System Reliability and Fault Tree Analysis of a steam-electric power station. Case study: Steam power system in Xylokamara, Chania, Greece

Αξιοπιστία συστήματος και ανάλυση σφάλματος με δένδρο αποφάσεων ατμοηλεκτρικού σταθμού παραγωγής ηλεκτρικής ενέργειας. Αντικείμενο μελέτης: ΑΗΣ Χανίων.

by

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Abstract

The Greek island of Crete contains an independent electrical network. The already high demand of power and energy is continuously growing for the island. This has led to the decision of interconnecting Crete with Greece's mainland. This will result to almost the total energy demand of the island coming through the interline cable and power plants in Crete will be out of order. In case of emergency though, some energy production units of Crete have to be on standby. One of those stand by production units is the ABB GT8 45MW gas turbine of the combined cycle of Xylokamara power plant in Chania city, which is the case study of this thesis.

The specific unit is chosen for the study because is a quite big and fast loading machine with perfect correspondence to frequency variations but with one disadvantage. The directive 2010/75/EU on industrial emissions does not allow this gas turbine to exceed the 70% of its nominal load. To deviate this restriction some expensive investments should be done and the final decision for that is depended on the reliability of this unit. In the present Thesis is analyzed whether this specific ABB gas turbine will be able to be efficient and reliable in case of the emergency.

Our analysis includes i) Fault Tree Analysis in order to allow us to construct and analyze fault tree diagrams, ii) Event Tree Analysis in order to allow us to analyze the possible outcomes of an event occurring and iii) Weibull Analysis in order to enable the construction of Weibull models for the component. The program used for the fault tree analysis is the commercial Isograph reliability workbench, suitable for safety analyses according to ISO26262. The data used are obtained from real world sources: the company's records and the official technical specifications for operation, maintenance and troubleshooting.

Περίληψη

Το νησί της Κρήτης στην Ελλάδα διατρέχεται από ένα ανεξάρτητο ηλεκτρικό δίκτυο. Η ήδη υψηλή ζήτηση ισχύος και ενέργειας από το νησί διαρκώς αυξάνεται. Αυτό οδήγησε στην απόφαση της ηλεκτρικής διασύνδεσης της Κρήτης με την ηπειρωτική Ελλάδα. Αποτέλεσμα αυτού θα είναι το σύνολο σχεδόν της ενεργειακής ζήτησης του νησιού να προέρχεται από την ηπειρωτική Ελλάδα μέσω του καλωδίου διασύνδεσης, και οι μονάδες παραγωγής ηλεκτρικής ενέργειας της Κρήτης να τεθούν εκτός λειτουργίας. Ωστόσο σε περίπτωση έκτακτης ανάγκης ορισμένες από αυτές τις μονάδες πρέπει να βρίσκονται σε επιφυλακή/ετοιμότητα. Μία από αυτές τις μονάδες είναι και ο αεριοστρόβιλος ABB GT8 45MW του συνδυασμένου κύκλου στο σταθμό της Ξυλοκαμάρας που βρίσκεται στην πόλη των Χανιών και αποτελεί το αντικείμενο της μελέτης της συγκεκριμένης διπλωματικής εργασίας.

Η συγκεκριμένη μονάδα επελέγη για τη μελέτη καθώς είναι αρκετά μεγάλη, αναλαμβάνει γρήγορα φορτίο και έχει τέλεια ανταπόκριση στις μεταβολές συχνότητας του δικτύου. Ωστόσο παρουσιάζει και ένα μειονέκτημα. Σύμφωνα με την οδηγία 2010/75/EU αναφορικά με της εκπομπές αερίων του θερμοκηπίου σε βιομηχανικές εγκαταστάσεις, δεν επιτρέπεται η συγκεκριμένη μονάδα να υπερβαίνει το 70% του ονομαστικού της φορτίου καθώς δεν είναι συμμορφωμένη με τα επιτρεπόμενα όρια εκπομπής ρίπων. Προκειμένου να παρακαμφθεί αυτός ο περιορισμός, πρέπει να γίνουν ορισμένες δαπανηρές επενδύσεις η τελική απόφαση για τις οποίες εξαρτάται κατά πολύ από της αξιοπιστία της μονάδας. Στην παρούσα μελέτη αναλύεται κατά πόσο η συγκεκριμένη μονάδα της ABB μπορεί να ανταπεξέλθει αξιόπιστα και ικανοποιητικά σε περίπτωση έκτακτης ανάγκης.

Η ανάλυσή μας περιλαμβάνει i) Ανάλυση Δένδρου Λαθών (Fault Tree Analysis) με σκοπό να μας επιτρέψει να κατασκευάσουμε και να αναλύσουμε Διαγράμματα Δένδρων Λαθών (Fault Tree Diagrams), ii) Ανάλυση Δένδρου Γεγονότων (Event Tree Analysis) με σκοπό να μας επιτρέψει να αναλύσουμε τα πιθανά αποτελέσματα ενός γεγονότος και iii) Ανάλυση Weibull (Weibull Analysis) με σκοπό να μας επιτρέψει την κατασκευή μοντέλων Weibull για τα στοιχεία του συστήματος. Το πρόγραμμα που χρησιμοποιήθηκε για την ανάλυση είναι το Isograph Reliability Workbench, ένα πρόγραμμα κατάλληλο για αναλύσεις ασφαλείας με βάση το πρότυπο ISO 26262. Τα δεδομένα της μελέτης μας, έχουν αντληθεί από αξιόπιστες πηγές όπως είναι: τα αρχεία της εταιρίας και οι επίσημες τεχνικές προδιαγραφές για τη λειτουργία, τη συντήρηση και την αντιμετώπιση τυχόν προβλημάτων.

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Table of Contents

List of Figures

List of Tables

1.Introduction

1.1 Background

Up to now the electrical grid of the island of Crete is independent, fed by three conventional power stations in Xylokamara Chania, Linoperamata Heraclion, Atherinolakkos Lasithi of 750 MW total. In parallel, there are 200 MW of wind generators and 100 MW coming from solar panels, which support the demand as much as the stability of the grid allows. The summer instant peak of power demand rises up to 700 MW and the annual consumption of energy is 3100 GWh. The demand of power and energy is continuously growing. At the same time the use of renewable energy sources is restricted due to network stability (renewable sources up to 40% of the power production). This has led to the decision of interconnection between Crete and the mainland of Greece. The advantage of this interconnection is that Crete will now belong to Europe network, a bigger and more stable network. This will lead to no restrictions on the renewable energy sources, while the incoming power via the interline cable will be produced more efficiently than that from the power plants of the island.

It is expected that this interconnection will result, almost the total energy production units of the island, to be disabled.

However, in case of emergency (e.g. cable failure, military purposes), some energy production units will have to be on standby to cover the increasingly need of power of the island. One of those energy production units could be the ABB combined cycle unit 134 MW consisting of two GT8 45MW gas-turbines and one V63 44MW steam-turbine, in Chania.

On the 1/1/2020 is applied in Greece, the directive 2010/75/EU of November 2010 on industrial emissions. This directive does not allow the combined cycle units to exceed the 70% of their load because of the inability from compliance with the emission limits of the gas of the Greenhouse effect.

Specifically, the limit for the NO_x is 90mg per N m^3 of the exhaust gasses while the exhaust of the gas-turbines of the combined cycle cannot contain less than 220 mg NO_x.

The combined cycle units have a high-performance level, that can remain high in a wide range of their load. This can make the combined cycle one of the energy production units that would be kept in reserve. However, in order for the combined cycle units to be kept in reserve there has to be compliance with the exhaust limit of the directive 2010/75/EU. This can be performed in two ways.

The first way is to convert the diesel oil fuel that is used, into natural gas. In order for this to happen there has to be found a way of transporting and storage of the natural gas. This is something very expensive and at the same time challenging since Crete, as a tourist attraction destination, is not allowing industrial facilities.

The second way is to inject water in the combustion chambers of the gas turbines during the operating hours, which is reducing the NO_x content in the exhaust gasses. The water injection system already exists in the gas turbine, however, it does not achieve the demanding limit of the 90 mg per m^3 , according to the 2010/75/EU. The Public Power Corporation S.A.-Hellas has turned to the manufacturer company of the gas turbines, ABB, for the design and implementation of new water infusion system for the combustion chambers of the gas turbines, that succeeds less emissions of the demanding limit. The cost for this implementation reached the amount of 4000000€.

The question to be answered is if this particular power production unit has the demanding reliability to deliver in case of an emergency moment that will be in need of it to operate and if the cost for these two investments is worth it.

1.2 Objective

The main goal of this thesis is to analyze the reliability of one of the gas-turbines of the ABB combined cycle.

This thesis is intended to identify the significance of the sub-systems of the gas-turbine and how even the slight faults in the components can set the gas turbine out of order. Thus, specifying the main components and their possibilities of failure is also a target of this thesis. This will be done by the Fault Tree Analysis method. Accordingly, the gas turbine system will be considered from a technical point of view to analyze the different sub-systems and components. This aims to determine the various failure modes and effects of those components, and analysis will reveal the root causes of the system failure. In addition, this study shall evaluate and assess the risk of this diesel engine failure.

This will provide a helpful foundation for the decision-making for the investments.

1.3 Methodology and Structure of the Thesis

In order to learn and study this object information had to be provided from the power plant station. Handbooks and manuals according the specific gas turbine were provided. To understand and learn every single component of the gas turbine, it was important to study the handbook of the sensors for various measurements according the gas-turbine. In order for this to happen, the first step was to read the KKS.

Due to the size of power plants and the fact that large number of parties participating are all in different locations, communication problems arise which can incur costs which cannot be estimated in advance. For that reason, the planners and operators of power stations employ a common, standard system for identifying installations and parts thereof, with which the data required to plan, construct and operate power stations can be collected and processed. This publication reviews the origin developments and application of the Power Station Designation System KKS.

As you will see in the second chapter of this thesis, the other very important part was to learn about the system analysis. Analytical methods were studied, such as Fault Tree Analysis, Markov Analysis and Weibull Analysis. The method used in this project was Fault Tree Analysis (FTA).

Fault Tree Analysis can analyze the combinations of events that can lead to a hazard and the range of possible outcomes of an initiative event. Fault Tree diagram represent the logical relationship between subsystems and component failures and how they combine to system failures. The top event of a Fault Tree represents the system of interest, in this case the failure of the gas turbine, and it is connected by logical gates to component failures known as basic events, in this case the faults happened or may happen on the gas turbine. After creating the diagram, failure and repair data is assigned to the components. The analysis is then performed to calculate reliability and availability, to calculate the parameters for the system and to identify critical components.

To perform the FTA analysis, historical data were obtained from the power station according the faults and failures of this specific gas turbine. Those faults were then applied on the Fault Tree diagram using the Weibull method, a method used when failures vary with time.

2. Theoretical background of System Analysis

2.1 Basic Concepts of System Analysis, The Purpose of System Analysis

System Analysis is a process of collecting and interpreting facts, identifying the problems, and decomposition of a system into its components.

System analysis is conducted for the purpose of studying a system or its parts in order to identify its objectives. It is a problem-solving technique that improves the system and ensures that all the components of the system work efficiently to accomplish their purpose.

Analysis specifies what the system should do.

The word System is derived from Greek word "Systema", which means an organized relationship between any set of components to achieve some common cause or objective.

A system is "an orderly grouping of interdependent components linked together according to a plan to achieve a specific goal." [1]

A system must have three basic constraints:

- A system must have some **structure and behavior** which is designed to achieve a predefined objective.
- **Interconnectivity** and **interdependence** must exist among the system components.
- The **objectives of the organization** have a **higher priority** than the objectives of its subsystems.

Types of Systems:

The systems can be divided into the following types:

- Physical or Abstract Systems
- Open or Closed Systems
- Adaptive and Non-Adaptive System
- Permanent or Temporary System
- Natural and Manufactured System
- Deterministic or Probabilistic System
- Social, Human-Machine, Machine System
- Man–Made Information Systems

2.1.1 Overview of inductive Methods

- **Failure mode and effects analysis (FMEA)** is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service. It is a common process analysis tool.

  "Failure mode" means the ways, or modes, in which something might fail. Failures are any errors or defects, especially ones that affect the customer, and can be potential or actual.

  "Effects analysis" refers to studying the consequences of those failures.

  Failures are prioritized according to how serious their consequences are, how frequently they occur, and how easily they can be detected. The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones.

  Failure modes and effects analysis also documents current knowledge and actions about the risks of failures, for use in continuous improvement. FMEA is used during design to prevent failures. Later it's used for control, before and during ongoing operation of the process. Ideally, FMEA begins during the earliest conceptual stages of design and continues throughout the life of the product or service. [2]

- **Failure Mode Effect and Criticality Analysis (FMECA)** is a method which involves quantitative failure analysis. The FMECA involves creating a series of linkages between potential failures (Failure Modes), the impact on the mission (Effects) and the causes of the failure (Causes and Mechanisms).

  FMECA is a bottom-up (Hardware) or top-down (Functional) approach to risk assessment. It is inductive, or data-driven, linking elements of a failure chain as follows: Effect of Failure, Failure Mode and Causes/Mechanisms.

  The intent of the Failure Mode, Effects & Criticality Analysis methodology is to increase knowledge of risk and prevent failure. [3]

  The tangible benefits of FMECA are offered in the following categories:

  - Design and development benefits
  - operation benefits
  - cost benefits

- **The preliminary hazard analysis (PHA)** technique is a broad, initial study used in the early stages of system design. It focuses on (1) identifying apparent hazards, (2) assessing the severity of potential accidents that could occur involving the hazards, and (3) identifying safeguards for reducing the risks associated with the hazards. This technique focuses on identifying weaknesses early in the life of a system, thus saving time and money that might be required for major redesign if the hazards were discovered at a later date. [4]

- **The Fault Hazard Analysis (FHA)**, also referred to as the Functional Hazard Analysis, method follows an inductive reasoning approach to problem solving in that the analysis concentrates primarily on the specific and moves toward the general. The

FHA is an expansion of Failure Mode and Effect Analysis (FMEA). In fact, when an FMEA has already been completed for a given system and information on the adverse safety effect of component or human failures is desired for that system, the safety engineer can often utilize the data from the FMEA as an input to the FHA. The FHA process begins with the establishment of a list of system or subsystem functions. An automobile brake system will be examined using the fault hazard analysis method to determine potential faults in the systems current design. The FHA is an excellent system safety engineering method which can be used to ensure system operational integrity. [5]

2.1.2 Failures vs success models

The operation of a system can be considered from two standpoints: we can enumerate various ways for system success, or we can enumerate various ways for system failure.

"Success" tends to be associated with the efficiency of a system, the amount of output, the degree of usefulness, and production and marketing features. These characteristics are describable by continuous variables which are not easily modeled in terms of simple discrete events, such as "valve does not open" which characterizes the failure space (partial failures, i.e., a valve opens partially, are also difficult events to model because of their continuous possibilities). Thus, the event "failure," in particular, "complete failure," is generally easy to define, whereas the event, "success," may be much more difficult to tie down. This fact makes the use of failure space in analysis much more valuable than the use of success space.

Another point in favor of the use of failure space is that, although theoretically the number of ways in which a system can fail and the number of ways in which a system can ·succeed are both infinite, from a practical standpoint there are generally more ways to success than there are to failure. Thus, purely from a practical point of view, the size of the population in failure space is less than the size of the population in success space. In analysis, therefore, it is generally more efficient to make calculations on the basis of failure space.

2.1.3 Failure rate prediction, Failure types

[6] As a definition, prediction is a statement about what will happen or might happen in the future. A failure means “an occurrence that happens when the delivered service gets out from correct service.” Failure prediction is about evaluation the risk of failure for some times in the future. Analysis of error events that have occurred in the system can be called failure prediction. To compute breakdown probabilities, not only one point of time in the future, but a time interval called prediction interval are considered, simultaneously.

The majority of industrial systems have a high level of complexity, nevertheless, in many cases, they can be repaired. Systems reliability often relies on their age, intrinsic factors (dimensioning, components quality, material, etc.) and use conditions (environment, load rate, stress, etc.). The parameter defining a machine's reliability is the failure rate (λ), and this value is the characteristic of breakdown occurrence frequency. In this context, failure rate analysis constitutes a strategic method for integrating reliability, availability and maintainability, by using methods, tools and engineering techniques to identify and quantify equipment and system failures that prevent the achievement of its objectives.

Let us define common words related to failure rate, as follow:

- <u>Failure:</u> A failure occurs when a component is not available. The cause of components failure is different; they may fail due to have been randomly chosen and marked as fail to assess their effect, or they may fail because any other component that were depending on else has brake down. In reliability engineering, a Failure is considered to event when a component/system is not doing its favorable performance and considered as being unavailable.
- <u>Error</u>: In reliability engineering, an error is said a misdeed which is the root cause of a failure.
- <u>Fault</u>: In reliability engineering, a fault is defined as a malfunction which is the root cause of an error. But within this chapter, we may refer to a component failure as a fault that may be conducted to the system failure. This is done where there is a risk of obscurity between a failure which is occurring in intermediate levels (referred to as a Fault) and one which is occurring finally (referred to as Failure).

The reliability of a machine is its probability to perform its function within a defined period with certain restrictions under certain conditions. The reliability is the proportional expression of a machine's operational availability; therefore, it can be defined as the period when a machine can operate without any breakdowns. The equipment reliability depends to failures frequency, which is expressed by MTBF[1]. Reliability predictions are based on failure rates. Failure intensity or λ(t)[2] can be defined as "the foretasted number of times an item will break down in a determined time period, given that it was as good as new at time zero and is functioning at time t". This computed value provides a measurement of reliability for an equipment. This value is currently described as failures per million hours (f/mh). As an example, a component with a failure rate of 10 fpmh would be anticipated to fail 10 times for 1 million hours time period. The calculations of failure rate are based on complex models which include factors using specific component data such as stress, environment and temperature. In the prediction model, assembled components are organized serially. Thus, failure rates for assemblies are calculated by sum of the individual failure rates for components within the assembly.

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[1] Mean time between failures
[2] Conditional failure rate

Failures generally be grouped into three basic types, though there may be more than one cause for a particular case. The three types included: early failures, random failures and wear-out failures. In the early life stage, failures as infant mortality often due to defects that escape the manufacturing process. In general, when the defective parts fail leaving a group of defect free products, the number of failures caused by manufacture problems decrease. Consequently, the early stage failure rate decreases with age. During the useful life, failures may be related to freak accidents and mishandling that subject the product to unexpected stress conditions. Suppose the failure rate over the useful life is generally very low and constant. As the equipment reaches to the wear-out stage, the degradation of equipment is related to repetitious or constant stress conditions. The failure rate during the wear-out stage increases dramatically as more and more occurs failure in equipment that caused by wear-out failures.

The most common ways that failure rate data can be obtained as following:

- Historical data about the device or system under consideration: Many organizations register the failure information of the equipment or systems that they produce, in which calculation of failure rates can be used for those devices or systems. For equipment or systems that produce recently, the historical data of similar equipment or systems can serve as a useful estimate.
- Government and commercial failure rate data: The available handbooks of failure rate data for various equipment can be obtained from government and commercial sources. MIL-HDBK-217F, reliability prediction of electrical equipment, is a military standard that provides failure rate data for many military electronic components. Several failure rate data sources are available commercially that focus on commercial components, including some non-electronic components.
- Testing: The most accurate source of data is to test samples of the actual devices or systems in order to generate failure data. This is often prohibitively expensive or impractical, so that the previous data sources are often used instead.

The different types of failure distribution are provided in Table 1. For an exponential failure distribution, the hazard rate is a constant with respect to time (that is, the distribution is “memoryless”). For other distributions, such as a Weibull distribution or a log-normal distribution, the hazard function is not constant with respect to time. For some such as the deterministic distribution it is monotonic increasing (analogous to “wearing out”), for others such as the Pareto distribution it is monotonic decreasing (analogous to “burning in”), while for many it is not monotonic.

Distributions			
Discrete		Continuous	
Binomial	covered	normal	covered
Poison	covered	exponential	covered
Multinomial	Beyond the scope	lognormal	covered
		Weibull	covered
		Extreme value	Beyond the scope

Table 1 Failure distribution types

2.2 Fault Tree Analysis

For fast technology innovation, the developments of new products are becoming much complicated not only due to its system functioning but also because of its system components. Therefore, the system reliability analysis is an important issue for academic research and practice. In the beginning, the idea of reliability of a system or a machine or a person was based on theoretical discussions. Later on, a mathematical shape was given to the concept of reliability of a system. The mathematical development of reliability gave thrust to many ideas in the field of electrical, mechanical and electronics engineering and allied industries. Fault tree analysis (FTA) is a powerful diagnosis technique and is widely used for demonstrating the root causes of undesired event in system failure. The concept of fault tree analysis was developed by Bell telephone laboratory in 1961. It is widely used in many fields such as in nuclear reactors, chemical and aviation industries. [7]

2.2.1 What is fault tree diagram

Fault tree diagrams (or negative analytical trees) are logic block diagrams that display the state of a system (top event) in terms of the states of its components (basic events). Fault tree diagrams are a graphical design technique.

An FTD is built top-down and in term of events rather than blocks. It uses a graphic "model" of the pathways within a system that can lead to a foreseeable, undesirable loss event (or a failure). The pathways connect contributory events and conditions, using standard logic symbols (AND, OR, etc.). The basic constructs in a fault tree diagram are gates and events. [8]

2.2.2 The basic elements of a Fault tree

The Fault tree mainly consists of the following elements:

- Specific stepwise logic is applied in the process.
- Specific logic symbols are used to illustrate the event relationships.
- A logic diagram is constructed showing the event relationships.

Gates and fault events constitute the building blocks of a fault tree. The gates in a fault tree are the logic symbols that interconnect contributory events and conditions. Fault trees use several graphical block representations, as shown below:

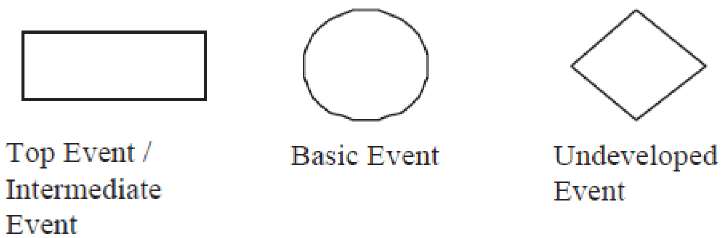


Figure 1: Basic components of a Fault tree

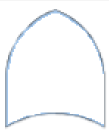
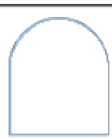
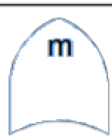
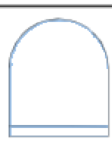
	OR	TRUE if any input is TRUE	≥2
	AND	TRUE if all inputs are TRUE	≥2
	VOTE	TRUE if *m* inputs are TRUE	≥3
	PRIORITY AND	TRUE if inputs occur in left to right order	≥2

Figure 2 Gates used in a fault tree

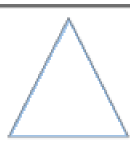
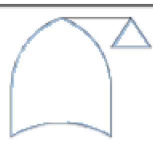
	Transfer In	Inputs appear elsewhere on same page or on another page
	Transfer Out	Output appears elsewhere on same page or on another page

Figure 3 Transfer in-Transfer out

a) **Top Event:** An undesired state of a system caused by an event occurring within the system. Top event is represented by rectangle.
b) **Intermediate Event:** An intermediate event is a fault event which occurs from a combination of other events via logic gates. Intermediate event is also represented by rectangle.
c) **Basic Event:** The circle describes a basic initiating fault event that requires no further development. In other words, it signifies that the appropriate limit of resolution has been reached.
d) **Undeveloped Event:** An event which is not further developed either because it is of insufficient consequence or because information is unavailable.
e) **OR Gate:** Output fault occurs if at least one of the input faults occurs.
f) **AND Gate:** Output fault occurs if all of the input faults occur.

2.2.3 Fault Tree Construction Fundamentals

2.2.3.1 Fault vs Failure

We first make a distinction between the rather specific word "failure" and the more general word "fault." Consider a relay. If the relay closes properly when a voltage is impressed across its terminals, we call this a relay "success." If, however, the relay fails to close under these circumstances, we call this a relay "failure." Another possibility is that the relay closes at the wrong time due to the improper functioning of some upstream component. This is clearly not a relay failure; however, untimely relay operation may well cause the entire circuit to enter an unsatisfactory state. We shall call an occurrence like this a "fault" so that, generally speaking, all failures are faults but not all faults are failures. Failures are basic abnormal occurrences, whereas faults are "higher order" events.

The proper definition of a fault requires a specification of not only what the undesirable component state is but also when it occurs. These ''what" and ''when" specifications should be part of the event descriptions which are entered into the fault tree. [9]

2.2.3.2 Fault Occurrence vs. Fault Existence

A fault may be repairable or not, depending on the nature of the system. Under conditions of no repair, a fault that occurs will continue to exist. In a repairable system a distinction must be made between the occurrence of a fault and its existence. Actually, this distinction is of importance only in fault tree quantification. [9]

2.2.3.3 Passive vs. Active Components

In most cases it is convenient to separate components into two types: passive and active (also called quasi-static and dynamic). A passive component contributes in a more or less static manner to the functioning of the system. Such a component may act as a transmitter of energy from place to place (e.g., a wire or bus-bar carrying current or a steam line transmitting heat energy), or it may act as a transmitter of loads (e.g., a structural member). To assess the operation of a passive component, we perform such tests as stress analysis, heat transfer studies, etc. Further examples of passive components are: pipes, bearings, journals, welds, and so forth. An active component contributes in a more dynamic manner to the functioning of its parent system by modifying system behavior in some way. A valve which opens and closes, for example, modifies the system's fluid flow, and a switch has a similar effect on the current in an electrical circuit. To assess the operation of an active component, we perform parametric studies of operating characteristics and studies of functional interrelationships. Examples of active components are: relays, resistors, pumps, and so forth. A passive component can be considered as the transmitter of a "signal." The physical nature of this "signal" may exhibit considerable variety; for example, it may be a current or force. A passive component may also be thought of as the "mechanism" (e.g., a wire) whereby the output of one active component becomes the input to a second active component. The failure of a passive component will result in the non-transmission (or, perhaps, partial transmission) of its "signal." In contrast, an active component originates or modifies a signal. Generally, such a component requires an input signal or trigger for its output signal. In such cases the active component acts as a "transfer function," a term widely used in electrical and mathematical studies. If an active component falls, there may be no output signal or there may be an incorrect output signal.

From a numerical reliability standpoint, the important difference between failures of active components and failures of passive components is the difference in failure rate values. Active component failures in general have failure rates above 1×10^{-4} per demand (or above 3×10^{-7} per hour) and passive component failures in general have failure rates below these values. In fact, the difference in reliability between the two types of components is, quite commonly, two to three orders of magnitude. In the above, the definitions of active components and passive components apply to the main function performed by the component; and failures of the active component (or failures of the passive component) apply to the failure of that main function. [9]

2.2.3.4 Component Fault Categories: Primary, Secondary, and Command

Faults are classified into three categories: primary, secondary and command. A primary fault is any fault of a component that occurs in an environment for which the component is qualified; e.g., a pressure tank, designed to withstand pressures up to and including a pressure Po, ruptures at some pressure $p \le p_0$ because of a defective weld. A secondary fault is any fault of a component that occurs in an environment for which it has not been qualified. In other words, the component fails in a situation which exceeds the conditions for which it was designed; e.g., a pressure tank, designed to withstand pressure up to and including a pressure p_0, ruptures under a pressure $p > p_0$. Because primary and secondary faults are generally component failures, they are usually called primary and secondary failures. A command fault in contrast, involves the proper operation of a component but at the wrong time or in the wrong place; e.g., an arming device in a warhead train closes too soon because of a premature or otherwise erroneous signal origination from some upstream device. [9]

2.2.3.5 Failure Mechanism, Failure Mode, and Failure Effect

The definitions of system, subsystem, and component are relative, and depend upon the context of the analysis. We may say that a "system" is the overall structure being considered, which in turn consists of subordinate structures called "subsystems," which in turn are made up of basic building blocks called "components."

In constructing a fault tree, the basic concepts of failure effects, failure modes, and failure mechanisms are important in determining the proper interrelationships among the events. When we speak of failure effects, we are concerned about why the particular failure is of interest, i.e., what are its effects (if any) on the system. When we detail the failure modes, we are specifying exactly what aspects of component failure are of concern. When we list failure mechanisms, we are considering how a particular failure mode can occur and also, perhaps, what are the corresponding likelihoods of occurrence. Thus, failure mechanisms produce failure modes which, in turn, have certain effects on system operation. [9]

2.2.4 Probability Theory-The Mathematical Description of Events

The basic mathematical technique involved in the quantitative assessment of fault trees is: probability theory. Probability theory is basic to fault tree analysis because it provides an analytical treatment of events, and events are the fundamental components of fault trees. The topics of probability theory which we shall consider include the concepts of outcome collections and relative frequencies, the algebra of probabilities, combinatorial analysis, and some set theory. [9]

2.2.5 Boolean algebra and application to Fault Tree Analysis

Boolean algebra is especially important in situations involving a dichotomy: switches are either open or closed, valves are either open or closed, events either occur or they do not occur. The Boolean techniques have immediate practical importance in relation to fault trees. A fault tree can be thought of as a pictorial representation of those Boolean relationships among fault events that cause the top event to occur. In fact, a fault tree can always be translated into an entirely equivalent set of Boolean equations. Thus, an understanding of the rules of Boolean algebra contributes materially toward the construction and simplification of fault trees. Once a fault tree has been drawn, it can be evaluated to yield its qualitative and quantitative characteristics. These characteristics cannot be obtained from the fault tree per se, but they can be obtained from the equivalent Boolean equations. [9]

2.2.6 Fault Tree Evaluation Techniques

Once a fault tree is constructed it can be evaluated to obtain qualitative and/or quantitative results. For simpler trees the evaluations can be performed manually; for complex trees computer codes will be required. Chapter XII discusses computer codes which are available for fault tree evaluations. Two types of results are obtainable in a fault tree evaluation: qualitative results and quantitative results. Qualitative results include: (a) the minimal cut sets of the fault tree, (b) qualitative component importances, and (c) minimal cut sets potentially susceptible to common cause (common mode) failures. As previously discussed, the minimal cut sets give all the unique combinations of component failures that cause system failure. The qualitative importances give a "qualitative ranking" on each component with regard to its contribution to system failure. The common cause/common mode evaluations identify those minimal cut sets consisting of multiple components which, because of a common susceptibility, can all potentially fail due to a single failure cause. The quantitative results obtained from the evaluation include: (a) absolute probabilities, (b) quantitative importances of components and minimal cut sets, and (c) sensitivity and relative probability evaluations. The quantitative importances give the percentage of time that system failure is caused by a particular minimal cut set or a particular component failure. The sensitivity and relative probability evaluations determine the effects of changing maintenance and checking times, implementing design modifications, and changing component reliabilities. Also included in the sensitivity evaluations are error analyses to determine the effects of uncertainties in failure rate data. Listed below is a summary of the type of results obtained from a fault tree evaluation. [9]

Qualitative Results	
a) Minimal cut sets	Combinations of component failures causing system failure
b) Qualitative importances	Qualitative rankings of contributions to system failure
c) Common cause potentials	Minimal cut sets potentially susceptible to a single failure cause
Quantitative Results	
a) Numerical probabilities	Probabilities of system and cut set failures
b) Quantitative importances	Quantitative rankings of contributions to system failure
c) Sensitivity evaluations	Effects of changes in models and data, error determinations

Table 2 Classes of results obtained from a fault tree evaluation

2.3 What is Markov Analysis

Markov analysis is a method of analysis that can be applied to both repairable and non-repairable types of system. The basic output of a Markov analysis is the average time spent by the system in each of its distinct states before the system moves (or makes a transition) into some other distinct state. For example, such a transition or change of state will occur if the system suffers a component failure or if a repair has been carried out. A distinct change in the state of the system will have taken place in both of these cases.

The output from the Markov analysis enables a complete description of the system to be obtained in terms of its reliability, availability and resource utilization (e.g. use of maintenance teams, spares holdings, buffers, etc.). Also, different system designs can be explored by comparing their reliability and availability performances as well as the effect of small tweaks to a given design under consideration. Results produced by a Markov analysis can then be used within a cost-benefit analysis to help identify the optimal design choice.

Markov analysis has the advantage of being an analytical method which means that the reliability parameters for the system are calculated in effect by a formula. This has the considerable advantages of speed and accuracy when producing results. Speed is especially useful when investigating many alternative variations of design or exploring a range of sensitivities. In contrast accuracy is vitally important when investigating small design changes or when the reliability or availability of high integrity systems are being quantified. [10]

Markov analysis is not very useful for explaining events, and it cannot be the true model of the underlying situation in most cases. Yes, it is relatively easy to estimate conditional probabilities based on the current state. However, that often tells one little about why something happened. In engineering, it is quite clear that knowing the probability that a machine will break down does not explain why it broke down. More importantly, a machine does not really break down based on a probability that is a function of whether or not it broke down today. In reality, a machine might break down because its gears need to be lubricated more frequently. [11]

2.4 What is Weibull Analysis

Weibull Analysis is a methodology used for performing life data analysis. Life data is the result of measurements of a product’s life. Weibull Analysis is an effective method of determining reliability characteristics and trends of a population using a relatively small sample size of field or laboratory test data.

The method is named for Mr. Waloddi Weibull who in 1937 invented the Weibull distribution. He presented a paper on the subject in 1951. Initial reaction to the paper initially ranged from uncertainty to total rejection. However, others in the field began to utilize and improve the method resulting in it being implemented by the U.S. Air Force in the 1970s, and later by the automotive industry. In industry today, Weibull Analysis is the foremost method for evaluating life data. [12]

Product life data can be measured in hours, miles, cycles or any other metric that applies to the period of successful operation of a particular product. Since time is a common measure of life, life data points are often called "times-to-failure" and product life will be described in terms of time throughout the rest of this guide. There are different types of life data and because each type provides different information about the life of the product, the analysis method will vary depending on the data type. With "complete data," the exact time-to-failure for the unit is known (e.g., the unit failed at 100 hours of operation). With "suspended" or "right censored" data, the unit operated successfully for a known period of time and then continued (or could have continued) to operate for an additional unknown period of time (e.g., the unit was still operating at 100 hours of operation). With "interval" and "left censored" data, the exact time-to-failure is unknown but it falls within a known time range. For example, the unit failed between 100 hours and 150 hours (interval censored) or between 0 hours and 100 hours (left censored).

Statistical distributions have been formulated by statisticians, mathematicians and engineers to mathematically model or represent certain behavior. The probability density function (pdf) is a mathematical function that describes the distribution. The pdf can be represented mathematically or on a plot where the x-axis represents time. The Weibull model can be applied in a variety of forms (including 1-parameter, 2-parameter, 3-parameter or mixed Weibull). Other commonly used life distributions include the exponential, lognormal and normal distributions. The analyst chooses the life distribution that is most appropriate to model each particular data set based on past experience and goodness-of-fit tests. [13]

Different types of Weibull Distributions:

<u>Exponential Distribution:</u>

The exponential distribution may be associated with component failures or maintenance tasks (for sampling times to failure and time to repair respectively). This distribution should be used to model the failure characteristics of components that do not exhibit any ageing. The distribution represents a constant failure rate (or repair rate). The expressions below represent the use of the distribution for failures. For repairs the failure rate should be replaced by the repair rate and the mean time to failure by the mean time to repair.

Probability Density Function, $f(t)$

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

Unreliability, $F(t)$

$$F(t) = 1 - e^{-\lambda t}$$

Failure Rate, $r(t)$

$$r(t) = \lambda$$

Mean Time to Failure, MTTF

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

<u>1-Parameter Weibull:</u>

The Weibull distribution is used to model the failure characteristics of components with time-dependent failure rates. A common use is to model the ageing characteristics of mechanical components. The 1-Parameter Weibull calculation method requires the user to specify the shape parameter of the distribution.

Probability Density Function for 1-parameter Weibull, $f(t)$

$$f(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} \mathrm{e}^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

Where η= characteristic life parameter or scale parameter, β=shape parameter

Unreliability, $F(t)$

$$F(t) = 1 - \mathrm{e}^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

Failure Rate, $r(t)$

$$r(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}}$$

Mean Time to Failure, MTTF

$$MTTF = \eta \Gamma \frac{1+\beta}{\beta}$$

Where Γ=gamma function

<u>2-Parameter Weibull:</u>

Expressions for the 2-Parameter Weibull are identical to the expression given above for the 1-Parameter Weibull method.

<u>3-Parameter Weibull:</u>

Probability Density Function for 3-parameter Weibull, $f(t)$

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \mathrm{e}^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

Where:

β=the shape parameter, η=scale parameter or characteristic life parameter, γ=location parameter

Unreliability, $F(t)$

$$F(t) = 1 - \mathrm{e}^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

Failure Rate, $r(t)$

$$r(t) = \frac{\beta(t-\gamma)^{\beta-1}}{\eta^{\beta}}$$

Mean Time to Failure, MTTF

$$MTTF = \gamma + \eta\Gamma\frac{1+\beta}{\beta}$$

Where Γ=gamma function

The Weibull shape parameter, β, is also known as the Weibull slope. This is because the value of β is equal to the slope of the line in a probability plot. Different values of the shape parameter can have marked effects on the behavior of the distribution. Weibull distributions with $\beta < 1$ have a failure rate that decreases with time, also known as infantile or early-life failures. Weibull distributions with β close to or equal to 1 have a fairly constant failure rate, indicative of useful life or random failures. Weibull distributions with $\beta > 1$ have a failure rate that increases with time, also known as wear-out failures. [14]

2.5 Reliability Allocation, Reliability Growth

2.5.1 Reliability Allocation

Reliability allocation refers to the optimization process on the reliabilities of all or some of the components of a given system in order to meet the target of overall system reliability with minimum cost. Reliability allocation needs to occur when the estimated or designed system reliability is not sufficient, or when the reliabilities of the components are severely imbalanced, causing a large over-design and waste of lifetime for some components. [15]

Reliability allocation is normally applied during the design and development stages of a system. Reliability allocation methods may recommend redundancy configurations to meet reliability targets as well as assigning reliability requirements of individual sub-systems and equipments. Some reliability allocations methods employ constraints on the system (such as cost and weight) whereas others employ grading (weighting) factors. [16]

2.5.2 Reliability Growth

Reliability growth analysis is the process of collecting, modeling, analyzing and interpreting data from the reliability growth development test program (development testing). In addition, reliability growth analysis can be done for data collected from the field (fielded systems). Fielded systems also include the ability to analyze data of complex repairable systems. Depending on the metric(s) of interest and the data collection method, different models can be utilized (or developed) to analyze the growth processes.

Reliability growth is the improvement in the reliability of a product (component, subsystem or system) over a period of time due to changes in the product's design and/or the manufacturing process. [17]

3. Case Study: Fault Tree analysis applied on gas-turbine of Xylokamara, Chania

3.1 Xylokamara, Chania power station

The electric grid of the island of Crete is supplied by three main thermal power stations. One of them is allocated in Xylokamara, Chania. In this station there are 5 open cycle gas-turbines and one combined cycle as follows.

- Thomassen B.V. 24 MW open cycle
- Fiat Avio SPA 30 MW open cycle
- Ansaldo 59 MW open cycle
- Ansaldo 59 MW open cycle
- General Electric (GE) LM2500+ 28 MW open cycle
- ABB combined cycle 134 MW consisting of:
    - ABB GT8 45 MW gas-turbine
    - ABB GT8 45 MW gas-turbine
    - ABB V63 44 MW steam-turbine

The fuel used for the gas-turbines is Diesel oil.

In the combined cycle the exhaust gasses are guided in a gas boiler producing adequate steam to drive a steam-turbine.

The subject of this Thesis is ABB GT8 45 MW gas-turbine.

3.2 ABB GT8 45 MW gas-turbine

The gas-turbine is a three-stage single combustion chamber turbine. An ABB gas-turbine generator set consists of the following parts:

1. Thermal block (MB)
2. Gear box (MBK10)
3. Generator (MKA10)
4. Air intake system (MBL01)
5. Exhaust gas system (MBR10)
6. Fuel pump module (MBN)
7. Fuel oil regulating system (MBX10)
8. Oil system (MBV10)
9. Control and switchgear module

The codification of the parts and the sensors of the gas turbine, where referred, are according to the German system for heavy machines KKS.

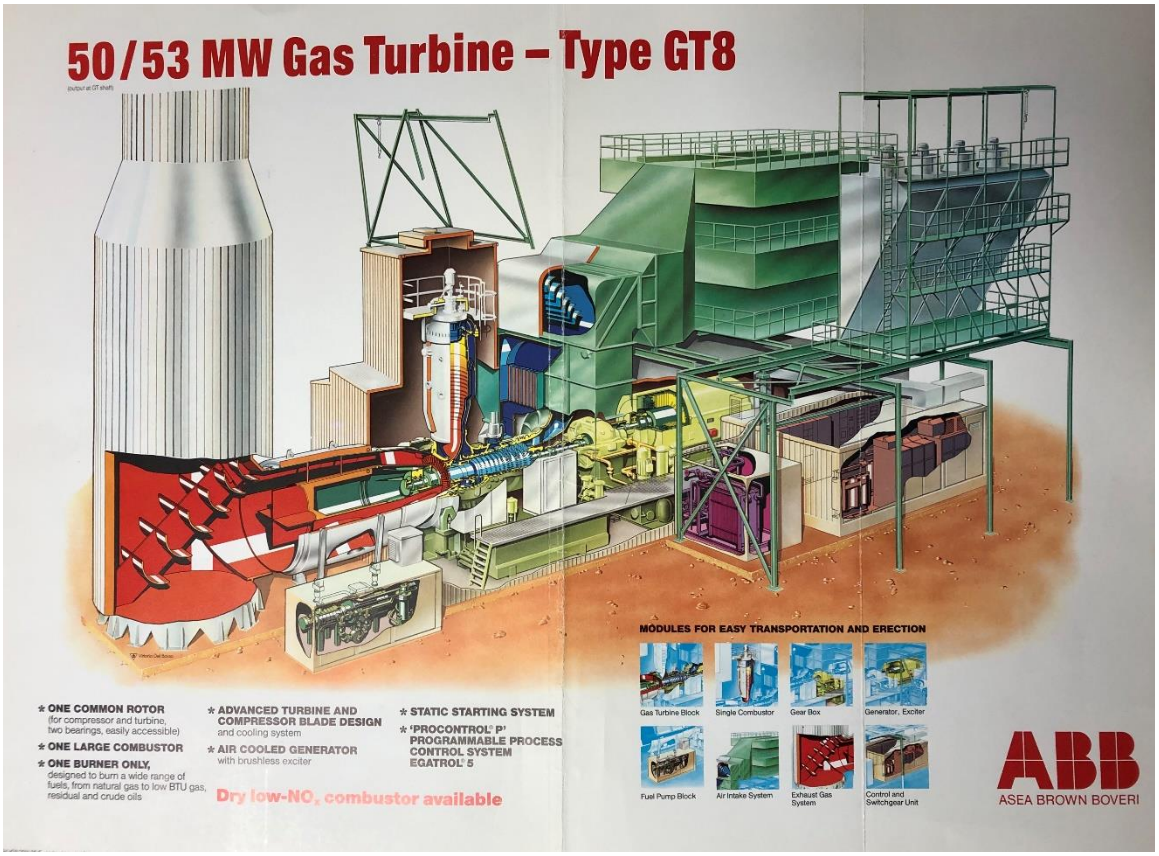


Figure 4 ABB GT8 gas turbine design

3.2.1 Thermal block

The thermal block consists of:

a) Compressor (MBA80)
b) Combustion chamber (MBM30)
c) Turbine (MBA30)

It has to convert the chemical energy of the fuel into mechanical energy at the coupling. This is achieved by burning the fuel in the combustion chamber and by expanding the combustion gasses in the turbine. The shaft will be driven and will rotate at nominal speed.

The combustor block consists of the combustor and the burner. The combustor is a single combustor with three liners and counter flow cooling. The individual burner mounted on the combustor varied depending on the type of fuel being burned.

The gas turbine block consists of the following major components:

- The rotating shaft and the blades generally referred to as the "rotor"
- The stator components i.e. the housings, vane carriers and vanes
- The bearings

The turbine drives a twelve-stage compressor that draws in air from the atmosphere across the intake portion. The air flow can be adjusted using the variable inlet guide vanes (IGV). The compressor is equipped with a blow-off system which during start-up and shutdown blows off a portion of the intake air into the environment. This prevents rotating stall and compressor damage due to blade failure. After being compressed in the compressor, the air flows through the compressor diffusor and the turbine outer housing to enter the combustor. Before combustor the compressed air is used to cool the components surrounded by the hot gasses. The hot combustion gasses flow out of the combustor and expand in the three-stage turbine giving energy to the rotor. Then depending on what is required the expanded gasses are either directed to the atmosphere across the exhaust channel or are put to further use in a waste heat boiler.

3.2.2 Gear box

The gear box has to adjust the rotational speeds between the gas-turbine and the generator. The gas-turbine rotates at 6340 rpm and the gear box reduces this speed to 3000 rpm for the generator in order to achieve the 50 Hz required by the grid.

3.2.3 Generator

The generator is a two-pole air-cooled synchronous 65 MVA with brushless exciter (rotating diodes). It converts the mechanical energy at the coupling into electrical energy.

3.2.4 Air intake system

The Air intake system consists of:

a) Air filters
b) Air intake channel

It has to clean the air used in the gas-turbine. This measure is need to prevent damage and fouling of the compressor and the turbine blading.

3.2.5 Exhaust gas system

The exhaust gas system consists of:

a) Exhaust diffusor
b) Chimney with silencers and waste heat boiler

It has the following tasks:

a) To guide the exhaust gas out of the turbine hall
b) To reduce the exhaust noise
c) To produce the steam for the steam turbine in connection with the use of a waste heat boiler.

3.2.6 Fuel pump module

The fuel pump module consists of:

a) Main fuel pump
b) Leakage fuel pump

It has to:

a) Supply the burner with fuel oil
b) Raise up the fuel oil pressure from about 6 bar to 90 bar
c) Pump any fuel oil leakage back to the fuel oil tank

3.2.7 Fuel oil regulating system

The fuel oil regulating system has to control the fuel flow to the combustion chamber

3.2.8 Oil system

The oil system consists of:

a) Lube oil system
b) Power oil system

It has the following tasks:

a) To lubricate and to cool the bearings of the turbogenerator set and those of the gear box
b) To actuate control and safety devices of the unit

3.2.9 Control and switchgear module

The control and switchgear module has the following tasks:

a) To control the gas-turbine alternator set during start-up, running and shutdown
b) To protect the gas-turbine alternator set from dangerous operating states
c) To supply the motor control center and the switch gear with the appropriate electrical energy.

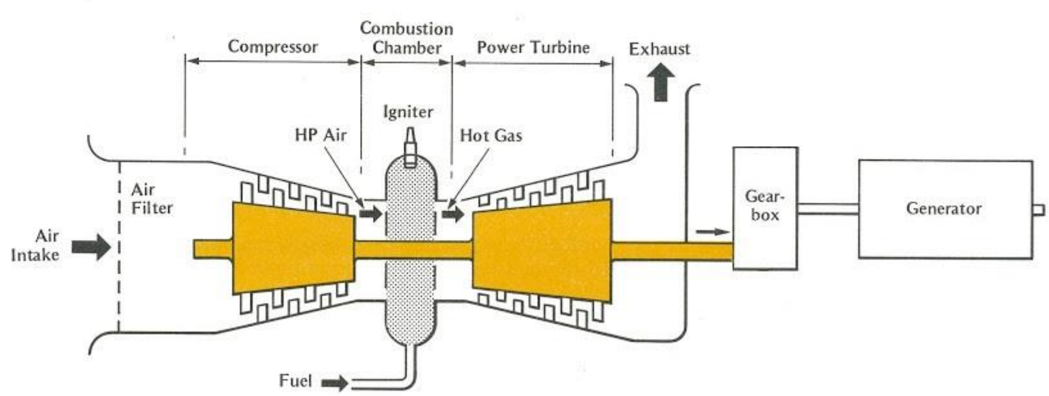


Figure 5 Gas-turbine design

3.3 Fault Tree Analysis on ABB GT8 45 MW gas-turbine

The first thing done for the FTA analysis was to part the gas turbine into subsystems, according to the manufacturer, forming the Intermediate Events. The sub-systems are as follow:

- Generator
- Air inlet system
- Compressor system
- Combustion system
- Turbine system
- Starting system
- Fuel regulating system
- Lubrication system
- Electrical auxiliaries' system
- Turbine control system
- Gear Box

Each subsystem mentioned above is crucial and equally responsible for the functionality of the gas turbine, meaning that if any of that subsystems fail, it results to the failure of the whole system. Having said that, the gas turbine's subsystems were constructed under an "OR" gate type. Below is presented the fault tree diagram of the subsystems, concluding to the top event, the failure of the total system.

The program used for the fault tree analysis is the isograph reliability workbench. A program that contains many modules depending on the reliability analysis the user prefers to use.

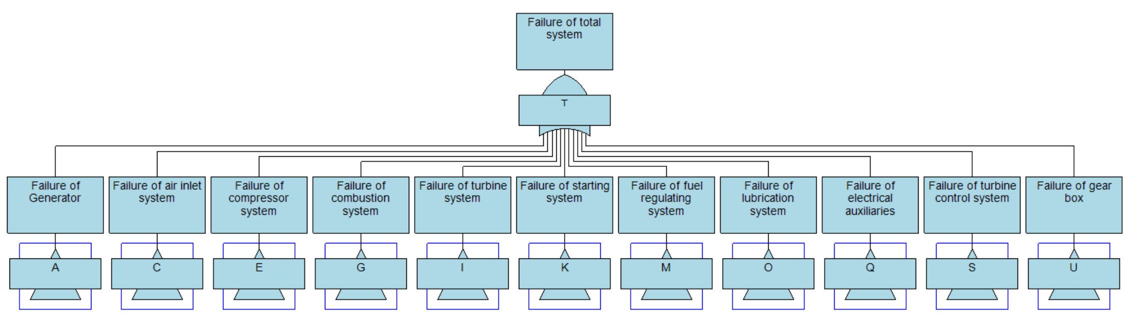


Figure 6 Proposed Fault tree of total system

The way to create each basic event was to collect all the sensors and counters by the manufacturer and wear out data from the power station.

3.3.1 Failure of generator

The turbine provides mechanical energy on the coupling, rotating at nominal speed. The alternator changes this mechanical energy into electrical energy by making a magnetic field to pass across the windings of a coil, so that a current flows in the coil.

The magnetic field is produced by an exciter. The exciter is fed with an excitation current by the voltage control system and like the alternator it produces an AC output. This output is rectified into DC by a set of diodes. The DC is then used in the rotor windings to produce a rotating magnetic field. One north pole and one south pole are used, so that at nominal speed an electrical energy with nominal frequency is provided.

The failure of the generator consists of 3 main intermediate events connecting through an "OR" gate and parting into many events.

1. A1: Generator's physical damage
    - 1.1. B1: Casing of the generator got damaged
    - 1.2. B2: Rotor bowing of generator
    - 1.3. B3: Guide ways of the generator failure
        - 1.3.1. B3_1: Guide ways of the generator got damaged
        - 1.3.2. B3_2: Temp in generator stator slots
            - 1.3.2.1. B3_21: MKA10CT005
            - 1.3.2.2. B3_22: MKA10CT006
2. A2: Generator's trips due to faults
    - 2.1. A3: Electric faults occur in generator
        - 2.1.1. B4: Earth fault occur in generator
        - 2.1.2. B5: Failure of generator due to short circuit fault
    - 2.2. A4: Failure of generator protection system
        - 2.2.1. B6: the failure of electronic protection relays
            - 2.2.1.1. Channel 1 (B6_1)
            - 2.2.1.2. Channel 2 (B6_2)
        - 2.2.2. B7: failure of current transformers
        - 2.2.3. B8: failure of voltage transformers as basic events
    - 2.3. A5: Failure of electric generator system consisting of the
        - 2.3.1. B9: excitation failure
        - 2.3.2. B10: breaker failure
        - 2.3.3. B11: automatic voltage regulator failure
        - 2.3.4. B12: failure of synchronization system.
3. A6: Generator's radial bearings failure
    - 3.1. B13: failure of pads of radial bearings
    - 3.2. B14: failure of thermocouples in the radial system bearings
        - 3.2.1. MKD21CT001
        - 3.2.2. MKD21CT002

3.2.3. MKD31CT001
3.2.4. MKD31CT002
3.3. B15: failure of vibration sensors
3.4. B16: damage of the shell of the radial bearings

Many of the above events are sensors and switches of the system. B3 refers to MKA10CT001-004, a display to show the operator the temperature. B3 also refers to MKA10CT005/6. A2 refers to MKA13CT012, MKA13CT016, MKA13CT022, MKA13CT026, MKB33CT012 and MKF10CP002, temperature sensors and pressure switches.

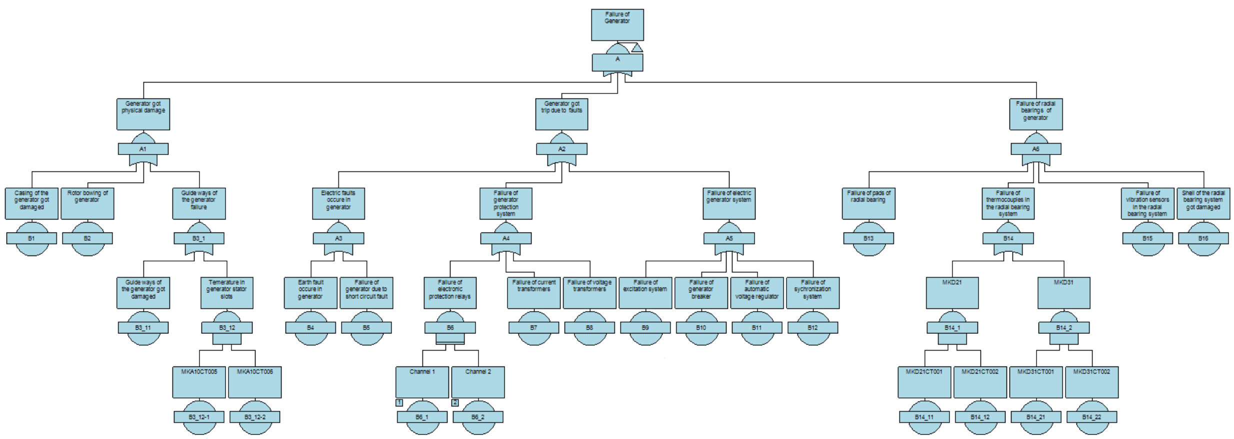


Figure 7 Proposed Fault tree of generator

3.3.2 Failure of air inlet system

Air inlet system, also referred as air intake system is compounded of two main intermediate events connecting through an "OR" gate.

1. Failure of ice warning system which parts into the following basic events:
   1.1. D1-Temperature sensor fails
   1.2. D2-Humidity sensor fails
   1.3. D3-Leakage from anti icing system
2. Failure of implosion doors system, an "AND" gate type which consists of a basic event and an intermediate event parting into 5 other basic events.
   2.1. Failure of air filtering system
      2.1.1. D4-Fail of preliminary filter differential pressure sensor
      2.1.2. D5-Fail of fine filter differential pressure sensor
      2.1.3. D6-Fail of total filter differential pressure sensor
      2.1.4. D7-Preliminary filters clogged
      2.1.5. D8-Fine filters clogged

2.2. Implosion doors' springs got damaged

D4, D5 and D6 are all branches of an "AND" gate. This is because, it needs all three pressure sensors to fail, for the systems failure.

It is easy to come to the conclusion that the air inlet system fails only if the ice warning system fails or the implosion doors are unable to open in case of filters' clogging. The failure of the filtering system forces the implosion doors to open so that air can insert into the system and prevent the destruction of compressor by suctioning the air filters themselves. Having the implosion doors open is not safe for the well being of the gas turbine since anything can insert into the air system and cause damage. However, it is an act of emergency and it only occurs if the gas turbine operator has not taken into consideration the failure of air filtering system.

D1 refers to MBL01CT000 sensor. D2 to MBL01CM001, D4 to MBL30CP001, D5 to MBL30CP002, D6 to MBL30CP003.

D7-Preliminary filters clogging is the most common event that happens to the gas turbine and has been changed 15 times over the 17 years taken under consideration for this thesis.

Below is presented the fault tree for the air inlet system.

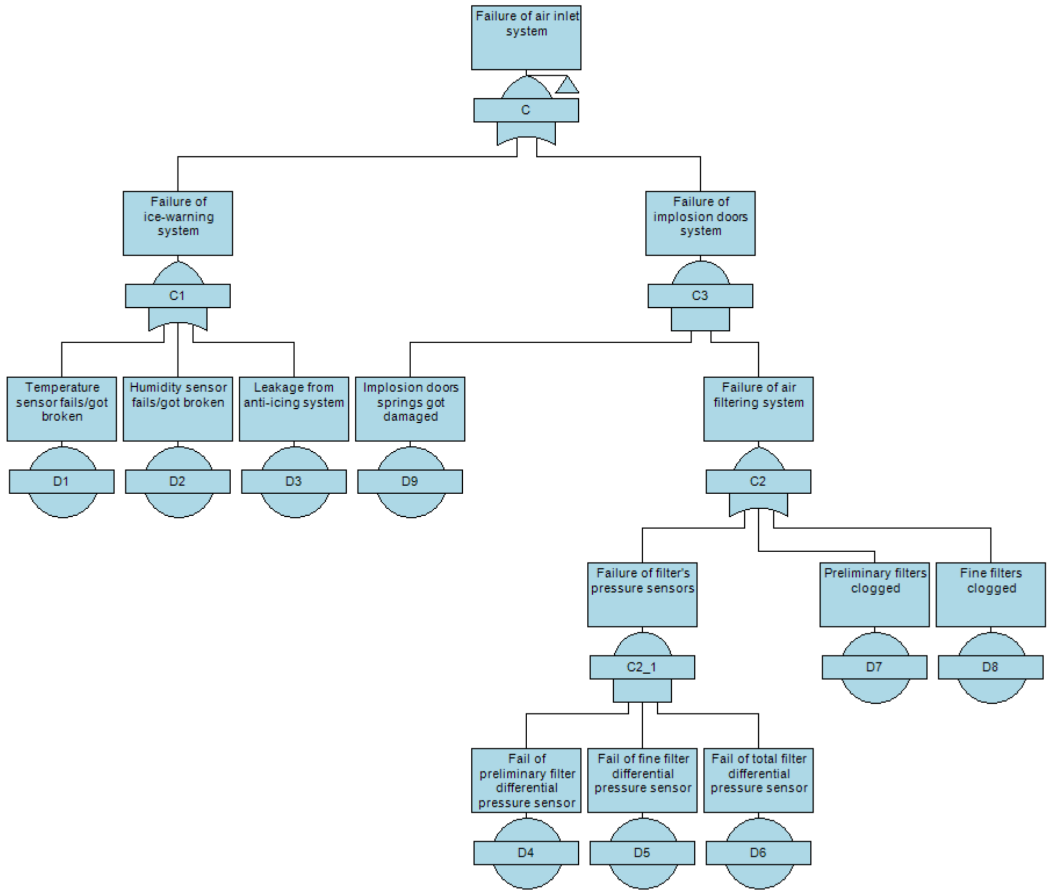


Figure 8 Proposed Fault tree of air inlet system

3.3.3 Failure of compressor system

The compressor system is a subsystem of the thermal block. Apart from adding heat to the flowing air, we have to have pressure, and this is provided by the compressor. It is fixed to the same shaft as the turbine and works in a rather similar, but opposite way to the turbine. In the compressor the rotating shaft moves the blades through the air and the blades add energy to the air, increasing its velocity, then changing the velocity into pressure energy. It is more difficult to compress than to expand the working medium in an axial blading, so we use 18 stages to compress the air while only 3 are used to expand the combustion gas.

The fault tree of the failure of the compressor system parts into four intermediate events. Each of those intermediate events parts into basic events or further intermediate events and then basic events as well, connecting through and "AND" or "OR" gate.

1. Blade system of compressor got corrupted (E1)
   1.1. Stationary blades got broken (F1)
   1.2. Inlet guide vanes of the blade system got broken (F2)
      1.2.1. MBA82CG001 (F2_11)

1.2.2. MBA82CG002 (F2_12)
1.2.3. IGV motor and gears failure (F2_2)
1.3. Rotor blades got broken (F3)
2. Failure of journal bearing of the compressor (E2)
2.1. Housing of the journal bearing got broken (F4)
2.2. Inner surface got damage (F5)
2.3. Failure of thermocouples of journal bearing (F6)
2.3.1. MBD21CT003 (F6_1)
2.3.2. MBD21CT004 (F6_2)
2.4. Failure of vibration sensors of journal bearing (F7)
3. Failure of thrust bearing of the compressor (E3)
3.1. Shoes of thrust bearing got damaged (F8)
3.2. Housing of the thrust bearing got broken (F9)
3.3. Failure of thermocouples of the thrust bearing (F10)
3.3.1. Thrust bearing temperature, compressor side (F10_1)
3.3.1.1. MBD22CT001 (F10_11)
3.3.1.2. MBD22CT002 (F10_12)
3.3.2. Thrust bearing temperature, generator side (F10_2)
3.3.2.1. MBD22CT011 (F10_21)
3.3.2.2. MBD22CT012 (F10_22)
4. Failure of blow off valves (E4)
4.1. Blow off valves stage 1 open (E5)
4.1.1. Failure of blow off valves stage 1 air regulator (F11)
4.2. Blow off valves stage 2 open (E6)
4.2.1. Failure of blow off valves stage 2 air regulator (F12)

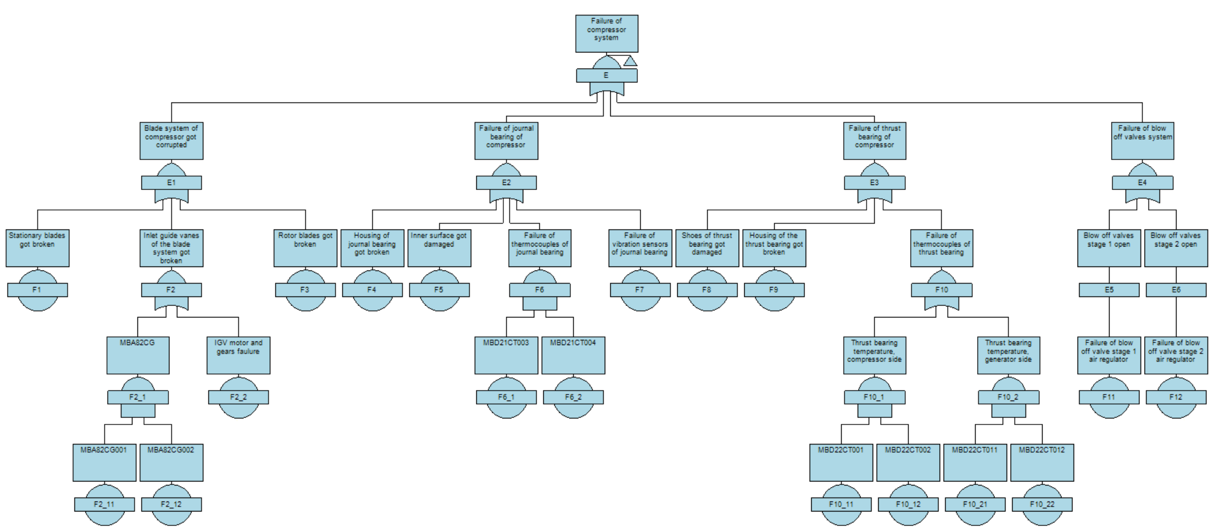


Figure 9 Proposed Fault tree of compressor system

The sensors and components used are the following:

- E5-MBA81AA011/12
- E6-MBA81AA021
- F2-MBA82CG001-2 connecting through and “AND” gate
- F6-MBD21CT003-4 thermocouples, connecting through an “AND” gate
- F7-MBD20CY001
- F10-MBD22CT001-004 and MBD22CT011-014, thermocouples and indicators

3.3.4 Failure of the combustion system

The combustion chamber is another component of the thermal block where heat is added to air coming from the compressor in order to increase its velocity and have at the end sufficient kinetic energy.

The failure of the combustion system event parts through an “OR” gate into three more intermediate events and one basic event as shown below:

1. Wear and tear occur in shells of the combustion chamber (G1)
    1.1. Failure of burner (H1)
    1.2. Failure of combustion chamber (H2)
2. Failure of cooling system of the combustion chamber (G2)
    2.1. Vessels of the cooling system blocked (H3)
    2.2. Air leak from the combustion chamber (H4)
3. Failure of flame detection system (G3)
    3.1. MBM30CN001 (G3_1)
    3.2. MBM30CN002 (G3_2)
    3.3. MBM30CN003 (G3_3)
4. Various leakages from the combustion chamber (G4)

A thermocouple used for burner cooling air (H1) is MBH41CT001 and flame detector MBM30CN001-003 for G3 connecting via “VOTE OR” gate, that returns 1 if two of the sensors return 1.

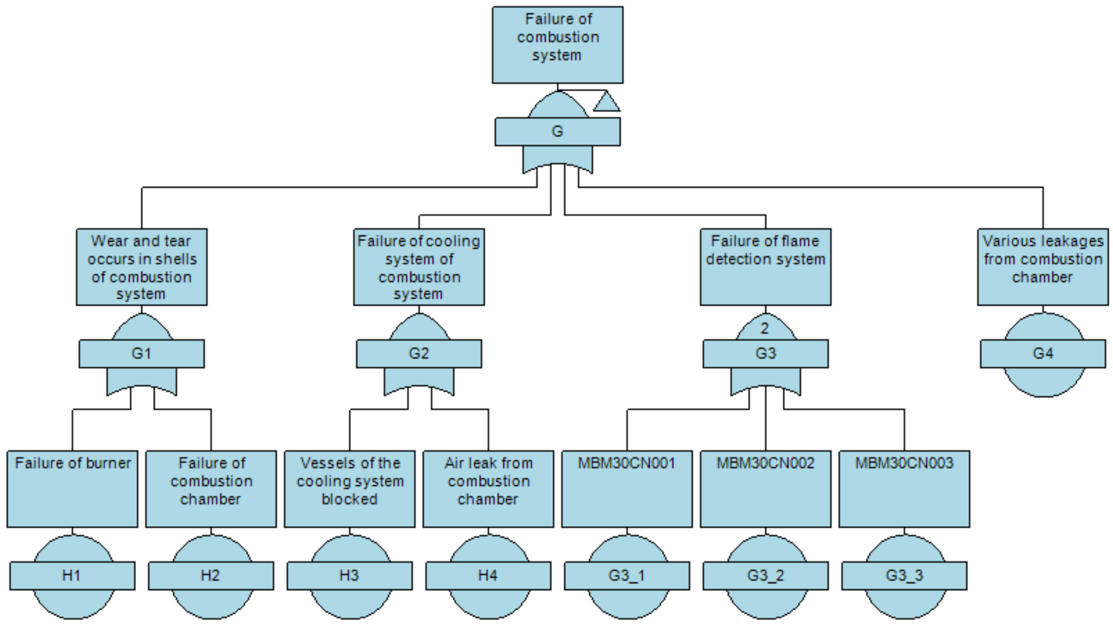


Figure 10 Proposed Fault tree of combustion system

3.3.5 Failure of the turbine system

The turbine transforms the kinetic energy of the hot gasses into work through its blades.

Below is shown the intermediate events and basic events of the failure of the turbine system.

1. Failure of vanes system (I1)
   1.1. Vanes got damaged (J1)
   1.2. Pins of the vane system got broken (J2)
2. Failure of rotor blade system (I2)
   2.1. Blades got damaged (J3)
   2.2. Pins of the blade system got broken (J4)
3. Failure of radial bearing turbine (I3)
   3.1. Failure of pads of radial bearing (J5)
   3.2. Failure of thermocouples in the radial bearing system (J6)
      3.2.1. MBD11CT005 (J6_1)
      3.2.2. MBD11CT006 (J6_2)
   3.3. Failure of vibration sensors of the radial bearing system (J7)
   3.4. Shell of the radial bearing system got damaged (J8)
4. Failure of exhaust system of turbine (I4)
   4.1. Failure of diverter valve motor (J9)

    4.2. Failure of sealing air fan (J10)
5. Turbine overspeed protection system (I5)
6. Turbine cooling system (I6)
    6.1. AC cooling fan failure (J11)
    6.2. DC cooling fan failure (J12)

The sensors and components used in this fault tree, referring to events are: J6-MBD11CT003-006 indicators and thermocouples that are connected throung and "AND" gate, J7-MBD10CY001.

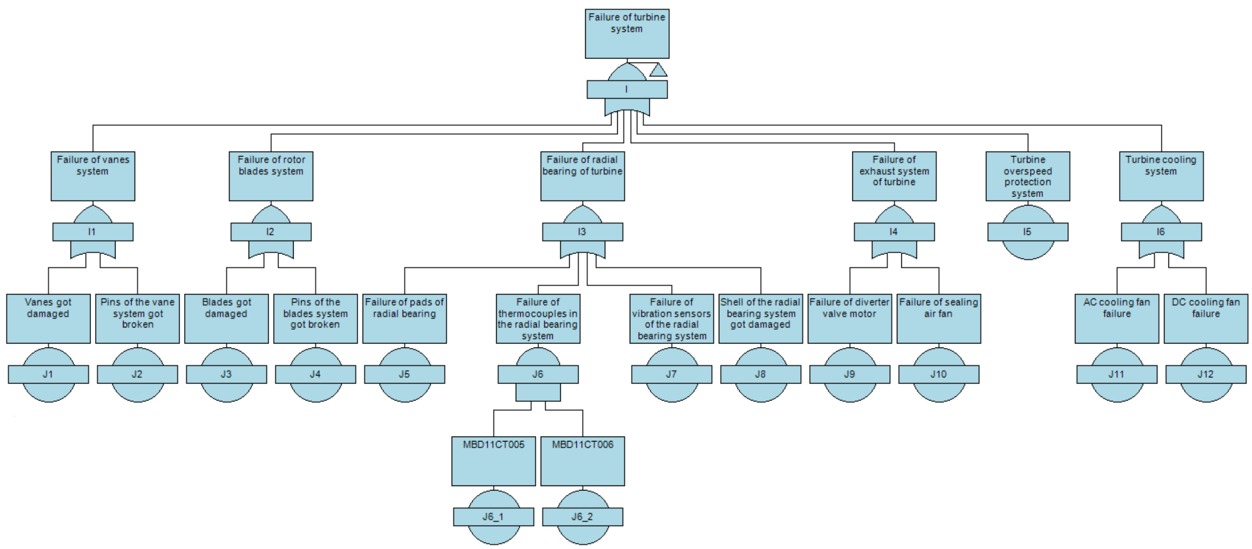


Figure 11 Proposed Fault tree of turbine system

3.3.6 Failure of the starting system

Air flow through the machine is continuous and the process is dynamic so without motion of the shaft the process cannot be happen. Because of this, a gas turbine cannot start from rest like a diesel engine. The turbine has to be run up to a minimum speed to get the dynamic action started. For that purpose, the generator is transformed into a synchronous motor with the aid of a thyristor bridge.

Failure of starting system parts into two intermediate vents connecting through an “OR” gate. Each intermediate event parts to three basic events.

1. Failure of frequency converter (K1)
    1.1. Failure of thyristors’ bridge (L1)
    1.2. Failure of thyristors firing control system (L2)
    1.3. Failure of converter cooling fan (L3)
2. Failure of igniter system (K2)
    2.1. Igniter got broken (L4)
    2.2. Energizing relay of igniter fails/got broken (L5)
    2.3. Failure of valves of ignition gas (propane) (L6)

The switches used here is the MBQ30CP002 and it refers to L6.

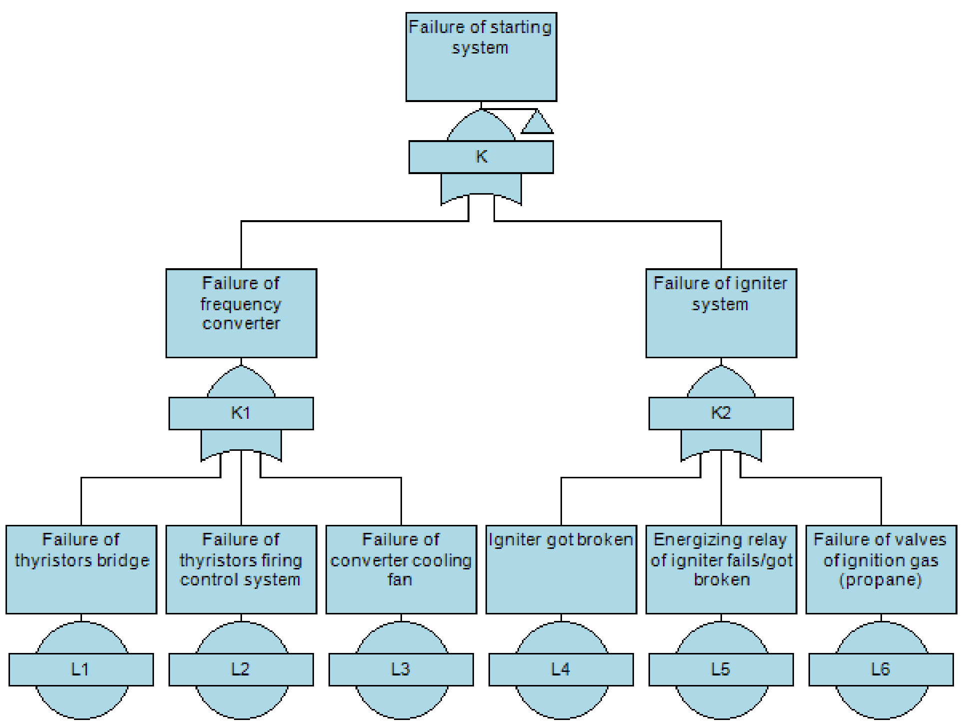


Figure 12 Proposed Fault tree of starting system

3.3.7 Failure of fuel regulating system

The fuel regulating system consists of the fuel system (fuel pump, valves, sensors) and the regulating system which controls the opening of burner to allow to pass the appropriate amount of fuel according the desired turbine speed/load. The fuel flow through burner is proportional to the opening of the burner. The working medium for burner movements is the power oil and its pressure is regulated by an electrohydraulic converter. The electrohydraulic converter transforms the electrical orders taken from turbine control system to oil pressure.

The failure of fuel regulating system is divided into two intermediate events.

1. Fail of fuel system (M1)
    1.1. Centrifugal fuel pump got damaged (N1)
    1.2. Motor of fuel pump got damaged (N2)
    1.3. Leak from fuel system pipes (N3)
2. Control oil system failure (M2)
    2.1. Power oil pump failure (N4)
    2.2. Motor of power oil pump failure (N5)
    2.3. Failure of electrohydraulic converter (N6)
    2.4. Failure of control oil valves (N7)
    2.5. Leak from control oil pipes or valves (N8)

N1 and N2 refer to MBN32CP001 pressure transducer, N4 refers to MBX21CP005 and MBX42CP001 pressure switch.

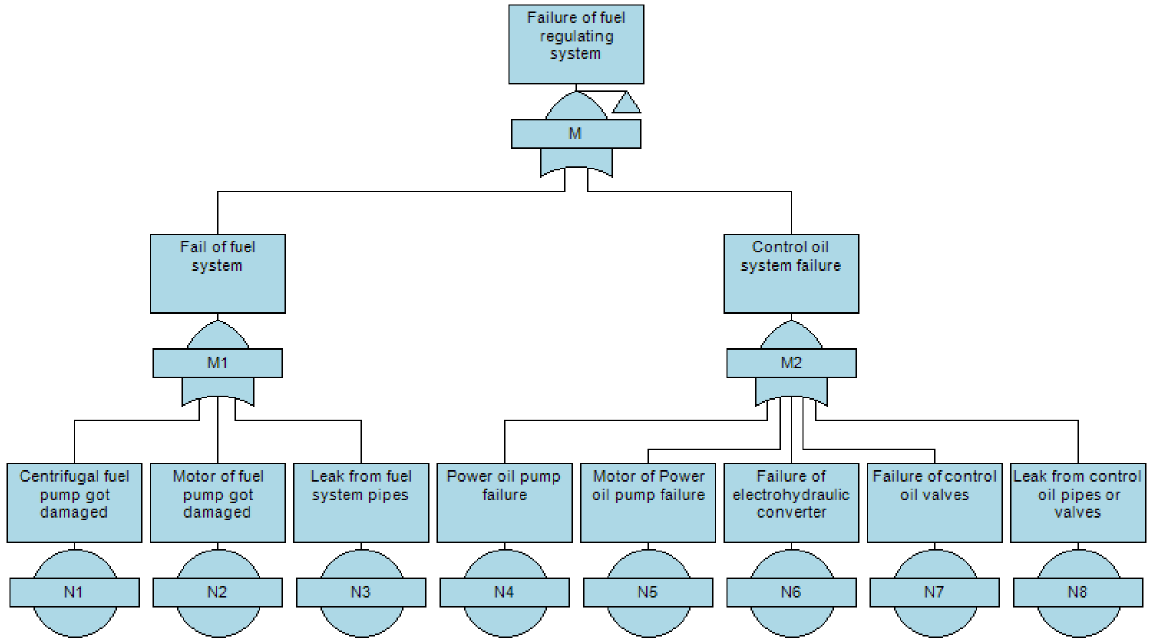


Figure 13 Proposed Fault tree of fuel regulating system

3.3.8 Failure of lubrication system

The lubrication system is responsible for the supply of the bearings with the sufficient amount of oil. It comprises three pumps (gear driven, electric AC, electric DC), filters, temperature and pressure sensors. The AC electric pump is operating during start-up and shut-down of turbine. During normal operation of turbine, the gear driven oil pump has sufficient pressure to feed the bearings with oil. The electric DC pump is operating only if the oil pressure falls below a safety level.

This failure system is divided to six intermediate events.

1. Failure of cooling system of the lubrication system (O1)
   1.1. Heat exchanger clogged (P1)
   1.2. Cooling water pump got damaged (P2)
   1.3. Failure of motor (P3)
2. Failure of main lubrication pump (O2)
   2.1. Main pump gear got damaged (P4)
3. Failure of auxiliary lubrication pump (O3)
   3.1. Failure of motor (P5)
   3.2. Failure of pressure sensor (P6)
   3.3. Failure of pump (P7)
4. Failure of emergency lubrication pump (O4)
   4.1. Failure of motor (P8)

   4.2. Failure of pressure sensor (P9)
      4.2.1. MBV40CP005 (P9_1)
      4.2.2. MBV40CP006 (P9_2)
   4.3. Failure of pump (P10)
5. Failure of rotor barring (O5)
   5.1. Failure of rotor positioning device (P11)
   5.2. Failure of rotor barring pump (P12)
6. Failure of oil mist extractor (O6)
   6.1. Failure of motor (P13)
   6.2. Failure of piping (P14)

P1 event refers to MBV40CT002 temperature switch. P6 event refers to MBV40CP002 and P9 to MBV40CP005-6 pressure switches connecting through an "AND" gate.

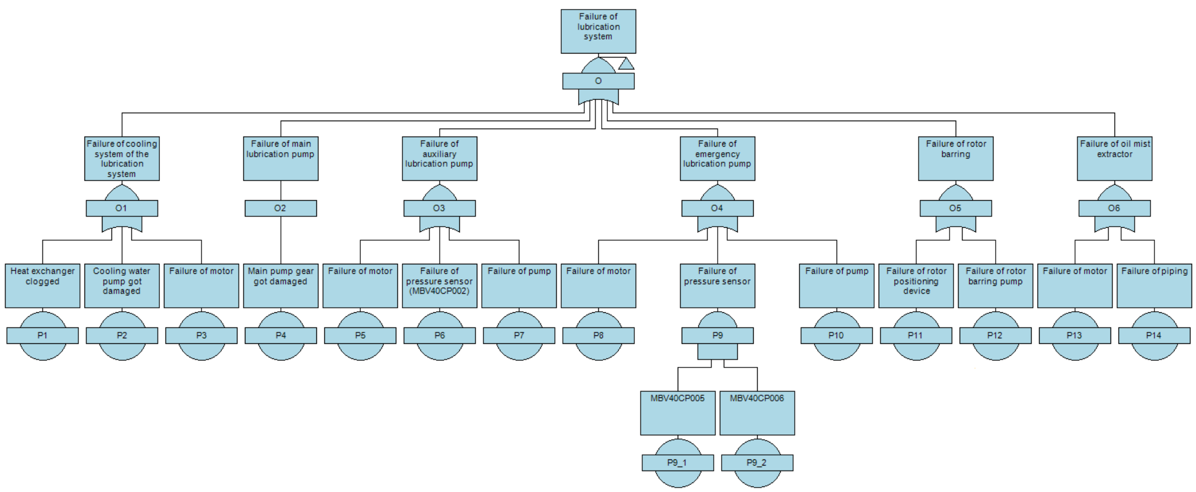


Figure 14 Proposed Fault tree of lubrication system

3.3.9 Failure of electrical auxiliaries

The electrical auxiliaries' system is responsible for the supply of power to all devices needed for turbine operation. Is divided in the following subsystems according to the voltage:

Medium voltage (11.5kV): Feeds starting converter and 11.5/0.4 auxiliaries transformer. Low voltage (400V): Feeds various motors and whatever operates with 400V AC. DC 125V: Feeds emergency motors and UPS system. DC 24V: Feeds turbine control system and sensors.

Failure of electrical auxiliaries' intermediate event parts into three other intermediate events, connected through an "OR" gate.

1. Failure of medium voltage system (11.5 kV) (Q1)
    1.1. Failure of medium voltage breaker (R1)
    1.2. Failure of medium voltage circuit (R2)
2. Failure of low voltage system (400V) (Q2)
    2.1. Failure of voltage breaker (R3)
    2.2. Failure of low voltage circuit (R4)
3. Failure of DC supply (Q3)
    3.1. Failure of 125 VDC charger (R5)
    3.2. Failure of 125 VDC batteries (R6)
    3.3. Failure of 125 VDC circuit (R7)
    3.4. Failure of 24 VDC charger (R8)
    3.5. Failure of 24 VDC batteries (R9)
    3.6. Failure of 24 VDC circuit (R10)

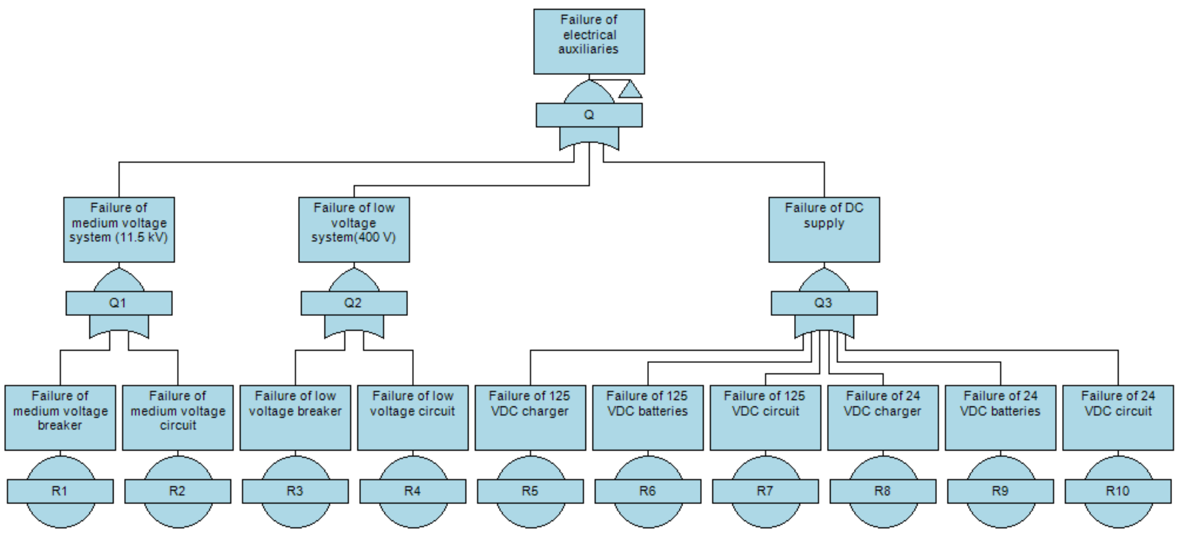


Figure 15 Proposed Fault tree of electrical auxiliaries

3.3.10 Failure of turbine control system

The turbine control system is responsible for the safe and reliable operation of the turbo set. The main control loops programmed in its processors are the open loop controls, closed loop controls, turbine protection and operation of autonomous drives.

The open loop controls comprise the start-up and shut down sequence.

The closed loop control comprises the fuel control and the frequency/load control. They interact and are responsible for the correct amount of fuel to be burned in order to achieved the desired frequency or load in generator terminals.

The turbine protection routines are responsible for the safe operation of turbo set. If any dangerous situation is detected the turbine immediately trips.

Finally, there are some drives (fans, pumps etc.) which are not a part of the closed or open loop controls but they are significant for the operation of the turbine. They called autonomous drives and controlled from turbine control system too.

From the scope of hardware, the turbine control system mainly consists of the following modules:

Input modules (digital and analog) which are responsible to read the various measurements and situations from the field.

Output modules (digital and analog) which are responsible to give the orders to the actuators at the field.

Programmable modules (controllers) which comprise the above-mentioned control loops, protections and operation of autonomous drives.

This intermediate event is very simple comparing to the previous ones.

1. Failure of electronic controller (S1)
2. Failure of input module (S2)
    2.1. Channel 1 (S2_1)
    2.2. Channel 2 (S2_2)
3. Failure of output module (S3)
    3.1. Channel 1 (S3_1)
    3.2. Channel 2 (S3_2)

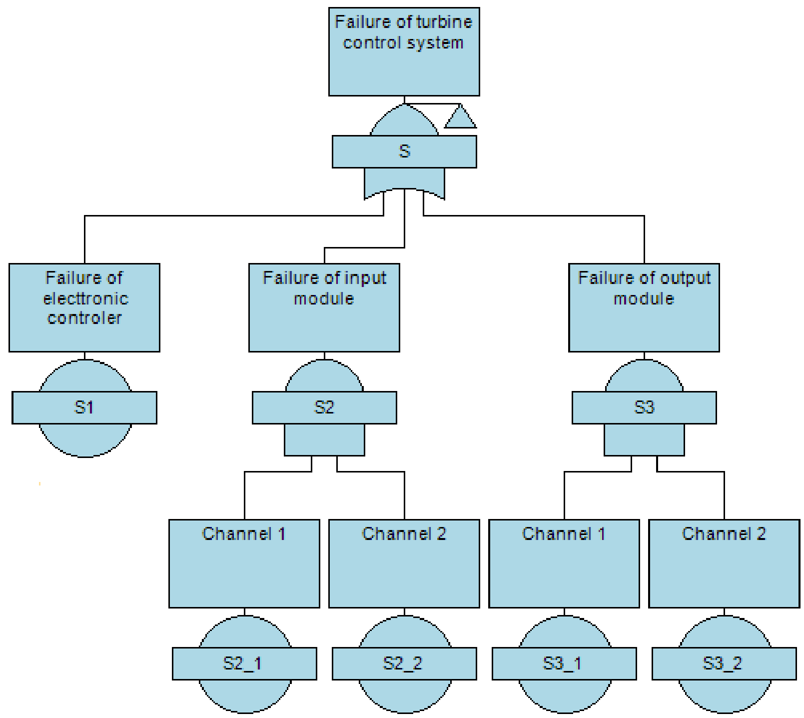


Figure 16 Proposed Fault tree of turbine control system

3.3.11 Failure of gear box

The gear box consists of the gears and their radial bearings.

Gear Box has a more complex fault tree, consisting of 8 thermocouples and 2 seismic pick-up sensors. According to that, it parts to intermediate and basic events.

1. Failure of gears of gear box (U1)
2. Failure of radial bearing of gear box (U2)
   2.1. Failure of pads of radial bearing (V1)
   2.2. Failure of thermocouples in the radial bearing system (V2)
      2.2.1. MBK11CT001 (V2_11)
      2.2.2. MBK11CT002 (V2_12)
      2.2.3. MBK12CT001 (V2_21)
      2.2.4. MBK12CT002 (V2_22)
      2.2.5. MBK13CT001 (V2_31)
      2.2.6. MBK13CT002 (V2_32)
      2.2.7. MBK14CT001 (V2_41)
      2.2.8. MBK14CT002 (V2_42)
   2.3. Failure of vibration sensors of the radial bearing system (V3)
      2.3.1. MBK10CY001 (V3_1)

2.3.2. MBK10CY002 (V3_2)

2.4. Shell of the radial bearing system got damaged (V4)

V2 basic event refers to thermocouples MBK11CT001/2, MBK12CT001/2, MBK13CT001/2, MBK14CT001/2 connecting via four “AND” gates. V3 basic event refers to MBK10CY001/2, seismic pick-up connecting via an “AND” gate.

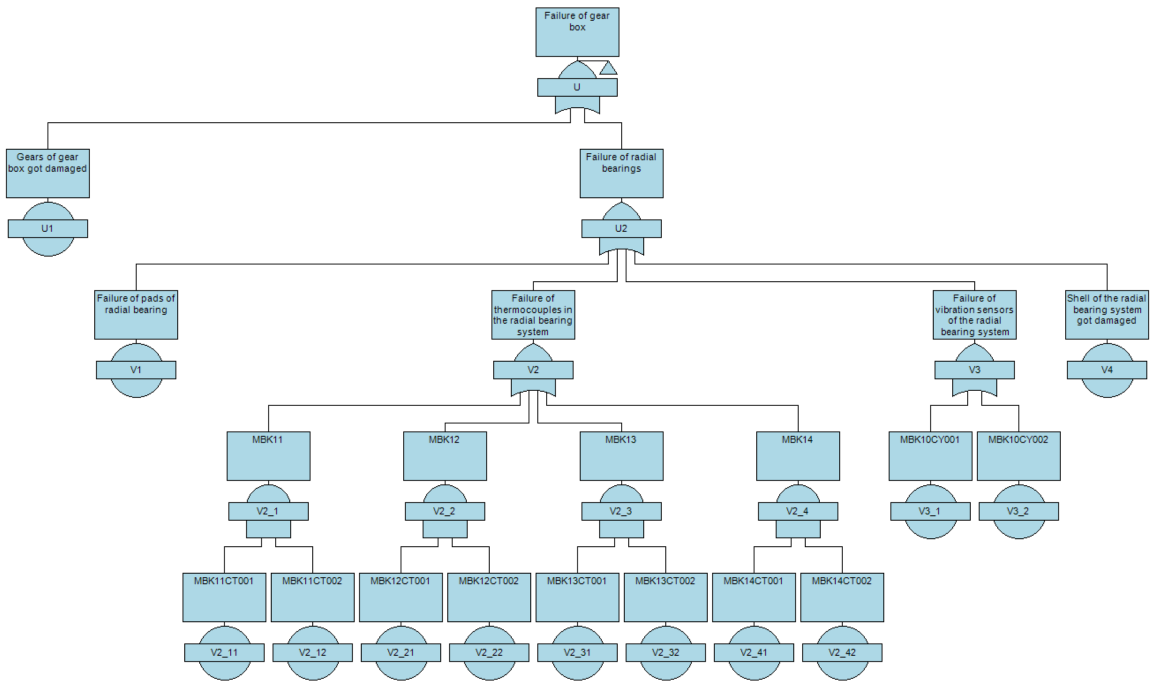


Figure 17 Proposed Fault tree of gear box

3.4 Failure model

In order to achieve this analysis, a failure model had to be made for each basic event. The program offers various failure models listed below:

- Fixed
  - Fixed probability of failure
  - Failures on demand, operator errors, software bugs, conditional events
- Rate, rate-MTTR, MTTF
  - Constant, exponentially-distributed failure rate
  - Repairable or non-repairable
- Time at risk
  - Non-repairable components with an exposure time
  - Usually in aerospace
- Dormant
  - Hidden or latent failures
  - Only revealed on testing

- IEC61508, IEC61508 FT
    - Safe and dangerous, detected and undetected failure modes
    - Imperfect testing
- Weibull
    - Failure rate varies with time

The model used for this analysis, is the Weibull model since the failure data, collected from the power plant, varied with time.

The Weibull distribution is quite often used in reliability analysis applications rather than other distributions because it has the advantage to adapt its form depending on the sample values. So, we can have as a result a variety of distribution shapes.

The data collected begin 1/1/2003 and end 31/12/2019. After collecting the data, they got assigned to the basic events of the fault tree and calculations had to be made in order to obtain the operating hours of each component. After that, 2 parameter Weibull set distribution was created for each basic event by applying the operating hours of every component before it failed. The isograph reliability workbench calculates itself the two Weibull parameters after the application of the operating hours has been assigned:

- β, the shape parameter
- η, the scale parameter (or characteristic life)

The Weibull sets were then assigned to the fault tree.

For some basic events no failures happened during the 17 years of system's lifetime, so a generic failure model had to be created. A rate model was created with zero failure rate.

4. Results

Tables 3 to 14 present the analysis results for each discussed sub-system. In the reliability analysis is included the Availability, the Frequency of failures and Reliability among all components of the subsystems in yearly scale.

Generator system Failure	
Availability	0.9999586
Frequency of failures (per year)	0.00008264
Reliability	0.998596

Table 3 Generator system Result Summary

Air inlet system Failure	
Availability	0.9999997249
Frequency of failures (per year)	0.0000005531
Reliability	0.999990598

Table 4 Air-inlet system Result Summary

Compressor system Failure	
Availability	0.9998562
Frequency of failures (per year)	0.0002864
Reliability	0.995143

Table 5 Compressor system Result Summary

Combustion system Failure	
Availability	0.9997486
Frequency of failures (per year)	0.0005015
Reliability	0.991509

Table 6 Combustion system Result Summary

Turbine system Failure	
Availability	0.9994327
Frequency of failures (per year)	0.001129
Reliability	0.98097

Table 7 Turbine system Result Summary

Starting system Failure	
Availability	0.9997718
Frequency of failures (per year)	0.0004545
Reliability	0.992301

Table 8 Starting system Result Summary

Fuel regulating system Failure	
Availability	0.998957
Frequency of failures (per year)	0.002075
Reliability	0.9653

Table 9 Fuel regulating system Result Summary

Lubrication system Failure	
Availability	0.9999732
Frequency of failures (per year)	0.00005353
Reliability	0.9990903

Table 10 Lubrication system Result Summary

Electrical auxiliaries system Failure	
Availability	0.9993974
Frequency of failures (per year)	0.001198
Reliability	0.97983

Table 11 Electrical auxiliaries system Result Summary

Turbine control system Failure	
Availability	0.999998065
Frequency of failures (per year)	0.000003878
Reliability	0.99993408

Table 12 Turbine control system Result Summary

Gear Box system Failure	
Availability	1
Frequency of failures (per year)	0
Reliability	1

Table 13 Gear Box system Result summary

Total system Failure	
Availability	0.997096
Frequency of failures (per year)	0.005773
Reliability	0.90627

Table 14 Total system Result Summary

Gear Box system's reliability and Availability is 100%, since there has never occurred any fault or failure during the 17 years time.

Along with the reliability analysis it is useful to present the importance analysis of each component of each sub-system. Importance measures establish the significance for all the events in the Fault Tree in terms of their contributions to the top event probability. Both intermediate events (gate events) as well as basic events can be prioritized according to their importance [18]. The importance analysis is based on three basic Fault Tree

Importance measures which include the Fussell-Vesely (FV) Importance, the Risk Achievement Worth (RAW) and the Risk Reduction Worth (RRW) [18]. The Fussell-Vesely importance indicates the relative contribution to the system failure probability from a component failure. Increasing the availability of components with high important values will have the most significant effect on system availability, consequence frequency or risk. The Risk Achievement Worth indicator represents the worth of the component associated with the Fault Tree event in achieving the present level of risk and indicates the importance of maintaining the present level of reliability for the component. The Risk Reduction Worth importance represents the maximum reduction in risk for an improvement to the component associated with the Fault Tree event.

Results

Summary · Importance · Cut sets · Correlation · Appearance

Event ID	Fussell-Vesely	Risk Reduction Worth	Risk Achievement Worth
M*	0.3589	1.56	344.7
Q*	0.2073	1.262	344.8
I*	0.1952	1.242	344.8
G*	0.08648	1.095	344.9
K*	0.07852	1.085	344.9
E*	0.04946	1.052	345
A*	0.01424	1.014	345
O*	0.009219	1.009	345
S*	0.0006656	1.001	345
C*	9.465E-05	1	345
U*	0	1	345

Figure 18 Importance of total failure model

Figure 17 regards M, fuel regulating system as the most important component of the system.

5. Conclusions and Further Research

Performing a reliability analysis through FTA approach a sufficient amount of data is needed, along with information from maintenance sheets and diagrams indicating connections between all components of the systems. The reliability and importance results, as derived from a quantitative analysis, seem to be expected according to the faults and failures happened through out the 17 years. However, the installation of the gas-turbine happened in 1992 and the data collected in this Thesis are since January 1^{st},2003 until December 31^{st},2019, since there were no records from the previous years.

In the generator protection system, electronic relays of channel 1 and channel 2 could be comprised. The exciter is a synchronous generator that its output is rectified to feed the generator rotor and should be further analyzed. Automatic voltage regulator and synchronization system comprise various modules which could be analyzed. Thyristors' firing control system could be expanded since it also comprises various modules. In turbine control system, controllers, input modules, output modules could be more analyzed, since it consists of various modules. Finally, at Electrical auxiliaries the medium and low voltage breakers could be recorded.

As a result, the data collected and the results of the analysis are not sufficient. When more failure data are available from other subsystems, a relative research could illustrate a more holistic view of the reliability of this gas turbine.

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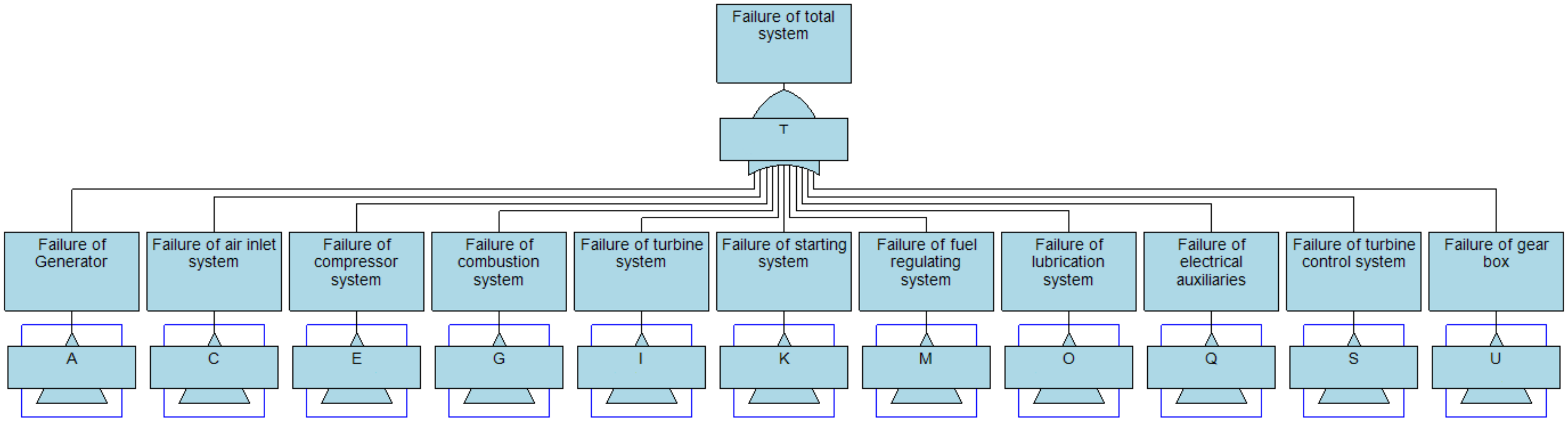
Appendix


Failure of total system
T
Failure of Generator
Failure of air inlet system
Failure of compressor system
Failure of combustion system
Failure of turbine system
Failure of starting system
Failure of fuel regulating system
Failure of lubrication system
Failure of electrical auxiliaries
Failure of turbine control system
Failure of gear box
A
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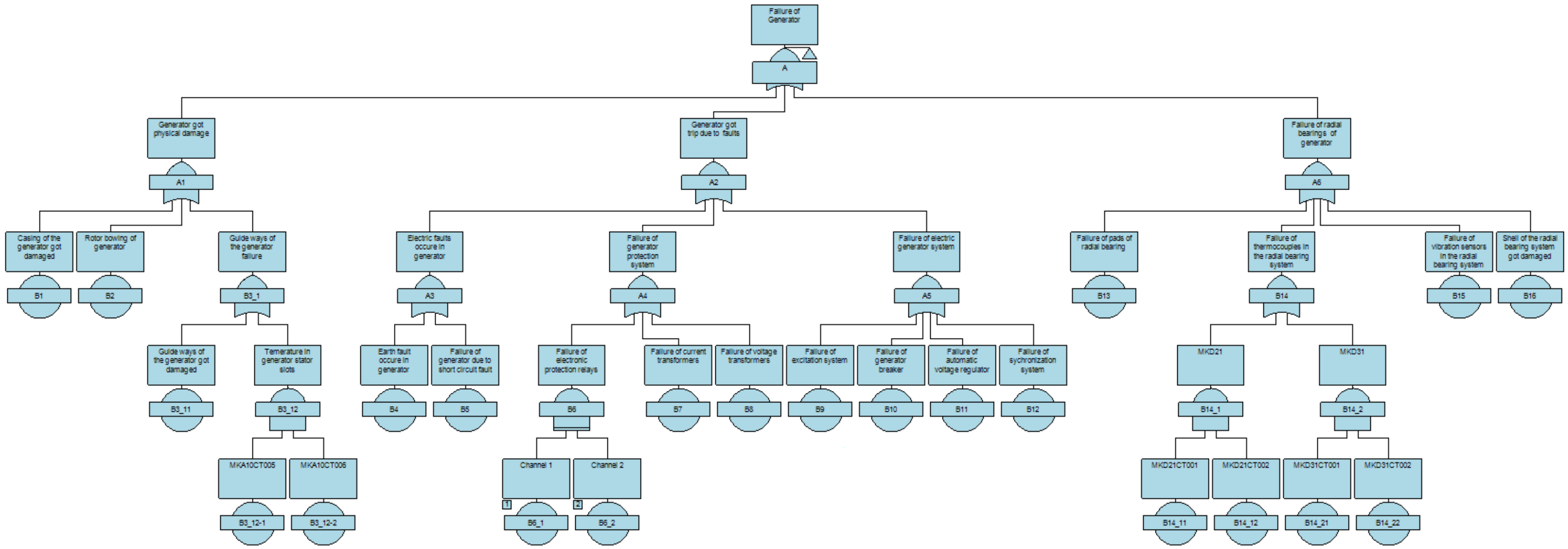
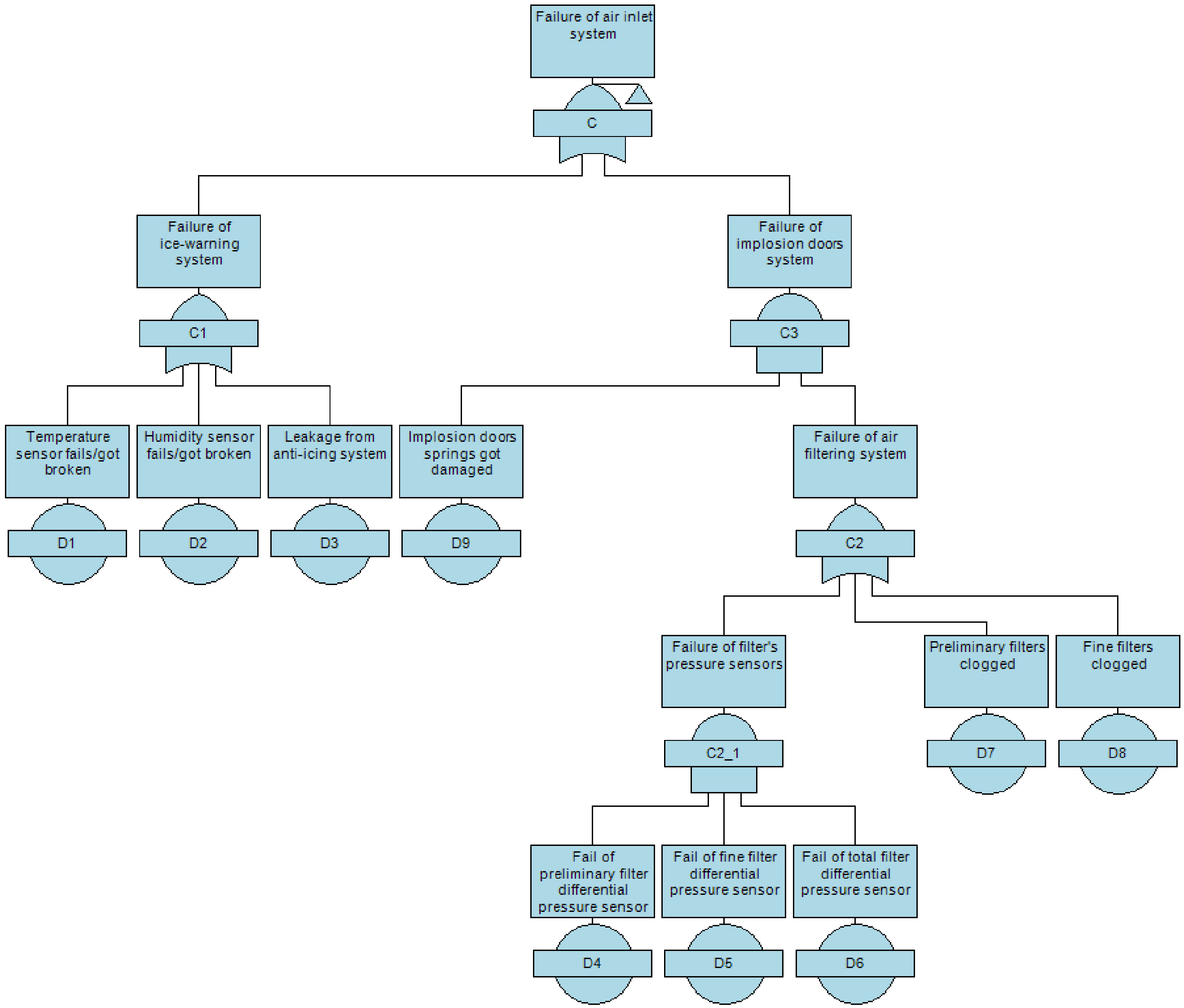
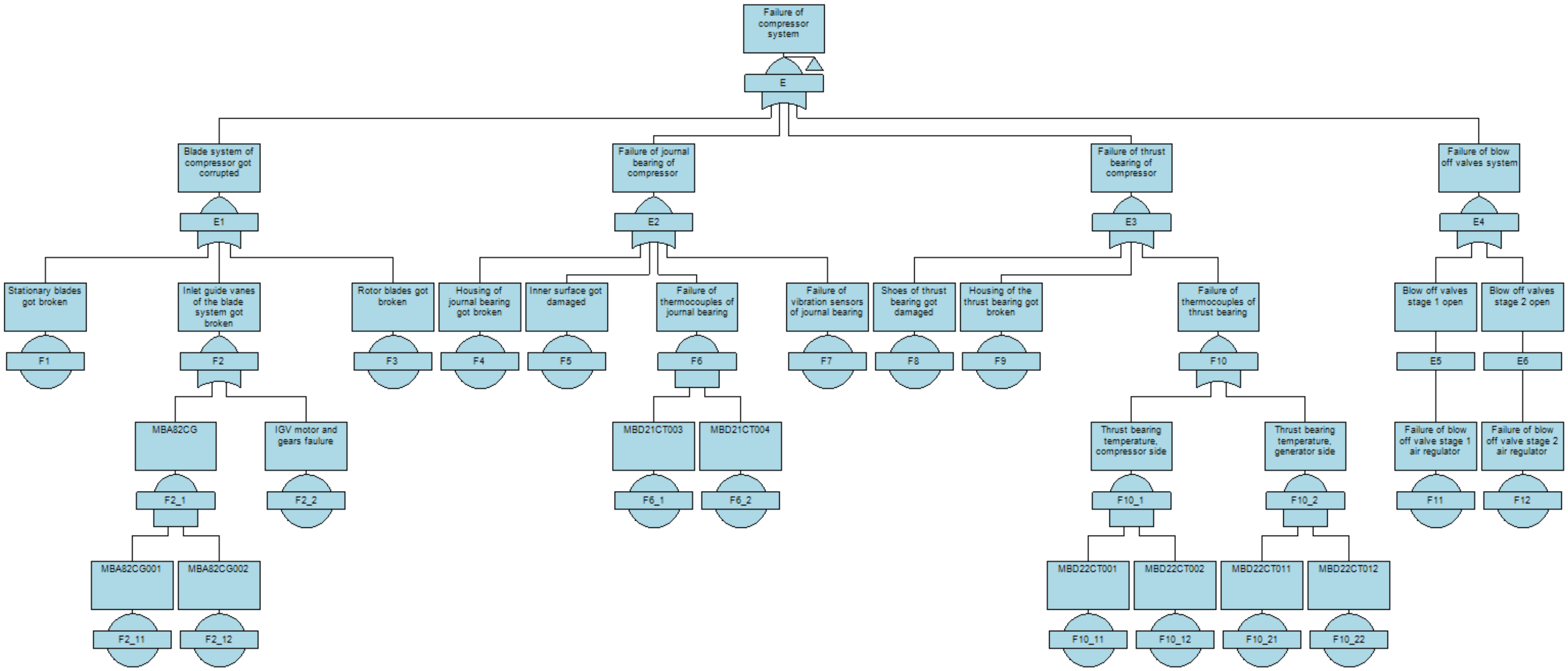
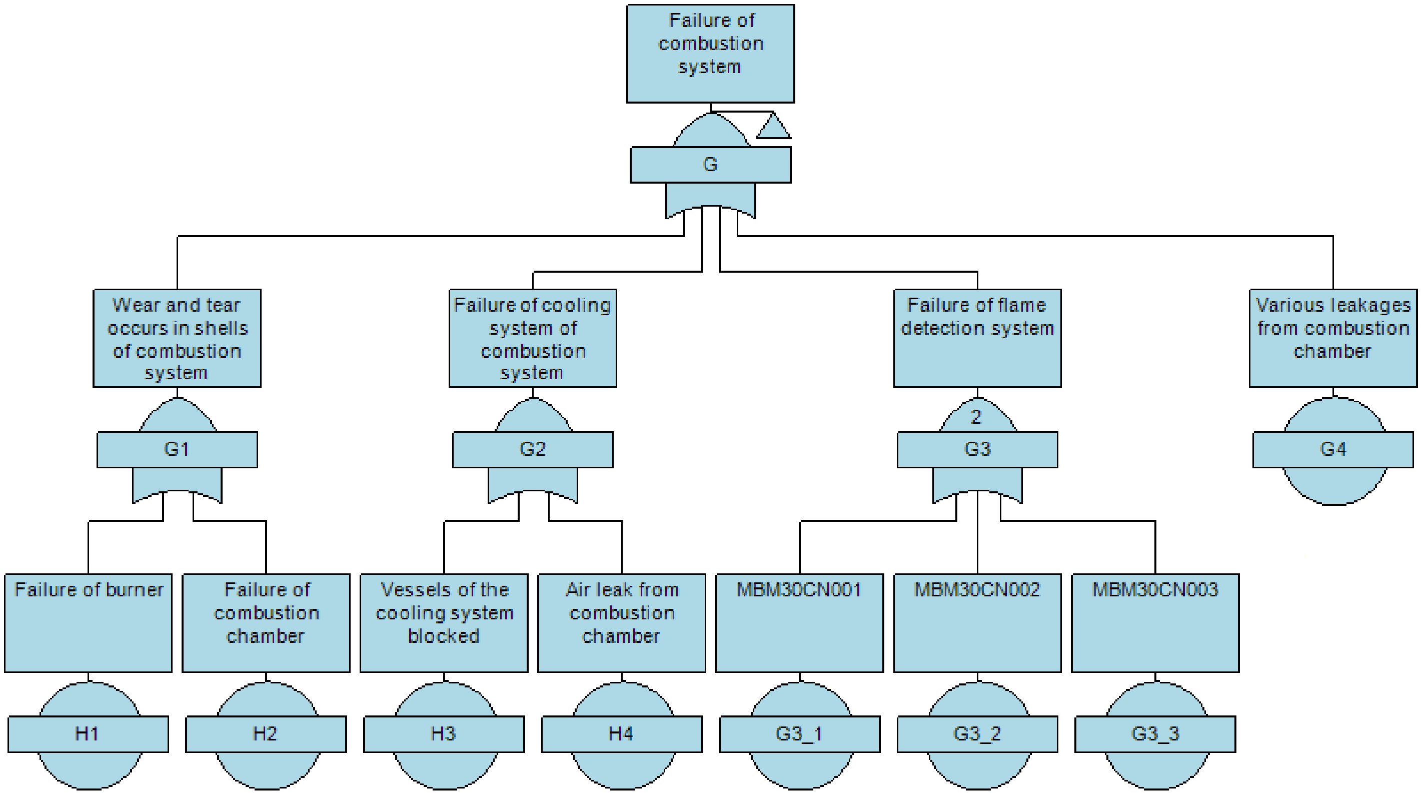
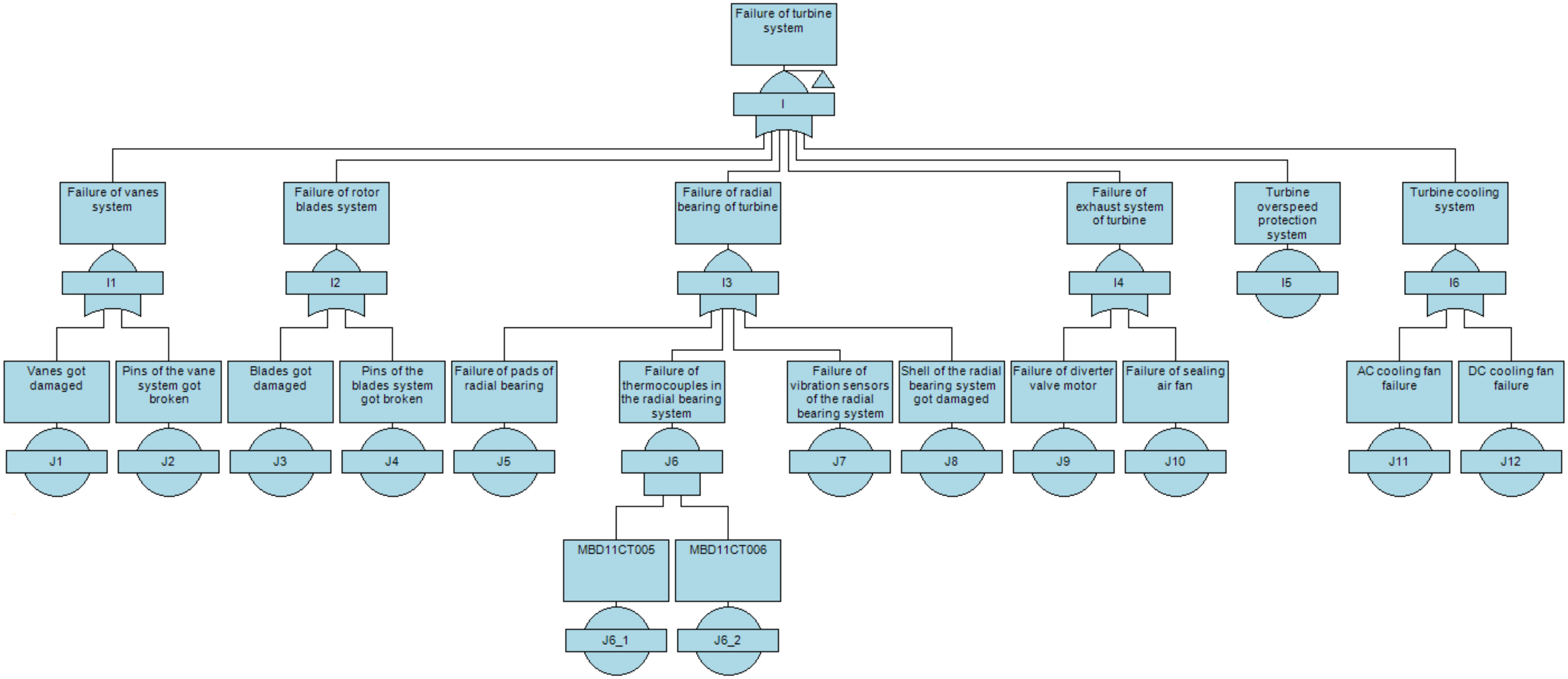


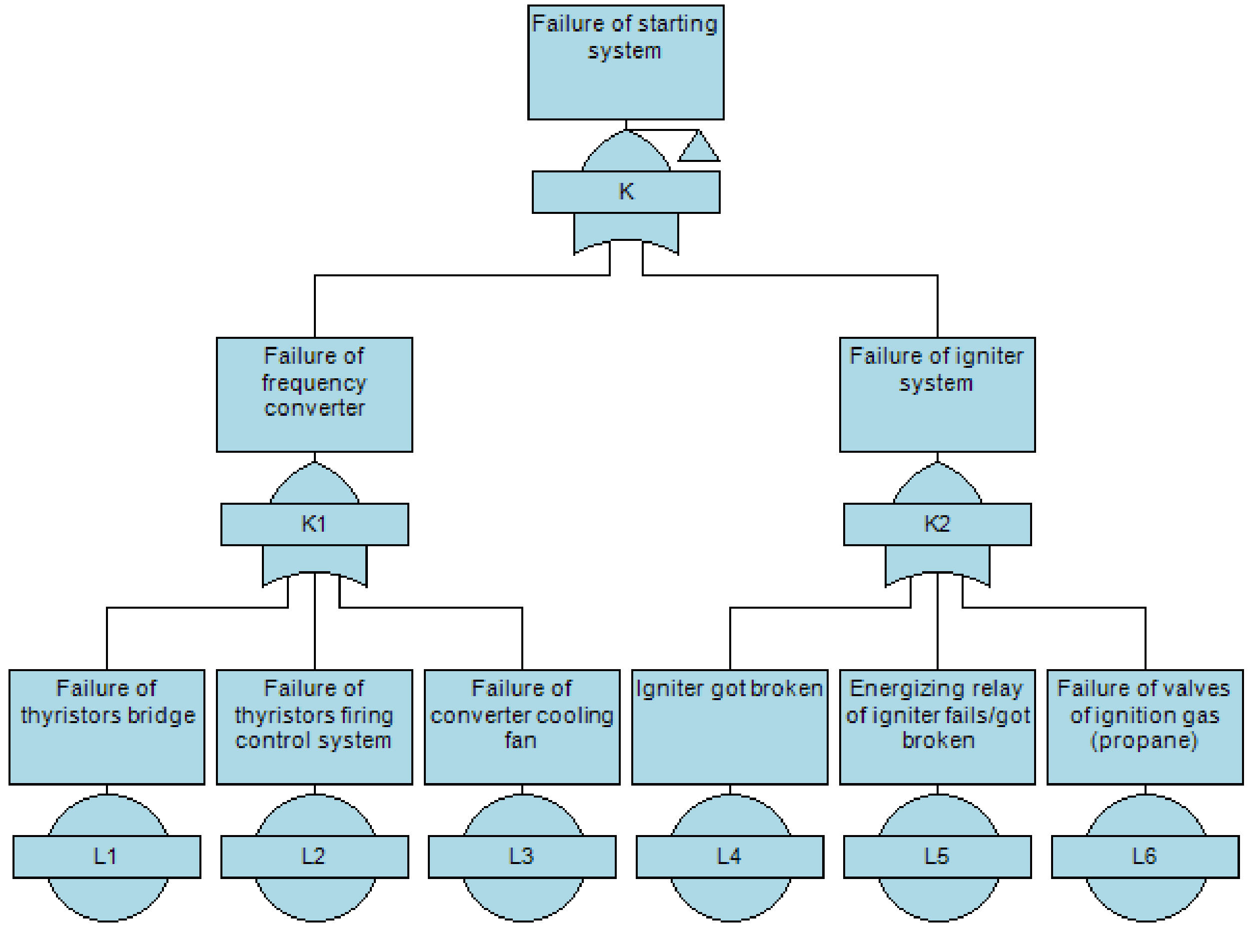
Failure of Generator
A
Generator got physical damage
A1
Casing of the generator got damaged
B1
Rotor bowing of generator
B2
Guide ways of the generator failure
B3_1
Guide ways of the generator got damaged
B3_11
Temerature in generator stator slots
B3_12
MKA10CT005
B3_12-1
MKA10CT006
B3_12-2
Generator got trip due to faults
A2
Electric faults occure in generator
A3
Earth fault occure in generator
B4
Failure of generator due to short circuit fault
B5
Failure of generator protection system
A4
Failure of electronic protection relays
B6
Channel 1
1
B6_1
Channel 2
2
B6_2
Failure of current transformers
B7
Failure of voltage transformers
B8
Failure of electric generator system
A5
Failure of excitation system
B9
Failure of generator breaker
B10
Failure of automatic voltage regulator
B11
Failure of sychronization system
B12
Failure of radial bearings of generator
A6
Failure of pads of radial bearing
B13
Failure of thermocouples in the radial bearing system
B14
MKD21
B14_1
MKD21CT001
B14_11
MKD21CT002
B14_12
MKD31
B14_2
MKD31CT001
B14_21
MKD31CT002
B14_22
Failure of vibration sensors in the radial bearing system
B15
Shell of the radial bearing system got damaged
B16

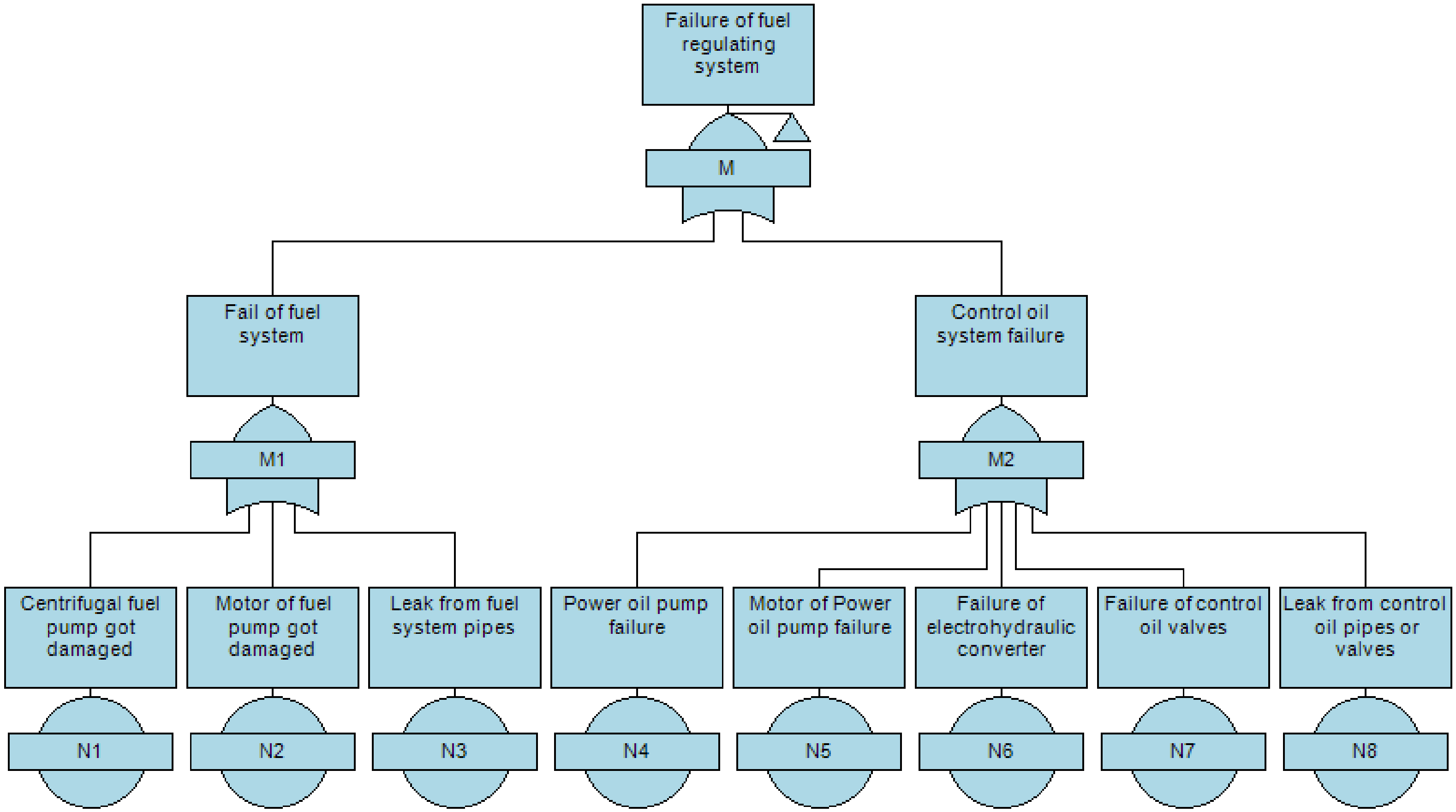

Failure of air inlet system
C
Failure of ice-warning system
C1
Failure of implosion doors system
C3
Temperature sensor fails/got broken
D1
Humidity sensor fails/got broken
D2
Leakage from anti-icing system
D3
Implosion doors springs got damaged
D9
Failure of air filtering system
C2
Failure of filter's pressure sensors
C2_1
Preliminary filters clogged
D7
Fine filters clogged
D8
Fail of preliminary filter differential pressure sensor
D4
Fail of fine filter differential pressure sensor
D5
Fail of total filter differential pressure sensor
D6

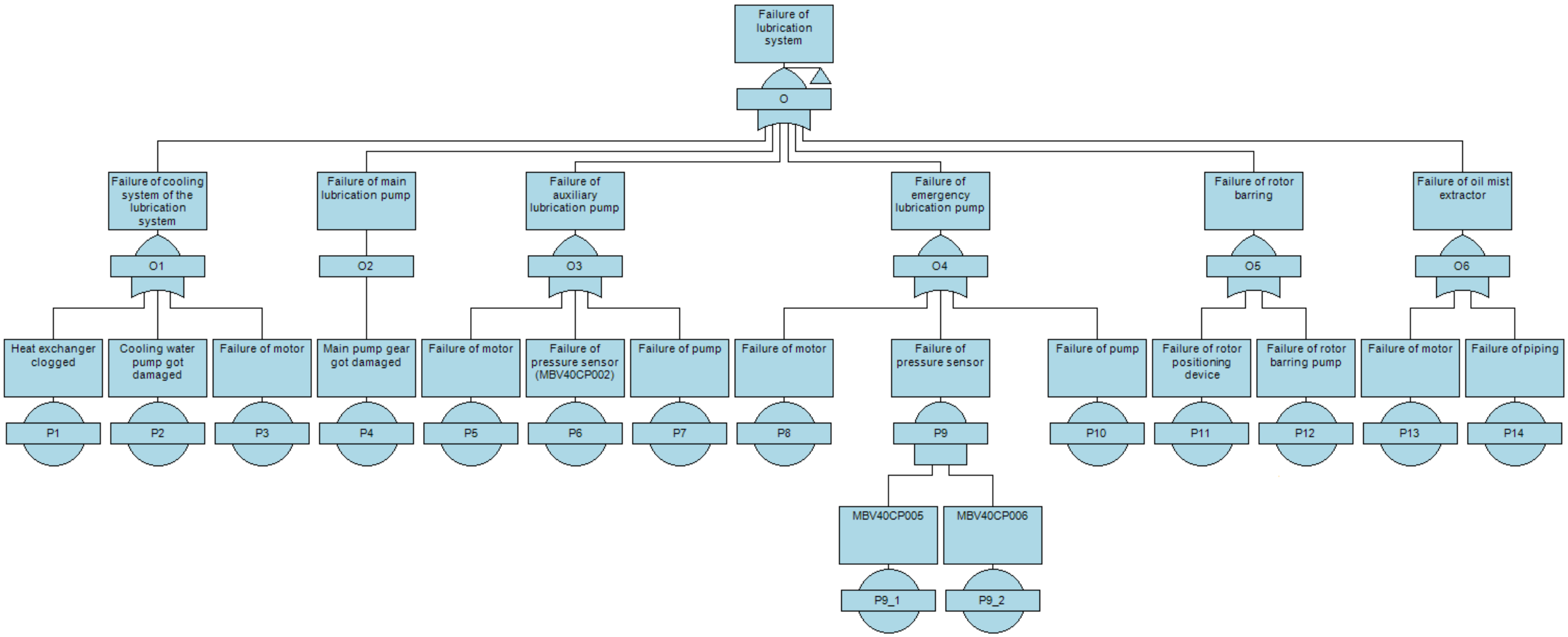

Failure of compressor system
E
Blade system of compressor got corrupted
E1
Failure of journal bearing of compressor
E2
Failure of thrust bearing of compressor
E3
Failure of blow off valves system
E4
Stationary blades got broken
F1
Inlet guide vanes of the blade system got broken
F2
Rotor blades got broken
F3
Housing of journal bearing got broken
F4
Inner surface got damaged
F5
Failure of thermocouples of journal bearing
F6
Failure of vibration sensors of journal bearing
F7
Shoes of thrust bearing got damaged
F8
Housing of the thrust bearing got broken
F9
Failure of thermocouples of thrust bearing
F10
Blow off valves stage 1 open
E5
Blow off valves stage 2 open
E6
MBA82CG
F2_1
IGV motor and gears faulure
F2_2
MBD21CT003
F6_1
MBD21CT004
F6_2
Thrust bearing temperature, compressor side
F10_1
Thrust bearing temperature, generator side
F10_2
Failure of blow off valve stage 1 air regulator
F11
Failure of blow off valve stage 2 air regulator
F12
MBA82CG001
F2_11
MBA82CG002
F2_12
MBD22CT001
F10_11
MBD22CT002
F10_12
MBD22CT011
F10_21
MBD22CT012
F10_22


Failure of combustion system
G
Wear and tear occurs in shells of combustion system
G1
Failure of cooling system of combustion system
G2
Failure of flame detection system
2
G3
Various leakages from combustion chamber
G4
Failure of burner
H1
Failure of combustion chamber
H2
Vessels of the cooling system blocked
H3
Air leak from combustion chamber
H4
MBM30CN001
G3_1
MBM30CN002
G3_2
MBM30CN003
G3_3

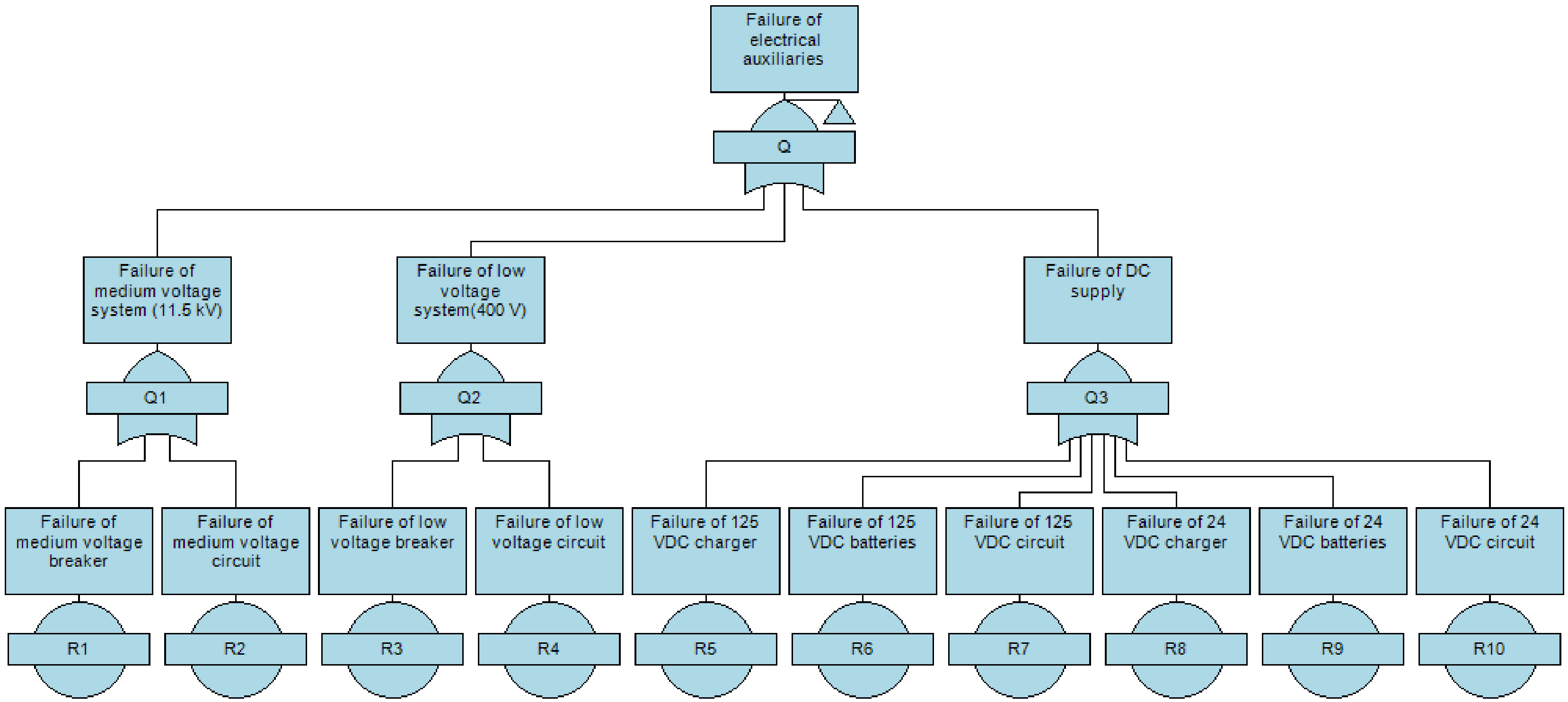

Failure of turbine system
I
Failure of vanes system
I1
Failure of rotor blades system
I2
Failure of radial bearing of turbine
I3
Failure of exhaust system of turbine
I4
Turbine overspeed protection system
I5
Turbine cooling system
I6
Vanes got damaged
J1
Pins of the vane system got broken
J2
Blades got damaged
J3
Pins of the blades system got broken
J4
Failure of pads of radial bearing
J5
Failure of thermocouples in the radial bearing system
J6
Failure of vibration sensors of the radial bearing system
J7
Shell of the radial bearing system got damaged
J8
Failure of diverter valve motor
J9
Failure of sealing air fan
J10
AC cooling fan failure
J11
DC cooling fan failure
J12
MBD11CT005
J6_1
MBD11CT006
J6_2

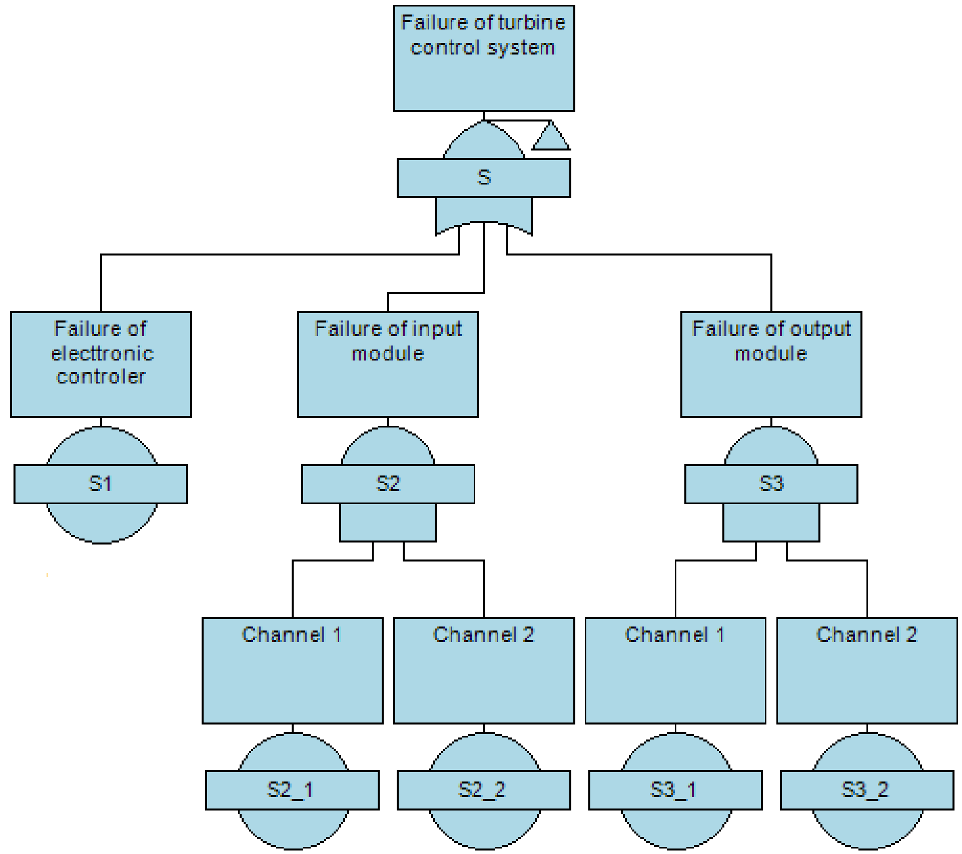

Failure of starting system
K
Failure of frequency converter
Failure of igniter system
K1
K2
Failure of thyristors bridge
Failure of thyristors firing control system
Failure of converter cooling fan
Igniter got broken
Energizing relay of igniter fails/got broken
Failure of valves of ignition gas (propane)
L1
L2
L3
L4
L5
L6

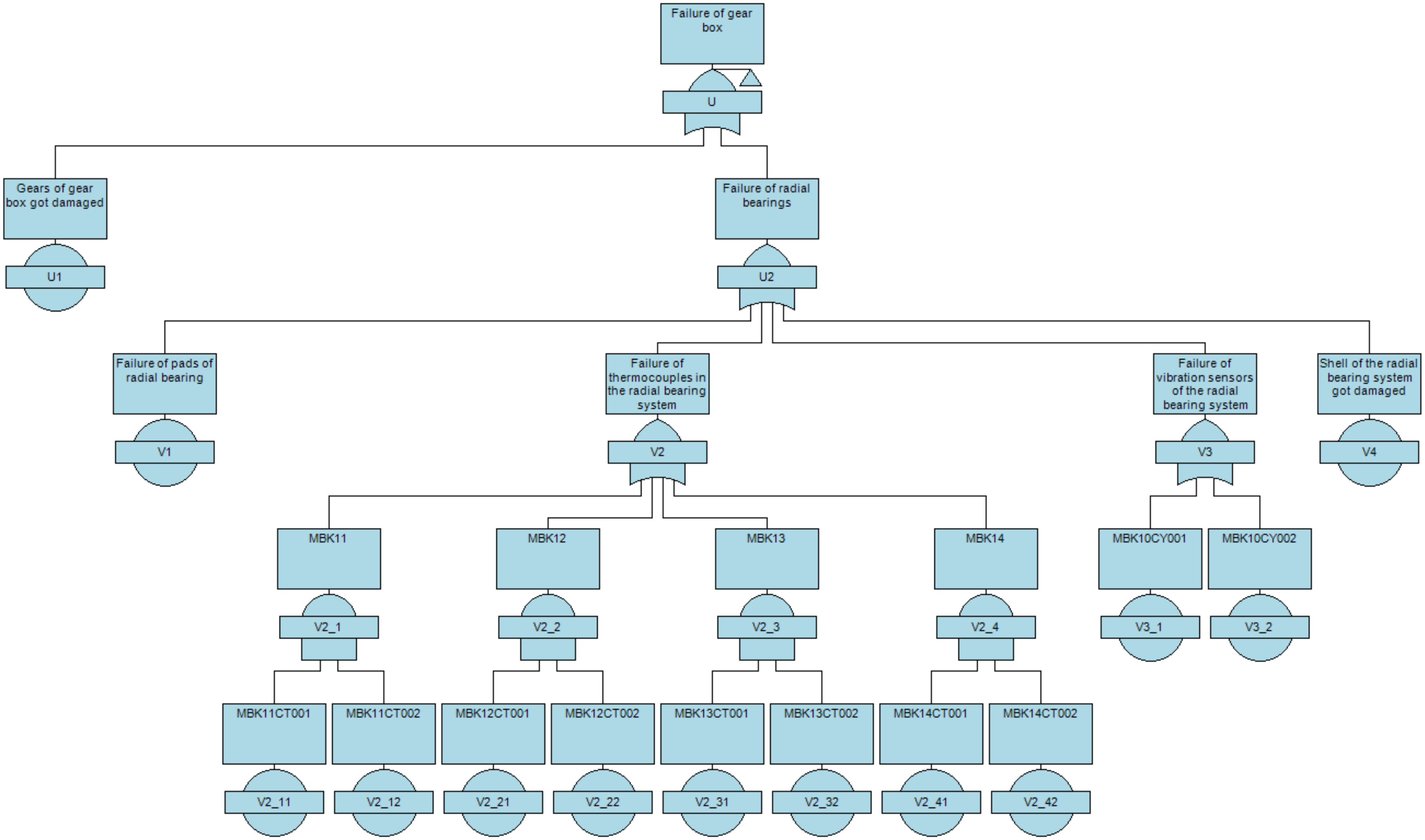

Failure of fuel regulating system
M
Fail of fuel system
Control oil system failure
M1
M2
Centrifugal fuel pump got damaged
Motor of fuel pump got damaged
Leak from fuel system pipes
Power oil pump failure
Motor of Power oil pump failure
Failure of electrohydraulic converter
Failure of control oil valves
Leak from control oil pipes or valves
N1
N2
N3
N4
N5
N6
N7
N8



Failure of lubrication system
O
Failure of cooling system of the lubrication system
O1
Failure of main lubrication pump
O2
Failure of auxiliary lubrication pump
O3
Failure of emergency lubrication pump
O4
Failure of rotor barring
O5
Failure of oil mist extractor
O6
Heat exchanger clogged
P1
Cooling water pump got damaged
P2
Failure of motor
P3
Main pump gear got damaged
P4
Failure of motor
P5
Failure of pressure sensor (MBV40CP002)
P6
Failure of pump
P7
Failure of motor
P8
Failure of pressure sensor
P9
Failure of pump
P10
Failure of rotor positioning device
P11
Failure of rotor barring pump
P12
Failure of motor
P13
Failure of piping
P14
MBV40CP005
P9_1
MBV40CP006
P9_2


Failure of electrical auxiliaries
Q
Failure of medium voltage system (11.5 kV)
Failure of low voltage system(400 V)
Failure of DC supply
Q1
Q2
Q3
Failure of medium voltage breaker
Failure of medium voltage circuit
Failure of low voltage breaker
Failure of low voltage circuit
Failure of 125 VDC charger
Failure of 125 VDC batteries
Failure of 125 VDC circuit
Failure of 24 VDC charger
Failure of 24 VDC batteries
Failure of 24 VDC circuit
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10


Failure of turbine control system
S
Failure of electtronic controler
S1
Failure of input module
S2
Failure of output module
S3
Channel 1
Channel 2
Channel 1
Channel 2
S2_1
S2_2
S3_1
S3_2



Failure of gear box
U
Gears of gear box got damaged
U1
Failure of radial bearings
U2
Failure of pads of radial bearing
V1
Failure of thermocouples in the radial bearing system
V2
Failure of vibration sensors of the radial bearing system
V3
Shell of the radial bearing system got damaged
V4
MBK11
V2_1
MBK12
V2_2
MBK13
V2_3
MBK14
V2_4
MBK10CY001
V3_1
MBK10CY002
V3_2
MBK11CT001
V2_11
MBK11CT002
V2_12
MBK12CT001
V2_21
MBK12CT002
V2_22
MBK13CT001
V2_31
MBK13CT002
V2_32
MBK14CT001
V2_41
MBK14CT002
V2_42

A: Failure of Generator		C: Failure of air inlet system		E: Failure of compressor system		G: Failure of combustion system		I: Failure of turbine system	
A1: Generator got physical damage	B1: Casing of the generator got damaged	C1: Failure of ice-warning system	D1: Temperature sensor fails/got broken	E1: Blade system of compressor got corrupted	F1:Stationary blades got broken	G1: Wear and tear occurs in shells of combustion system	H1: Failure of burner	I1: Failure of vanes system	J1: Vanes got damaged
	B2: Rotor bowing of generator		D2: Humidity sensor fails/got broken		F2: Inlet guide vanes of the blade system got broken		H2: Failure of combustion chamber		J2: Pins of the vane system got broken
	B3: Guide ways of the generator got damaged		D3:Leakage from anti-icing system		F2_1: MBA82	G2: Failure of cooling system of combustion system	H3: Vessels of the cooling system blocked	I2: Failure of rotor blades system	J3: Blades got damaged
	B3_1: Guide ways of the generator got damaged	C2: Failure of air filtering system	C2_1: Failure of air filtering system pressure		F2_11: MBA82CG001		H4: Air leak from combustion chamber		J4: Pins of the blades system got broken
	B3_2: Temp in generator stator slots		D4: Fail of preliminary filter differential pressure		F2_12: MBA82CG002	G3: Failure of flame detection system		I3: Failure of radial bearing of turbine	J5: Failure of pads of radial bearing
	B3_21: MKA10CT005		D5: Fail of fine filter differential pressure		F2_2: IGV motor and gears failure	G3_1: MBM30CN001			J6: Failure of thermocouples in the radial bearing system

	B3_22: MKA10CT006		D6: Fail of total filter differential pressure sensor		F3: Rotor blades got broken	G3_2: MBM30CN002			J6_1: MBD11CT005
A2: Generator got trip due to faults			D7: Preliminary filters clogged	E2: Failure of journal bearing of compressor	F4: Housing of journal bearing got broken	G3_3: MBM30CN003			J6_2: MBD11CT006
A3: Electric faults occur in generator	B4: Earth fault occure in generator		D8: Fine filters clogged		F5: Inner surface got damaged	G4: Various leakages from combustion			J7: Failure of vibration sensors of the radial bearing
	B5: Failure of generator due to short circuit fault	C3: Failure of implosion doors system	D9: Implosion doors springs got damaged		F6: Failure of thermocouples of journal bearing				J8: Shell of the radial bearing system got damaged
A4: Failure of generator protection system	B6: Failure of electronic protection relays				F6_1: MBD21CT003			I4: Failure of exhaust system of	J9:Failure of diverter valve motor
	B6_1:Electronic protection relays channel 1				F6_2: MBD21CT004				J10: Failure of sealing air fan
	B6_2:Electronic protection relays channel 2				F7: Failure of vibration sensors of journal bearing			I5:Turbine overspeed protection system	
	B7: Failure of current transformers			E3: Failure of thrust bearing of compressor	F8: Shoes of thrust bearing got damaged			I6: Turbine cooling system	J11: AC cooling fan failure
	B8: Failure of voltage transformers				F9: Housing of the thrust bearing got				J12: DC cooling fan failure
A5: Failure of electric generator system	B9: Failure of excitation system				F10: Failure of thermocouples of thrust bearing				

	B10: Failure of generator breaker				F10_1: Thrust bearing temperature compressor side				
	B11: Failure of automatic voltage regulator				F10_11: MBD22CT001				
	B12: Failure of sychronization system				F10_12: MBD22CT002				
A6: Failure of radial bearings of generator	B13 : Failure of pads of radial bearing				F10_2: Thrust bearing temperature generator side				
	B14: Failure of thermocouples in the radial bearing system				F10_21: MBD22CT011				
	B14_1: Bearing MKD21				F10_22: MBD22CT012				
	B14_11: MKD21CT001			E4: Failure of blow off valves system					
	B14_12: MKD21CT002			E5:Blow off valves stage 1 open	F11: Failure of blow off valve stage 1 air regulator				
	B14_2: Bearing MKD31			E6: Blow off valves stage 2 open	F12: Failure of blow off valve stage 2 air regulator				
	B14_21: MKD31CT001								
	B14_22: MKD31CT002								
	B15: Failure of vibration sensors in the radial bearing								
	B16: Shell of the radial bearing system got damaged								

K: Failure of starting system		M:Failure of fuel regulating system		O: Failure of lubrication system		Q: Failure of electrical auxiliaries		S:Failure of turbine control system	U: Failure of gear box	
K1: Failure of frequency converter	L1: Failure of thyristors bridge	M1: Fail of fuel system	N1: Centrifugal fuel pump got damaged	O1: Failure of cooling system of the lubrication system	P1: Heat exchanger clogged	Q1: Failure of medium voltage system (11.5 kV)	R1:Failure of medium voltage breaker	S1:Failure of electronic controler	U1:Gears of gear box got damaged	
	L2: Failure of thyristors firing control		N2: Motor of fuel pump got damaged		P2: Cooling water pump got damaged		R2: Failure of medium voltage circuit	S2:Failure of input module	U2: Failure of radial bearings	V1: Failure of pads of radial bearings
	L3: Failure of converter cooling fan		N3: Leak from fuel system pipes		P3: Failure of motor	Q2: Failure of low voltage system(400 V)	R3:Failure of low voltage breaker	S2_1:Failure of input module channel 1		V2: Failure of thermocouples in the radial
K2: Failure of igniter system	L4: Igniter got broken	M2:Control oil system failure	N4: Power oil pump failure	O2: Failure of main lubrication pump	P4: Main pump gear got damaged		R4:Failure of low voltage circuit	S2_2:Failure of input module channel 2		V2_1: Bearing MBK11
	L5: Energizing relay of igniter fails/got		N5: Motor of Power oil pump failure	O3: Failure of auxiliary lubrication pump	P5: Failure of motor	Q3: Failure of DC supply	R5: Failure of 125 VDC charger	S3:Failure of output module		V2_11: MBK11CT001
	L6: Failure of valves of ignition gas (propane)		N6: Failure of electrohydraulic converter		P6: Failure of pressure sensor (MBV40CP002)		R6: Failure of 125 VDC batteries	S3_1:Failure of output module channel 1		V2_12: MBK11CT002

			N7:Failure of control oil valves		P7: Failure of pump		R7: Failure of 125 VDC circuit	S3_2:Failure of output module channel 2		V2_2: Bearing MBK12
			N8: Leak from control oil pipes or valves	O4:Failure of emergency lubrication	P8: Failure of motor		R8: Failure of 24 VDC charger			V2_21: MBK12CT001
					P9: Failure of pressure sensor (MBV40CP005-6)		R9: Failure of 24 VDC batteries			V2_22: MBK12CT002
					P9_1: MBV40CP005		R10: Failure of 24 VDC circuit			V2_3: Bearing MBK13
					P9_2: MBV40CP006					V2_31: MBK13CT001
					P10: Failure of pump					V2_32: MBK13CT002
				O5:Failure of rotor barring	P11: Failure of rotor positioning device					V2_4: Bearing MBK14
					P12:Failure of rotor barring pump					V2_41: MBK14CT001
				O6:Failure of oil mist extractor	P13: Failure of motor					V2_42: MBK14CT002
					P14:Failure of piping					V3: Failure of vibration sensors of the radial bearing system

										V3_1: MBK10CY001
										V3_2: MBK10CY002
										V4: Shell of the radial bearing system got

KKS No.	Object	Device/Setting/Range	ERROR	AUTOMATIC ACTIONS	OPERATOR ACTIONS
=MBA02	**BEARING SUPPORT COOLING**				
=MBA02CP001	Diff. pressure switch for air suction filter Switching point increasing Switching pointdecreasing	-60 mmWC -45 mmWC	Dirty filter		Change filters
=MBA02CP002	Pressure switch for bearing support cooling Switching point decreasing	100 mmWC	Low pressure after filter	Start emergency fan.	Check AC fan. Check filters
=MBA02CP003	Pressure switch for bearing support cooling Switching point decreasing	100 mmWC	Low pressure after filter	Start emergency fan.	Check AC fan. Check filters
=MBA02CP004	Pressure switch for pressure after fan Switching point decreasing Switching point increasing	100 mmWC 108 mmWC	Low pressure after filter	GT load shedding	
=MBA30	**GAS TURBINE**				
=MBA30CS001	Turbine speed		In case there is a difference more than 2% between CS001 and CS002 : "Difference between Channels"		
=MBA30CS002	Nominal speed generator Nominal speed measuring wheel Measuring wheel	3000 rpm 3000 rpm 60 teeth	In case there is a difference more than 2% between CS001 and CS002 : "Difference between Channels"		
=MBA30CT009	Rotor end face temperature cooling air, exhaust end Range of instrument Characteristic Alarm limit increasing	50-400 °C 360 °C	Insufficient turbine cooling		Planned shut down for checking cooling holes
=MBA30CT011-018	Exhaust gas temperature Range	Thermocouple NiCr-Ni 0°-600 °C 4-20 mA	The system uses the mean value of the 8 thermocouples. There are 2 alarm stages: TE2>580 TE2>600	If TE2>580 PLS. If TE2>600 Turbine trip	
=MBA31	**Fuel drain from Turbine**				
=MBA31CL001/002	Level Fuel Drain Tank Float Switch 1 Float Switch 2	not adjustable switch for drain pump Alarm level	As settings		
=MBA80	**COMPRESSOR**				
=MBA80CP005-8	Depression before 1st stationary row At 0% load At 100% load	1120 mmWC 1820 mmWC	Just for indication		
=MBA80CP011/012	Compressor discharge pressure		Just for indication		
=MBA80CT001-4	Compressor end temperature	Thermocouples Chromel-Alumel	Just for indication		
=MBA80CT005	Rotor cooling-air temperature, compressor Range of instrument Alarm limit increasing Reset limit decreasing	Thermocouple NiCr-Ni 0…1000 °C 0…41.263 mV 380 °C 375 °C	Insufficient turbine cooling. As settings		
=MBA80CT006	Rotor cooling-air temperature, compressor Range of instrument	Thermocouple NiCr-Ni 0…1000 °C 0…41.269 mV	Insufficient turbine cooling. As settings		
=MBA81	**COMPRESSOR BLOW-OFF SYSTEM**				
=MBA81AA011/012	Blow off valves stage 1		If open during operation alarm "Blow off valves stage 1 open"		
=MBA81AA021	Blow off valves stage 2		If open during operation alarm "Blow off valves stage 2 open"		
=MBA82	**COMPRESSOR VARIABLE INLET GUIDE VANES** Start up and load control				
=MBA82CG001-2	Angle measurement inlet guide vanes		In case there is a difference more than 2% between CG001 and CG002 : "Difference between Channels". In case there is a difference more than 2,4% between CG001 and CG002 : "IGV setting incorrect"	If IGV setting incorrect turbine trip	
=MBD10/11	**TURBINE BEARING**				
=MBD10CY001	Absolute vibration supervision	Seismic pick-up	> 10mm/sec alarm vibrations high. >17mm/sec alarm vibrations very high	If vibrations very high..turbine trip	
=MBD11CP001	Lube oil pressure after orifice				

=MBD11CT003	Oil drain temperature turbine bearing	Thermometer 0… 120 °C	Just for indication	
=MBD11CT004	Oil drain temperature turbine bearing	Thermometer 0… 120 °C	Just for indication	
=MBD11CT005	Oil drain temperature turbine bearing	PT 100(100 Ω/0 °C) 0… 1000 °C	As settings	As settings
	Alarm limit increasing	70 °C		
	Reset value	68 °C		
	Trip value increasing	80 °C		
	Reset value	78 °C		
=MBD11CT006	Oil drain temperature turbine bearing	PT 100(100 Ω/0 °C) 0… 1000 °C	As settings	As settings
	Alarm limit increasing	70 °C		
	Reset value	68 °C		
	Trip value increasing	80 °C		
	Reset value	78 °C		
=MBD20/21	**COMPRESSOR BEARING**			
=MBD20CY001	Absolute vibration supervision	Seismic pick-up	> 10mm/sec alarm vibrations high. >17mm/sec alarm vibrations very high	If vibrations very high..turbine trip
=MBD21CP001/2	Lube oil pressure after orifice		Just for indication	
=MBD21CT004	Oil drain metal temperature compressor bearing	PT 100(100 Ω/0 °C)	As settings	As settings
	signal input P13	0… 1000 °C		
	Alarm limit increasing	70 °C		
	Reset value	68 °C		
	Trip value increasing	80 °C		
	Reset value	78 °C		
=MBD21CT003	Oil drain temperature compressor bearing	Thermometer 0… 120 °C	Just for indication	
=MBD22	**THRUST BEARING**			
=MBD22CP001/002	Lube oil pressure after orifice		Just for indication	
=MBD22CT001/002	Thrust bearing temperature, compressor side	Double thermoelement NiCr-Ni 'Typ K' 0…1000 °C	As settings	As settings
	Alarm limit increasing	125 °C		
	Reset value	123 °C		
	Trip limit increasing	130 °C		
	Reset value	128 °C		
=MBD22CT003/004	Thrust bearing temperature, compressor side	Double thermoelement NiCr-Ni	Just for indication	
=MBD22CT011/012	Thrust bearing temperature, generator side	Double thermoelement NiCr-Ni 'Typ K' 0…1000 °C	As settings	As settings
	Alarm limit increasing	125 °C		
	Reset value	123 °C		
	Trip limit increasing	130 °C		
	Reset value	128 °C		
=MBD22CT013/14	Thrust bearing temperature generator side	Double thermoelement NiCr-Ni	Just for indication	
=MBD30/31	**INTERMEDIATE SHAFT BEARING**			
=MBD30CY001	Absolute vibration supervision	Seismic pick-up	> 10mm/sec alarm vibrations high. >17mm/sec alarm vibrations very high	If vibrations very high..turbine trip
=MBD31CP001/002	Lube oil pressure after orifice		Just for indication	
=MBD31CT003	Oil drain temperature intermediate bearing	Thermometer 0… 120 °C	Just for indication	
=MBD31CT004	Oil drain temperature intermediate bearing	PT 100(100 Ω/0 °C) 0… 1000 °C	As settings	As settings
	Alarm limit	65 °C		
	Reset value	63 °C		
	Trip limit	75 °C		
	Reset value	73 °C		
=MBH31	**COOLING AND SEALING AIR SYSTEM TURBINE EXHAUST GAS SIDE**			
=MBH31CF001	Sealing air massflow	Annubar measurement		
	Probe type	ANR73		
	Pipe inner diameter	101.7 mm		
	Characteristic sealing air flow			
=MBH32	**COOLING AIR SYSTEM FOR VANE CARRIER**			

=MBH32CF001	Cooling air massflow	Annubar measurement		
	Probe type	ANR73		
	Pipe inner diameter	64.9 mm		
	Characteristic cooling air massflow			
=MBH33	**COOLING AND SEALING AIR SYSTEM FOR TURBINE AND COMPRESSOR**			
=MBH33CP004	Differential pressure sealing air GT-side	Differential pressure transmitter	Just for indication	
	Characteristic	0...2.5 bar		
	Signal input P13	4...20 mA		
=MBH33CP008	Pressure measurement before Labyrinth		As settings	
	GT inlet	Pressure transmitter		
	Characteristic	0...20 bar		
	Signal input P13	4...20 mA		
	Alarm limit increasing	0.5		
=MBH41	**COOLING SYSTEM FOR COMBUSTER**			
=MBH41CT001	Cooling air temperature burner	Dial Thermometer	At switching point swiches off burner cooling	
	Switching point decreasing	50 °C	compressor	
=MBK10	**GEAR BOX**			
	Type: MAAG G72-S / 50 Hz			
	Main ratio			
	Power transmission			
	Serial No:	6340/3000 rpm		
	Gear wheel speed	55 MW		
	Gear wheel clearances	2-840660		
=MBK10CY001/2	**Absolute vibration supervision**		> 10mm/sec alarm vibrations high.	If vibrations very high..turbine trip
		Seismic pick-up	>17mm/sec alarm vibrations very high	
=MBK11 / 12 / 13 / 1	**GEAR JOURNAL BEARINGS**			
=MBK11CT001/2	Bearing metal temperature	Thermocouple NiCr-Ni	As settings	As settings
	Signal input P13	0...1000 °C		
	Alarm limit increasing	130 °C		
	Reset value	128 °C		
	Trip value increasing	135 °C		
	Reset value	133 °C		
=MBK12CT001/2	Bearing metal temperature	Thermocouple NiCr-Ni	As settings	As settings
	Signal input P13	0...1000 °C		
	Alarm limit increasing	130 °C		
	Reset value	128 °C		
	Trip value increasing	135 °C		
	Reset value	133 °C		
=MBK13CT001/2	Bearing metal temperature	Thermocouple NiCr-Ni	As settings	As settings
	Signal input P13	0...1000 °C		
	Alarm limit increasing	130 °C		
	Reset value	128 °C		
	Trip value increasing	135 °C		
	Reset value	133 °C		
=MBK14CT001/2	Bearing metal temperature	Thermocouple NiCr-Ni	As settings	As settings
	Signal input P13	0...1000 °C		
	Alarm limit increasing	130 °C		
	Reset value	128 °C		
	Trip value increasing	135 °C		
	Reset value	133 °C		
=MBK15	**GEAR THRUST BEARING**			
=MBK15CT001/2	Gear Thrust bearing	Thermocouple NiCr-Ni	As settings	As settings
	Alarm limit increasing	125 °C		
	Reset value	123 °C		
	Trip value increasing	130 °C		
	Reset value	128 °C		
=MBK15CT011/12	Gear Thrust bearing	Thermocouple NiCr-Ni	As settings	As settings
	Alarm limit increasing	125 °C		
	Reset value	123 °C		
	Trip value increasing	130 °C		
	Reset value	128 °C		
	Characteristic bearing metall temp.			
=MBL01	**AIR BEFORE AIR INTAKE LINE**			
=MBL01CM001	Humidity air atmosphere	0...100%		
=MBL01CT000	Ambient temperature	PT100 (100 Ω/0 °C)		
		0...1000 °C		

=MBL01CU001	Ice-warning If : Ambient temperature and: Humidity air ambient	 -7 °C...+7°C >70%	As settings		Open anti-icing motor valve to guide hot air from compressor's discharge to air inlet
=MBL30	**AIR INTAKE LINE**				
=MBL30AA001	Implosion doors with limit switches	Alarm if door open	Alarm: "Implosion doors open" in case that the implosion doors open due to high depression		
=MBL30CP001	Differential pressure air intake prelim. Filter Range Switching point increasing	 Differential pressure switch 0...500 Pa 250 Pa	Alarm: "Filterhouse malfunction" in case of switcing point reached		Change preliminary filters
=MBL30CP002	Differential pressure air intake fine Filter Range Switching point increasing	Differential pressure switch 0...750 Pa 600 Pa	Alarm: "Filterhouse malfunction" in case of switcing point reached		Change fine filters
=MBL30CP003	Differential pressure air intake total Filter Range Switching point increasing	Differential pressure switch 0...1000 Pa 900 Pa	Alarm: "Filterhouse malfunction" in case of switcing point reached		Change both filters
=MBM30	**COMBUSTION CHAMBER**				
=MBM30CN001-003	Flame supervision Type of amplifier	Photocell, infrared detection	Flame failure if during operation 1 of 3 does not detect flame	Turbine trip if during operation 2 of 3 do not detect flame	
=MBN31	**LIQUID FUEL SUPPLY SYSTEM**				
=MBN31CF001	Liquid fuel flow	oval wheel meter 0...11.67l/s 4-20mA	Just for indication		
=MBN31CP002	Differencial pressure on filter Alarm limit increasing Reset value	diff. pressure switch 0.7 bar 0.1 bar	Alarm:"Fuel filter malfunction" at switcing point		Change fuel filter
=MBN31CP003	Pressure before fuel pump Safety limit decreasing Reset value Orifice diameter	pressure switch 2.0 bar 2.4 bar 2.5 mm	At safety limit alarm:"Low pressure before fuel pump"		
=MBN32	**LIQUID FUEL SYSTEM FROM FUEL PUMP**				
=MBN32AA002	Liquid fuel filling shut off valve limit switch	Hydraulic valve NAMUR			
=MBN32AA005	Liquid fuel Trip shut off valve limit switch	Hydraulic valve NAMUR			
=MBN32AP001	Fuel pump	Sulzer Motor			
=MBN32CP001	Pressure after fuel pump Orifice diameter P13 input signal Trip limit decreasing Reset value	pressure transducer 2.5 mm 0...100 bar 4-20mA 30 bar 31 bar	Nominal pressure after fuel pump: 90 bar. Turbine trip at 30 bar		
=MBN32CP004	Pressure after fuel pump Range At 0% load (MP 11.1)	pressure gauge 0...160 bar 90 bar	Just for indication		
=MBN34	**FUEL RETURN SYSTEM**				
=MBN34CF001	Liquid fuel return flow P13 input signal	oval wheel meter 0...1.167l/s 4-20mA	Just for indication		
=MBQ30	**IGNITION GAS SYSTEM (PROPANE)**				
=MBQ30CP002	Propane gas pressure Alarm limit decreasing Reset value	Pressure switch 1.0 bar 1.1 bar	At decreasing point alarm:"Ignition gas low pressure"		
=MBU30	**WATER INJECTION SYSTEM**				
=MBU30CP001	Pressure before control valve limit decreasing Reset value	Pressure switch 19.0 bar 19.7 bar	At decreasing point alarm:"Water injection low pressure"		

=MBU30CF001	Flow water af inj. System Transmitter P13 input signal	Flowmeter 0...3.5l/s 4...20 mA	Just for indication and control purposes		
=MBV10	**LUBE OIL STORAGE**				
=MBV10CL001	Level in lube oil tank Alarm limit increasing	 Magnet level indication Approx. 290 mm from top of tank	At increasing point alarm:"Lube oil level high"		
=MBV10CT010	Lube oil temperature supervision Alarm limit decreasing Heater "on" at Heater "off" at	Thermostat in lube oil tank 18 °C 20 °C 22 °C	At decreasing point alarm:"Lube oil tank temperature low"	At 20 °C heater on At 22 °C heater off	
=MBV21	**LUBE OIL SUPPLY SYSTEM**				
=MBV21CP003	Filter differential pressure Alarm limit increasing	Differential pressure switch 0.8 bar	At increasing point alarm:"Lube oil filter high DP"		Change filters
=MBV40	**LUBE OIL DISTRIBUTION**				
=MBV40CP002	Lube oil pressure Trip limit decreasing (60%) Reset value Measuring orifice diameter	Pressure switch 1.20 bar 1.40 bar 2.5 mm	At decreasing point alarm:"Lube pressure low"	Turbine trip Auxiliary lube oil pump on	
=MBV40CP005	Lube oil pressure limit decreasing (40%) Reset value Measuring orifice diameter	Pressure switch 0.8 bar 0.86 bar 2.5 mm	At decreasing point alarm:"Lube pressure too low"	Emergency lube oil pump on	
=MBV40CP006	Lube oil pressure limit decreasing (40%) Reset value	Pressure switch 0.8 bar 0.93 bar	At decreasing point alarm:"Lube pressure too low"	Emergency lube oil pump on	
=MBV40CT002	Lube oil temperature Alarm limit increasing limit increasing	Temperature switch 50 °C 40°C	At 50 °C alarm:"Lube oil temperature high	At 40 °C water circulation pump on	
=MBX21	**POWER OIL SUPPLY**				
=MBX21CP005	Power oil pressure Alarm limit decreasing Reset value Measuring orifice diameter	Pressure switch 17.0 bar 18.6 bar 2.5 mm	At decreasing point alarm:"Power oil pump malfunction"		
=MBX22	**HIGH PRESSURE POWER OIL SUPPLY FOR ROTOR BARRING**				
=MBX22CP001	HP oil filter differential pressure Alarm limit increasing	Pressure switch Not adjustable	At increasing point alarm:"Power oil filter high DP"		
=MBX42	**CENTRAL POWER OIL SYSTEM**				
=MBX42CP001	Central power oil pressure Trip limit decreasing Reset value Diameter of meaasuring orifice	Pressure switch 17.0 bar 19.2 bar 2.5 mm	At decreasing point alarm:"Central Power oil pressure low"	Turbine trip	
=MBX43	**CONTROL OIL SYSTEM LIQUID FUEL CONTROL VALVE**				
=MBX43CP001	Control oil pressure Trip limit increasing Reset value Diameter of measuring orifice	Pressure switch 8.0 bar 7.2 bar 2.5 mm	At decreasing point alarm:"Control oil pressure low"	Turbine trip	
=MBX62	**EMERGENCY OIL SYSTEM**				
=MBX62CP010	Emergency oil pressure channel 1 Alarm limit decreasing Reset value	Manotest 0.58 bar 0.8 bar	At decreasing point alarm:"emergency oil pressure low"		
=MKA10	**GENERATOR TEMPERATURES MEASUREMENT**				
=MKA10CT001-004	Temperatures in generator stator slots Signal input	 0...1000 °C	Just for indication		
=MKA10CT005/6	Temperatures in generator stator slots Signal input Switching point increasing Switching point decreasing	 0...1000 °C 120 °C 115 °C	At increasing point alarm:"Temperature in stator slots high"		
=MKA13	**GENERATOR AIR COOLING**				
=MKA13CT012	Warm air temperature supervision Switching point stage 1 increasing Switching point stage 2 increasing	 90 °C (alarm) 100 °C (pls)	At stage 1 increasing point alarm:"Warm air temperature high"	At stage 2 increasing point PLS	
=MKA13CT016	Cold air temperature supervision Switching point increasing	 65 °C	At increasing point alarm:"Cold air temperature high"		

=MKA13CT022	Warm air temperature supervision		At stage 1 increasing point alarm:"Warm air temperature high"	At stage 2 increasing point PLS
	Switching point stage 1 increasing	90 °C (alarm)		
	Switching point stage 2 increasing	100 °C (pls)		
=MKA13CT026	Cold air temperature supervision		At increasing point alarm:"Cold air temperature high"	
	Switching point increasing	65 °C		
=MKB33	**STARTING DEVICE**			
=MKB33CT012	Warm air temperature supervision exciter		At stage 1 increasing point alarm:"Exciter warm air temperature high"	At stage 2 increasing point PLS
	Switching point stage 1 increasing	95 °C (alarm)		
	Switching point stage 2 increasing	110 °C (pls)		
=MKD10/11	**GENERATOR DRIVEN SIDE BEARING**			
=MKD10CT002	Lube oil drain temperature		As settings	As settings
	Switching point stage 1 increasing	70 °C (alarm)		
	Switching point stage 2 increasing	80 °C (trip)		
=MKD10CY020	Absolute vibration supervision		> 10mm/sec alarm vibrations high.	If vibrations very high..turbine trip
		Seismic pick-up	>17mm/sec alarm vibrations very high	
=MKD20/21	**GENERATOR NON-DRIVEN SIDE BEARING**			
=MKD20CT002	Lube oil drain temperature	PT100 (100 Ω/0 °C)	As settings	As settings
	Switching point stage 1 increasing	70 °C (alarm)		
	Switching point stage 2 increasing	80 °C(trip)		
=MKD20CY020	Absolute vibration supervision		> 10mm/sec alarm vibrations high.	If vibrations very high..turbine trip
		Seismic pick-up	>17mm/sec alarm vibrations very high	
=MKD31	**GENERATOR NON-DRIVEN SIDE 2 BEARING**			
=MKD31CT001	Bearing metal temperature	Thermocouple NiCr-Ni	As settings	As settings
	Alarm limit increasing	115 °C		
	Reset value	113 °C		
	Trip limit increasing	120 °C		
	Reset value	118 °C		
=MKD31CT002	Bearing metal temperature	Thermocouple NiCr-Ni	As settings	As settings
	Alarm limit increasing	115 °C		
	Reset value	113 °C		
	Trip limit increasing	120 °C		
	Reset value	118 °C		
=MKD31CY020	Absolute vibration supervision		> 10mm/sec alarm vibrations high.	If vibrations very high..turbine trip
		Seismic pick-up	>17mm/sec alarm vibrations very high	
=MKF10	**COOLING WATER SYSTEM GENERATOR**			
=MKF10CP002	Pressure measurement cooling water before pump	Pressure switch	At decreasing point alarm:"Generator cooling water low pressure before pump"	
	Alarm limit decreasing	0.15 bar		

Faults occurred	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total number of faults	Average
B10	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0.117647
B11	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	2	0.117647
B12	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	2	0.117647
B6	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	0.117647
B9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0.058824
D1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0.058824
D3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.058824
D7	1	2	0	1	0	1	1	0	1	1	2	1	1	0	0	0	3	15	0.882353
D8	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	2	0.117647
F11	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	3	0.176471
F12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0.058824
F2	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	3	0.176471
F6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0.058824
G3	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	3	0.176471
G4	1	0	1	0	1	1	2	0	1	0	0	1	0	1	0	0	0	9	0.529412
H1	1	0	2	1	0	1	0	2	0	0	0	0	1	0	0	1	2	11	0.647059
H2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0.058824
I5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.058824
J1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.058824
J11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0.058824
J3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.058824
J7	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0.235294
J9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.058824
L2	0	0	0	0	0	0	0	0	1	0	0	0	0	2	1	0	0	4	0.235294
L5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0.058824
N1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2	0	4	0.235294
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0.058824
N3	0	0	0	0	0	0	2	0	2	0	0	1	0	0	0	0	0	5	0.294118
N7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.058824
N8	0	2	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	4	0.235294
P12	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	3	0.176471
P14	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	3	0.176471
P2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0.058824
P4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0.058824
P5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0.058824
P7	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.058824
R1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3	0.176471
R2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	2	0.117647
R3	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	3	0.176471
R4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0.058824
R6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0.058824
S1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	3	0.176471
S2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.058824
Total faults per year	7	6	8	9	3	4	10	4	6	6	2	6	6	10	3	12	11		

	Operating hours of components before failure														
B10	21013	113557													
B11	75592,28	139224,8533													
B12	63306,5	19437,25													
B6	108611,9333	7009,75													
B9	136523,9333														
D1	134750,3833														
D3	58561,1666														
D7	504,8	12995,2167	2024,117	14390,533	17468,95	9974,5333	17334,6	8383,39967	8072,9	1482,8	8343,8164	7867,2	33484,885	1801,55	3788,683
D8	57457,5333	49772,5													
F11	65456,3833	40849,1833	38086,633												
F12	138799,35														
F2	4149,2833	47720,356	63263,384												
F6	139323														
G3	18450	104233,23	1966,25												
G3_2	122684,23														
G4	504,8	19364,817	23869,15	7149,016	2600,4166	7568,0167	10871,7	30126,3	15959,6166						
H1	7561,1	18062,3	338,0834	1104,11667	16957,2	22663	1296,3	38041,6333	26859,4333	9139,3	6117,717				
H2	127358,5														
I5	26609,3667														
J1	32835,55														
J11	140470,5333														
J3	4931														
J7	26767,71667	837,6	909,9333	5317											
J9	117392,95														
L2	71850,56667	42603,75	7688,6663	1575,03333											
L5	138120,15														
N1	53906,01667	61221,93337	16592,45	5101,033											
N2	136985,45														
N3	55382,533	2069,7	13359,833	1105,7	1290,3003										
N7	8652,65														
N8	8825,5	337,2497	11829,6	32685,5											
P12	29959,11667	53693,55	25911												
P14	86888	47638,75	9856,3												
P2	61164														
P4	37476,75														
P5	97953														
P7	21155														
R1	3794,0667	115431,1833	2271,333												
R2	79952,25	23118,1833													
R3	37552,51667	49811,48333	12565,633												
R4	141302,55														
R6	131557,75														
S1	21825	31337,75	92160,1												
S2	15105,95														

Summary results for gate A	
Parameter	Point Value
Unavailability	4.14E-05
Frequency	8.264E-05 per yr
CFI	8.264E-05 per yr
Number expected failures	0.001405
Unreliability	0.001404
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.0007039 yrs
Mean unavailability	4.14E-05
Risk reduction factor	2.42E+04
Q/T	2.436E-06 per yr
Used method	Cross product
Number of compact sets	3
Number of expanded sets	14

Summary results for gate C	
Parameter	Point Value
Unavailability	2.75E-07
Frequency	5.531E-07 per yr
CFI	5.531E-07 per yr
Number expected failures	9.40E-06
Unreliability	0.000009402
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	4.677E-06 yrs
Mean unavailability	2.75E-07
Risk reduction factor	3.64E+06
Q/T	1.618E-08 per yr
Used method	Cross product
Number of compact sets	2
Number of expanded sets	4

Summary results for gate E	
Parameter	Point Value
Unavailability	0.0001438
Frequency	0.0002864 per yr
CFI	0.0002864 per yr
Number expected failures	0.004869
Unreliability	0.004857
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.002444 yrs
Mean unavailability	0.0001438
Risk reduction factor	6956
Q/T	8.457E-06 per yr
Used method	Cross product
Number of compact sets	4
Number of expanded sets	14

Summary results for gate G	
Parameter	Point Value
Unavailability	0.0002514
Frequency	0.0005015 per yr
CFI	0.0005016 per yr
Number expected failures	0.008525
Unreliability	0.008491
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.004273 yrs
Mean unavailability	0.0002514
Risk reduction factor	3978
Q/T	1.479E-05 per yr
Used method	Cross product
Number of compact sets	4
Number of expanded sets	8

Summary results for gate I	
Parameter	Point Value
Unavailability	0.0005673
Frequency	0.001129 per yr
CFI	0.00113 per yr
Number expected failures	0.0192
Unreliability	0.01903
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.009644 yrs
Mean unavailability	0.0005673
Risk reduction factor	1763
Q/T	3.337E-05 per yr
Used method	Cross product
Number of compact sets	6
Number of expanded sets	13

Summary results for gate K	
Parameter	Point Value
Unavailability	0.0002282
Frequency	0.0004545 per yr
CFI	0.0004546 per yr
Number expected failures	0.007727
Unreliability	0.007699
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.00388 yrs
Mean unavailability	0.0002282
Risk reduction factor	4381
Q/T	1.343E-05 per yr
Used method	Cross product
Number of compact sets	2
Number of expanded sets	6

Summary results for gate M	
Parameter	Point Value
Unavailability	0.001043
Frequency	0.002075 per yr
CFI	0.002078 per yr
Number expected failur	0.03528
Unreliability	0.0347
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.01773 yrs
Mean unavailability	0.001043
Risk reduction factor	958.6
Q/T	6.136E-05 per yr
Used method	Cross product
Number of compact sets	2
Number of expanded se	8

Summary results for gate O	
Parameter	Point Value
Unavailability	2.68E-05
Frequency	5.353E-05 per yr
CFI	5.354E-05 per yr
Number expected failures	0.0009101
Unreliability	0.0009097
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.0004556 yrs
Mean unavailability	2.68E-05
Risk reduction factor	3.73E+04
Q/T	1.576E-06 per yr
Used method	Cross product
Number of compact sets	6
Number of expanded sets	14

Summary results for gate Q	
Parameter	Point Value
Unavailability	0.0006026
Frequency	0.001198 per yr
CFI	0.001198 per yr
Number expected failures	0.02036
Unreliability	0.02017
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.01024 yrs
Mean unavailability	0.0006026
Risk reduction factor	1660
Q/T	3.544E-05 per yr
Used method	Cross product
Number of compact sets	3
Number of expanded sets	10

Summary results for gate S	
Parameter	Point Value
Unavailability	1.94E-06
Frequency	3.88E-06
CFI	3.878E-06 per yr
Number expected failures	6.59E-05
Unreliability	0.00006592
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	3.289E-05 yrs
Mean unavailability	1.94E-06
Risk reduction factor	5.17E+05
Q/T	1.138E-07 per yr
Used method	Cross product
Number of compact sets	3
Number of expanded sets	3

Summary results for gate T	
Parameter	Point Value
Unavailability	0.002904
Frequency	0.005773 per yr
CFI	0.005789 per yr
Number expected failures	0.09813
Unreliability	0.09373
MTTF	Not calculated
MTBF	Not calculated
MTTR	Not calculated
Total down time	0.04936 yrs
Mean unavailability	0.002904
Risk reduction factor	344.4
Q/T	0.0001708 per yr
Used method	Esary-Proschan
Number of compact sets	11
Number of expanded sets	11

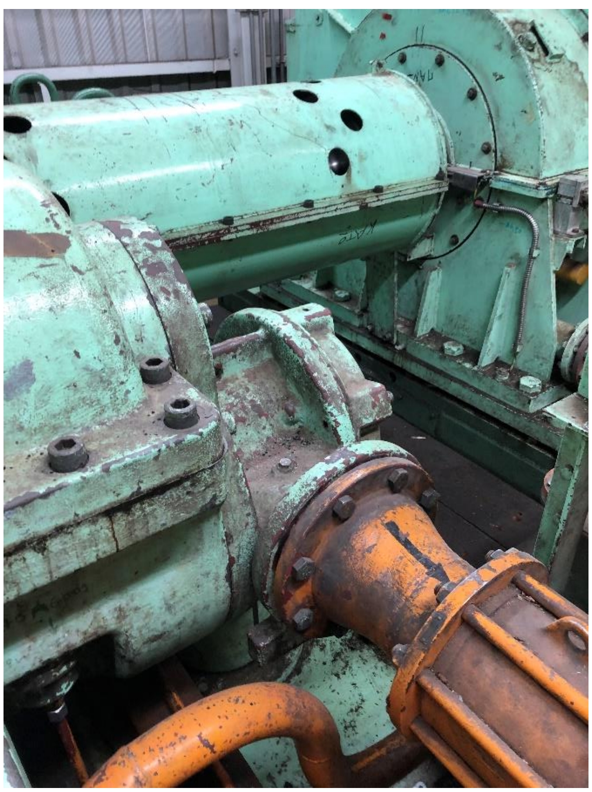
Results

Summary   Importance   Cut sets   Correlation   Appearance

Event ID	Fussell-Vesely	Risk Reduction Worth	Risk Achievement Worth
M*	0.3589	1.56	344.7
Q*	0.2073	1.262	344.8
I*	0.1952	1.242	344.8
G*	0.08648	1.095	344.9
K*	0.07852	1.085	344.9
E*	0.04946	1.052	345
A*	0.01424	1.014	345
O*	0.009219	1.009	345
S*	0.0006656	1.001	345
C*	9.465E-05	1	345
U*	0	1	345

Appendix 1 Inlet guide vanes

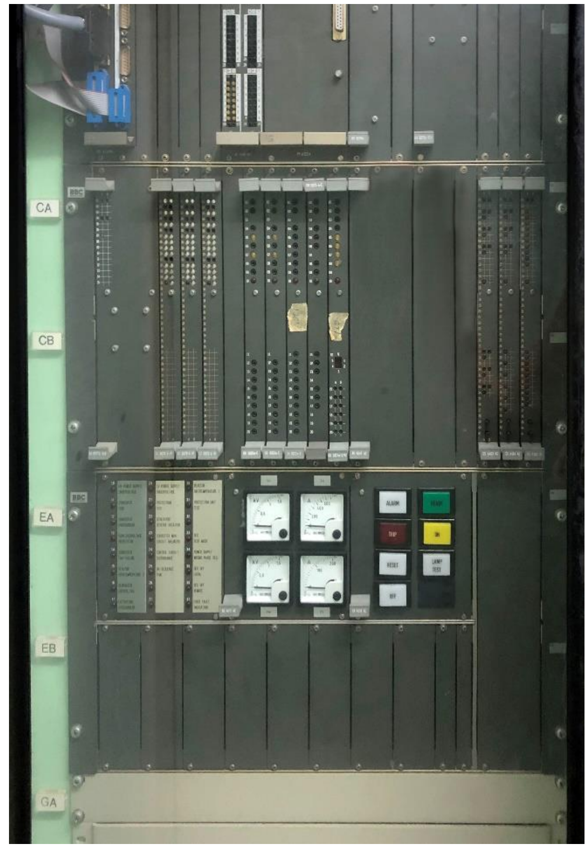
Appendix 2 Diverter valve motor (J9)



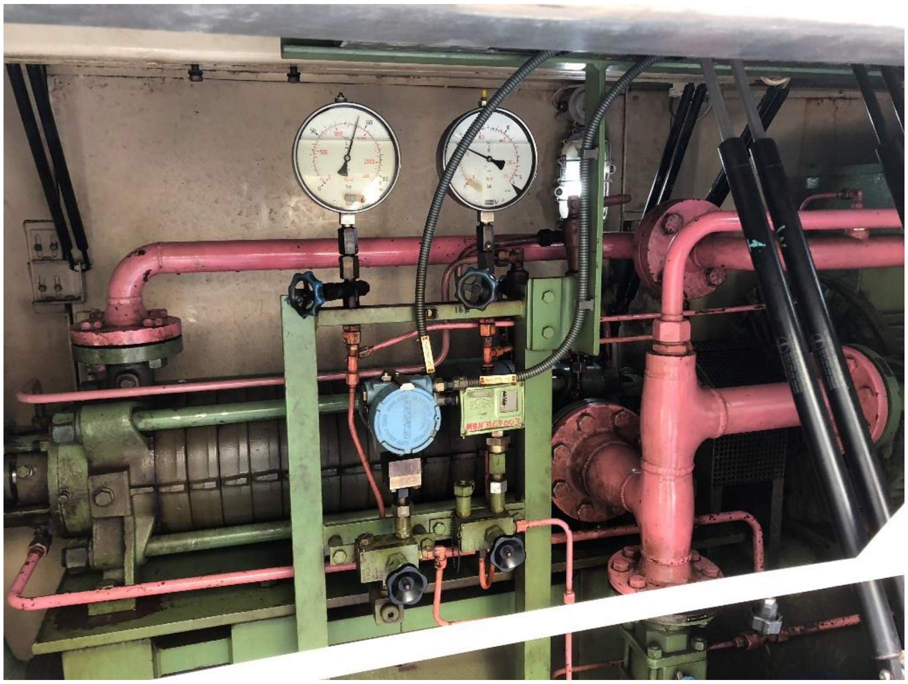
Appendix 3 Main lubrication pump (O2)

Appendix 6 Auxiliary lubrication pump (O3)

Appendix 5 Frequency converter



Appendix 4 Electronic protection relays (B6)



Appendix 8 Certifigual fuel pump (N1)

Appendix 9 Motor of power oil pump (N5)

Appendix 7 Control oil valves (N7)