault occurs if the (single) input fault occurs in the presence of enabling condition (The enabling condition is represented by a</p>

	CONDITION EVENT drawn to the right of the gate)
C. Transfer Symbols	
	TRANSFER IN- is developed further at the occurrence of the corresponding TRANSFER OUT (e.g., on another page)
	TRANSFER OUT- Indicates that this portion of the tree must be attached at the corresponding TRANSFER IN

Appendix 4:- Outage of Gilgel Gibe II hydropower plants with unit generator

Month	Power Plant	Unit No.	Problem	type PO/ FO/ MO	Date	TRIP TIME	CONNECTED TIME	Duration	Load(MW) before tripped	Cause of Interruption	Action taken
UG-1											
Hamle	Gilgel Gibe II	1	Stopped	FO	12/11/2007	22:27:00	24:00:00	1:33:00		Due to Primary cooling pump-2 fault.	Not Restored.
Tahisas	Gilgel Gibe II	1	Tripped	FO	15/04/2008	15:36:00	17:29:00	1:53:00		Due to oil leakage on locking device.	Restored.
Miazia	Gilegl Gibe II	1	Tripped	FO	06/08/2008	14:33	16:21	1:48:00	70	Due to oil temperature sensor collapsed.	Restored.
Miazia	Gilegl Gibe II	1	Tripped	FO	06/08/2008	20:42	24:00:00	3:18:00	80	Due to Excitation problem.	Not Restored.
Miazia	Gilegl Gibe II	1	Tripped	FO	07/08/2008	00:00	16:00	16:00:00	80	Due to turbine Bearing oil level low trip.	Not Restored.
Miazia	Gilegl Gibe II	1	Stopped	FO	18/08/2008	19:36	24:00:00	4:24:00		Due to turbine Bearing oil level low trip.	Not Restored.
Miazia	Gilegl Gibe II	1	Stopped	FO	19/08/2008	00:00	24:00:00	24:00:00		Governor tripping contact.	Not Restored.
Miazia	Gilegl Gibe II	1	Stopped	FO	20/08/2008	00:00	14:33	14:33:00		Due to turbine guide bearing sump oil level too low.	Restored.
UG-2											
Hamle	Gilgel Gibe II	2	Stopped	FO	14/11/2007	18:09	20:28:00	2:19:00		Due to Primary cooling pump-2 fault.	Restored.
Hamle	Gilgel Gibe II	2	Stopped	FO	14/11/2007	22:23	24:00:00	1:37:00		Due to thrust bearing too high temperature.	Not Restored.
Hamle	Gilgel Gibe II	2	Tripped	FO	24/11/2007	19:16	23:00	3:44:00	95	Due to main Shaft seal water supply failure & Governor channel-A failure.	Restored.
Nehase	Gilgel Gibe II	2	Stopped	FO	30/12/2007	00:07	10:17	10:10:00		Generator hot air temperature high RTD40.	Restored.
Meskerem	Gilgel Gibe II	2	Stopped	FO	02/01/2008	11:19	17:11	5:52:00		Due to Shaft seal flow low.	Restored
Meskerem	Gilgel Gibe II	2	Stopped	FO	04/01/2008	00:12	10:04	9:52:00		Due to TGB oil level low.	Restored

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Yekatit	Gilegl Gibe II	2	Tripped	FO	25/06/2008	09:05	17:48	08:43	65	Due to thrust bearing too high temperature.	Not Restored.
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UG-3

Megabit	Gilegl Gibe II	3	Tripped	FO	20/07/2008	18:42	24:00:00	05:18	40	Due to turbine protection circuit mechanical trip relay active.	Not Restored.
Megabit	Gilegl Gibe II	3	Tripped	FO	21/07/2008	00:00	16:18:00	16:18:00	40	Due to upper guide bearing oil level too low.	Not Restored.
Megabit	Gilegl Gibe II	3	Tripped	FO	21/07/2008	21:06	24:00:00	2:54:00	70	Due to thrust bearing too high temperature.	Not Restored.

UG-4

Hamle	Gilgel Gibe II	4	Stopped	FO	28/11/2007	23:29	24:00:00	0:31:00		VIBRATION	Not Restored.
Hamle	Gilgel Gibe II	4	Stopped	FO	29/11/2007	00:00	24:00:00	24:00:00		Due to Shaft seal flow low.	Not Restored.
Hamle	Gilgel Gibe II	4	Stopped	FO	30/11/2007	00:00	10:40	10:40:00		Due to guide vane faults	Restored.
Nehase	Gilgel Gibe II	4	Stopped	FO	01/12/2007	00:30	7:18:00	6:48:00		VIBRATION	Restored.
Meskerem	Gilgel Gibe II	4	Stopped	FO	01/01/2008	03:07	11:16	8:09:00		Due to the failure of Unit-4 primary cooling pump 1 .	Restored
Tahisas	Gilgel Gibe II	4	Tripped	FO	12/04/2008	18:37:00	24:00:00	5:23:00	35(280)	Due to turbine guide bearing sump oil level too low.	Restored.
Tahisas	Gilgel Gibe II	4	Tripped	FO	28/04/2008	07:29:00	9:35:00	2:06:00	65	Due to TGB oil level low.	Not Restored.
Tir	Gilgel Gibe II	4	Tripped	FO	06/05/2008	10:25:00	24:00:00	13:35:00	90	Due to thrust bearing too high temperature.	Not Restored.
Tir	Gilgel Gibe II	4	Tripped	FO	07/05/2008	00:00:00	15:17:00	15:17:00	90	Due to thrust bearing too high temperature.	Restored.
Yekatit	Gilegl Gibe II	4	Tripped	FO	22/06/2008	19:34	21:57:00	02:23	80	Due to TGB oil level low.	Restored.
Megabit	Gilegl Gibe II	4	Stopped	FO	26/07/2008	23:54	24:00:00	0:06:00	20	Due to governor oil pressure too low.	Not Restored.
Megabit	Gilegl Gibe II	4	Stopped	FO	27/07/2008	00:00	6:07:00	6:07:00	20	Due to main Shaft seal water supply failure & Governor channel-A failure.	Restored

Gilgel gibe III hydropower plant

