Root cause analysis of the unpremeditated failure of induced draft fan motor during commissioning

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Abstracts

The objective of this research is to provide answers and identify the possible causes of the MV (medium voltage) motor failure. The research will assist the OEM(original equipment manufacturer) in reviewing their current processes used and the principal contractor's site preservation team, to ensure that before operating non-operated equipment it will be checked and maintained in the storage period described by the OEM. The research will contribute to determining the causes of the thermal boiler 2 induction fan motor failures during the hot commissioning phase. The introduction of procedures and techniques to support principal contractor construction and commissioning to identify the potential challenges that will have an impact on the completion of the boilers, as this type of failure will delay the project by 18 weeks due to replacement material lead time.

The IDF (induced draft fan) motor failure results in an insufficient combustion air supply to the burners as well as an inadequate drying and transport of pulverised fuel. Failure at the flue gas system leads to the inadequate distribution of flue gases to the chimney. The induction motors are advanced electromechanical devices used to transform electrical energy into mechanical energy. Root cause analysis was used as one of the processes for identifying the cause of failures and the proposed prevention process for future operations. The problem-solving analysis methods selected include FMECA (failure mode effect and criticality analysis), FTA (fault tree analysis) and fishbone diagrams. Poor communication between all involved parties and a lack of management by the client plays a part in the failure.

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List of Abbreviations

ABB	ASEA Brown Boveri
AC	Alternating Current
AFI	Application for Inspection
AP	Authorised Person
CIRSC	Completion of Installation and Release of Systems for Commissioning
CO_2	Carbon Dioxide
CTO	Construction Turnover
CWPC	Commissioning Working Party Chairman
DC	Direct Current
DCS	Distributed Control Systems
DeNOx	Desulphurization Oxides of Nitrogen
DOL	Direct on Line
EC&I	Electrical Control & Instrumentation
ECO	Economizer
EN	European Standard
FAT	Factory Acceptance Test
FBD	Functional Block Diagram
FDF	Forced Draft Fan
FGD	Flue Gas Desulfurization
FMECA	Failure Mode Effect and Criticality Analysis
FTA	Fault Tree Analysis
GAH	Gas Air Heater
HV	High Voltage
IDF	Induced Draft Fan
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IR	Insulation Resistance

ITP	Inspection Test Plan
KET	Kusile Execution Team
KKS	Kraftwerk Kennzeichen System (Identification System for Power Stations)
LOP	List of Open Punch List
MB	Break-down torque
MHPS	Mitsubishi Hitachi Power System
MN	Rated Torque
MRPE	Murray & Roberts Project Energy
MS	Starting Torgue
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MV	Medium Voltage
MWe	Megawatts Electric
NDT	Non-Destructive Testing
OEM	Owner Equipment Maintenance
PAF	Primary Air Fan
PD	Potential Discharge
P&ID	Piping & Instruments Drawing
PI	Polarization Index
PJFF	Pulse Jet Fabric Filter
PSR	Plant Safety Regulation
QA	Quality Assurance
RAM	Reliability Availability Maintainability
RBD	Reliability Block Diagram
RP	Responsible Person
RCA	Root Cause Analysis
SAH	Steam Heater
SAT	Site Acceptance Test
VPI	Vacuum Pressure Impregnation

DECLARATION

I hereby declare that the thesis/dissertation/ minor dissertation submitted for the Masters in Engineering in the Engineering management faculty at the University of Johannesburg, apart from the help recognised, is my work and has not previously been submitted to another university or institution of higher education for a degree.

Name: Makondo Tinyiko Eric

Signature:

Date: 30 June 2019

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For my late parents Mr Wilson Hlengani Makondo and Mrs Mphephu Emmlinah Makondo, brothers and sisters Oriel, Kenneth, Noel, Simon Phanuel, Eunice and Marcia and my wife Daphne and my three sons Nyiko, Nkuriso and Ntsako, I thank all of them for the guidance, patience and support.

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1. Chapter 1

1.1 Introduction

[1] Principal contractor has comprehensive building records for both supercritical and ultra-supercritical versions depending on local circumstances to produce extremely efficient boilers. In thermal power plants, rising steam circumstances (stress and heat) can allow effectiveness increases in power generation machinery, enabling an owner to decrease their energy consumption and CO_2 (Carbon Dioxide) emissions. [2]Describes the electricity growth supply has increased with a now projected shortage to support demand in South Africa. The client identifies the need to add a baseload capacity of an extra 9600MW(megawatts) and intends to add this baseload capacity to the existing fleet of power stations.

The client had awarded the boiler contracts to the principal contractor with a gross of 12 x 800 MW (megawatts) each. The principal contractor is liable for the full layout, manufacture, supply, performance control functions, inspection and assembly and commissioning of the additional facility, at the thermal power station in South Africa. The thermal power station, when complete, will be the only South African power utility that will use the flue gas desulphurisation system (FGD). The description of the coal to electricity distribution is that the principal contractor is awarded the scope of design, supply and commissioning of the item listed in figure 1 below as 1, 2, 4 and 5. The generation of electricity in the thermal power plant is as follows;

1) The coal mill pulverises the raw coal which is then injected into the burner and furnace.
2) The pulverised fuel combustion in the steam generator furnace flue gases rises to 1,450 degrees celsius, and the high steam temperature is generated.

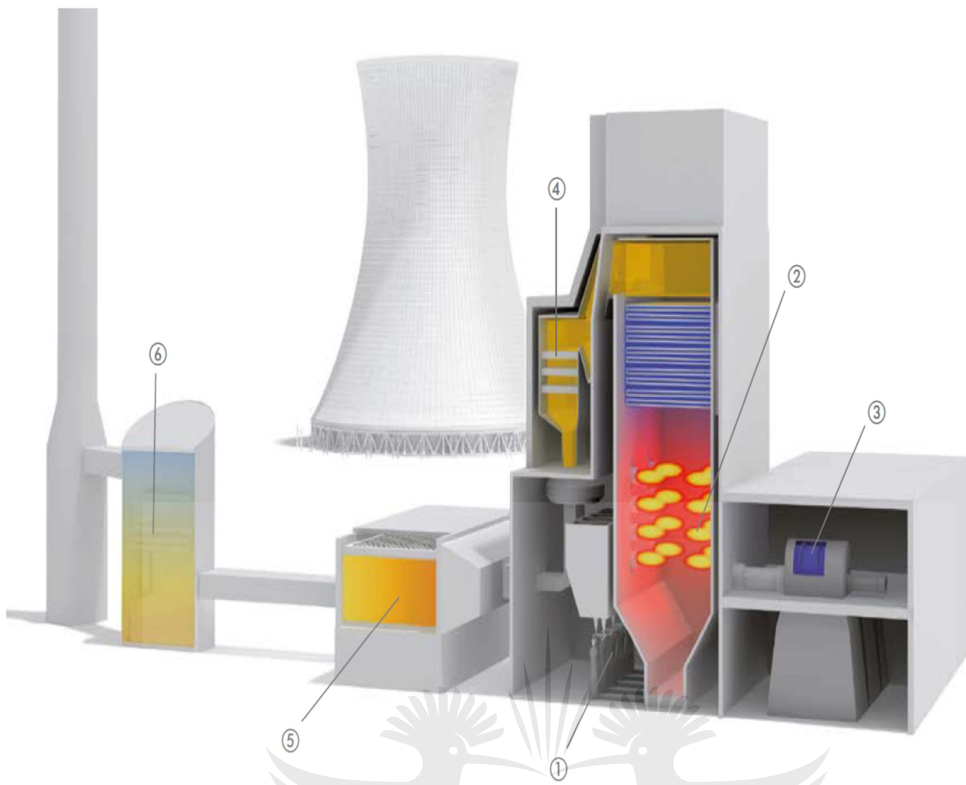

Figure 1.Generation of electricity in a typical coal plant [3]

3) The high steam from the furnace is sent to the turbine converting mechanical energy into electrical energy.

4) With the inclusion of catalysts, the nitrogen oxides in the flue gas interact in the DeNOx scheme to generate nitrogen and water vapour.

5) Flue gas and ash particles flow through the precipitator (pulse jet fabric filter) all other gases are removed through the induced draft fans to the flue gas desulphurisation system (FGD).

6) Flue gases remaining after PJFF, use FGD technology to extract sulfur dioxide from the power plant's ventilation flue gas and release it through the chimney into the atmosphere.

1.2. Background of the study

The induced draft fans (IDF) play a critical role in the safe discharge of the flue gas system at Thermal power station. The IDF motor with serial no: D004972-02 was manufactured and tested by the OEM at the end of 2011. The motor, together with other fan systems, was stored within the supplier's premises, annual inspections have been undertaken successfully and documented with reports as per [4]available for five years until December 2015. The motor was moved to site December 2015 and site has the records for all necessary testing on the non-operated working motor. The hot commissioning of the motor commenced on the 13 June 2017 at approximately 15:42:51 without load. The 15KV AC motor failed approximately 2 minutes later where the nominal motor current is 463.6A, and the startup current is approximately 2085A as per design. Principal contractor commissioning team records show the distributed control systems (DCS) current range is set for 600A max.

After run-up the motor current drops to a no-load current of 134A according to the DCS, approximately 2 minutes later the current goes off the scale, and about 1 second later the switchgear switches the motor off. [5]Describes the importance of increasing the hold points and verification for all critical equipment during the factory acceptance test process. The improvement of preventative maintenance with the preservation activities should be included during the project life cycle of the equipment. The IDF motors were only tested for operations after five years of storage at which stage the warranty expired between the principal contractor and the OEM.[5]Emphasises that the preventive maintenance shall be performed on all equipment whenever the opportunity is available. [6]Describes the insulation failures causes by the environment when the motor is stored and not operating. [7]Describes insulation deficiency during the system design and motor manufacture and are caused by the poor selection of insulation materials or an inferior manufacturing process. The OEM supplied all reports to confirm that the MV motors were tested in the warehouse for five years, and the same reading was achieved on-site at three-monthly intervals. [8]Emphasises the importance of training operators for system use, reliability and sensitivity of motor protection systems. [9]Describes how unbalanced voltages affect motor accelerating torque, causing failures.

[10], [11]emphasises the condition monitoring of the motors shall be done periodically for reliability and efficiency. The further relative position of IDF can be detail in full with figure 3 of the boiler air and flue gas system.

1.3 Statement of the problem

The purpose of the study is to identify the factors that caused the Induction motor failure during commissioning. The failure of the boiler 2 ID fan MV motor occurred during the planned MV motor direction check and test run. Shortly after the start of the test run the motor tripped, a noticeable noise was emitted by the motor and smoke could be seen in the vicinity. The IDF motors have a design life estimate of 30 years. During the time of the incident, the motor effectively only runs for 4 minutes for the first time before failure. The study requirement is develop to determine the problem that causes premature failure even after the motor passed its factory acceptance test (FAT) and site acceptance test (SAT). The IDF motor is the most expensive of all MV motors procured on-site at R 6,405 k each as base dated to 9 September 2009. The failure of the induction motor during operations will have a major effect on the plant safe discharge of the flue gas systems, and the performance of the boiler will be halved to 400MW.

1.4 Delimitations of the research problems

The research study is limited to the thermal power station in Mpumalanga as the only power station in South Africa using 15000 V AC (alternative current) MV motors with FGD. The scope is limited to only the boiler contractor's scope of works for supply, installation and commissioning of boiler induced draft fan motors. However, the design study method will be used to bridge the gap between the information requirements to conclude the study. There will be a limitation on the participant of the study and will be based on the current skills in the commissioning of power plants in South Africa to back up the study. The client is Generation and assumes responsibility for the successful commissioning of the plant

1.5 Research goals and objectives

The objective of this research is to provide answers to the questions above and identify the causes of MV motor failure. The introduction of processes and techniques to support the principal contractor construction and commissioning teams to identify potential challenges that may have an impact on boiler completion due to this type of failure. [12]Describes the commissioning procedure as the last critical stage of the project before the plant handover to the client.

1.6 Research questions

The following research questions will form the bases of this case study

a) How was the motor handled from the time it left the factory until it was put into service?

b) How many times was the motor started before the failure and what was the cumulative running time of the motor before the failure and did the failure occur on start-up or when the motor was at full speed?

c) The motor was manufactured 6 years before being installed and commissioned, was the winding completely dry and were polarisation index| (PI) and insulation resistance tests conducted?

d) What was the condition of the switchgear that operated this motor and was the motor protection set up correctly, were there any other equipment failures at the time of the motor failure?

e) Was the motor safety clearance certificate available from the clients commissioning?

f) Was the commissioning engineer on duty trained to perform the task?

1.7 Assumptions

The current test procedures during the factory and site acceptance tests and site implementation are based on a set agreement with the client's requirements. The process will be established to ensure all findings and recommendations are used to create the pre-commissioning, cold commissioning and hot commissioning check sheet that have contributed to the MV IDF motor failure at the thermal power station. The preservation team will also be provided with the new check sheet to accommodate the revised testing intervals as per the recommendations from the OEM. The impact of increases in efficiency and high return on time utilisation during the commissioning phase of the new power plant. The researcher has made the following assumptions:

1) The use of approved commissioning procedures by the principal contractor will eliminate delays during the handover process.
2) The current preservation procedures recommended by the OEM need revision to add additional site type tests to determine the signs of failure during the construction process.
3) The use of qualified engineers will eliminate the trial and error process on critical and expensive equipment.
4) The current integration between the contractor and client for all commissioning requirements needs review.

1.8 The benefit of the study

The research will assist the OEM in looking at the current processes used and the principal contractor site preservation team to ensure that all not yet operated equipment will be checked and maintained as set out and described by the OEM. The research will also assist the principal contractor commissioning team in identifying all check sheet requirements before commencing with hot commissioning **c**urrently 9no. MV motors are out of warranty and a latent defect cannot be ignored but will be challenging to prove as the current cost of replacing the winding is estimated at R 2,500k per motor which is equal to 40% of the cost of a new ID fan Motor. The cost of delaying the project by 18 weeks due to supplier lead time will cost an estimated R108m/zar for standing time as per the current cost of 54m/Zar per month.

1.9 Research design

The case study will apply to this research with the focus on thermal power station boiler 2 IDF motor. [13]Describes the case study research approach as the explanation that deals with questions that are operational links and trace records over time. [13]Furthermore supports that the evidence strength of the case study is based on the conditions that deal with evidence documents, interviews beyond what is available in the current records of the study. [13]Describes the case study research as a challenge that requires the researcher skills and expertise. The use of RCA (root cause analysis), Fish-bone method, FMECA (failure mode effect and criticality analysis) and FTA (fault tree analysis) to determine the causes of the IDF motor failure. The main aim is to understand the causes of failures on equipment after all the factors and acceptance tests are archived and acceptance by all parties.

The research case study selection is based on the following;

- Understanding the impact of current ID fan motor FMECA risk assessment
- Determining the root cause analysis of motor failure during commissioning with the use of the fishbone and FTA methods.

The data collection methods were chosen as per [13]to focus on survey questionnaires and company records of all four parties (Client, Principal Contractor, OEM and Electrical Subcontractor). [13]Describes the use of sampling methods determining the accuracy of results and low costs.

1.10 The research outline

The research will be done in six chapters;

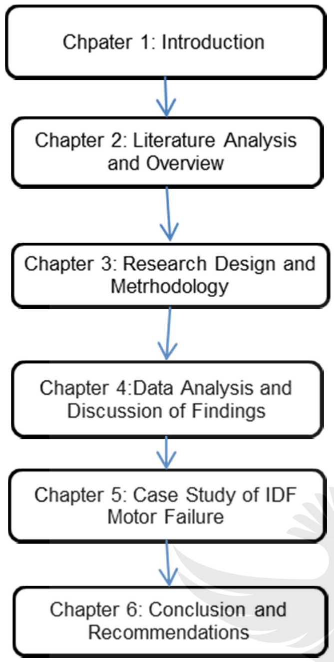

Figure 2: Research Outline

Chapter 1: **Introduction,** will discuss the background of the thermal power station and the role of principal contractor in the installation and commissioning of the boiler plants. Moreover, the questions that will be answered together with the plan and limitations and research methods suggested for this type of study.

Chapter 2: Literature review will focus on the preservation, induction motor design as per the client's standards and all type tests to be completed before the equipment leaves the OEM and after the installation process to keep the motors under test before hot commissioning. It will predict based on the different records of thermal stresses, electrical, mechanical and environmental failures of MV motors.

The investigation on the impact of unbalanced voltage supplies and the check sheet that shall be used to accommodate all the different contractors before commissioning of the plant.The integrated predictive analysis of large power induction motors focusing on the RCA of FTA and fishbone method and also focusing on the reliability block diagram.

Chapter 3: Research Design and Methodology will predict based on reviewing the current failure records from the DCS and severity of the motor damage together with all documentation that was approved during pre-commissioning, cold commissioning and hot commissioning of the MV motors and other auxiliary plants like oil lubricant systems and the availability of the associated systems to the plant. The questionnaires will be used to ascertain more information from the construction and, preservation team as well as the contractor commissioning, client commissioning and the OEM on the suggested causes of the motor failures. There shall also be a rigorous assessment of the physical damage caused to the motor. The RCA process with the use of the technique of FMECA, FTA for further investigation of the failure of MV motor during the final commissioning stage.

Chapter 4: **the summary of all findings** will be discussed in this chapter with the analysis of the findings based on the OEM testing, construction, preservation and commissioning activities of the plant. The analysis of the different organisations for this case study (Client, Principal contractor, subcontractor, preservation, and commissioning teams while the OEM and client commissioning teams are separate).

Chapter 5: Case study about the interpretation of the DCS and switchgear reports and Testing the temperature measurements of the thermocouples.

Chapter 6: Conclusions and Recommendations, that the paper will conclude with the findings and recommendations to be made to Principal Contractor procurement, construction, Commissioning and engineering teams to ensure that the recommended processes are followed for the remaining 9. No 15kV MV motors for K3 to K6.

1.11 Conclusion

The research will contribute to determining the root causes of the thermal boiler 2 induction fan motor failures during hot commissioning. The current site integrated processes between the different suppliers and contractors on-site will require improvement. There are no papers that support the precise way of commissioning due to the function being managed by the OEM and not the construction team. This chapter will highlight the background of the study, problem statement, benefits of the study, research questions, research methodology, research design, delimitation of the study and assumptions. Chapter 2 will focus on literature from multiple sources to assist the process of investigating the root causes of the induction motor failures. The theories will assist in the interpretation of the current testing records and the ones to be determined in chapter 3.

2. Literature Overview

2.1. Introduction

The aim of this study expressly investigates the root causes of the induction fan motor failure during hot commissioning at thermal power station boiler 2. The content of this literature overview is for the following aspects;

1) Understand the importance of Induced draft fan motors at the thermal power station
2) The preservation procedures for extended storage time for the MV Induction motors
3) Understanding the causes of the different failures of the MV induction motors.
4) Commissioning procedures, pre-commissioning, cold commissioning and hot commissioning of different plant equipment.
5) The improvement of the construction, preservation, and commissioning check sheets.
6) The importance of factory type tests

2.2. Background

[14],[15],[16],[17]Describes the operation of the boiler furnace and that the full combustion air is conveyed by two forced draught fans (FDF) arranged in parallel that is designed to be axial flow motors with variable pitch command. The total amount of air is taken from inside the boiler housed by two lines. These two air flows flow downwards into one header line where a silencer is mounted. Downstream of the device the duct is divided into two parallel lines and connected to the inlet housing of the respective FDF. [14],[15],[16],[17]emphasises that the combustion air is heated up in the gas air heater (GAH) by two parallel trains; the combustion air passes the steam air heater (SAH) which comprises of two parallel units as well. The boiler operation process describes that before the combustion air passes the GAH's the amount of primary air required for the operation of the mills is transported using the centrifugal primary air fan (PAF) from each of the two lines between FDF and SAH. Downstream the GAH hot combustion air will be distributed to the burners, and the primary air is also transported via the mills to the burners.

The relative position of the different components of the boiler air and flue gas system is shown in figure 2.

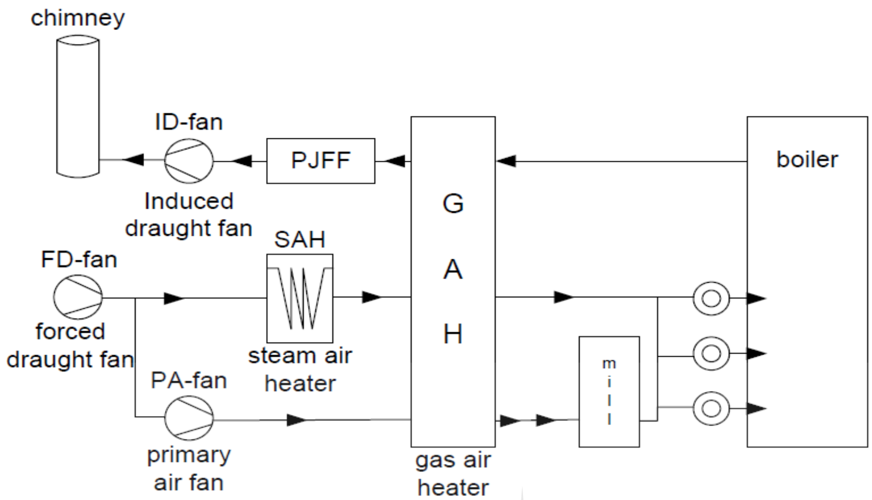

Figure 3: A schematic block diagram that illustrates the function of the air flue gas system [3]

[3],[14],[15],[17] Furthermore argues that the flue gas is taken out of the boiler furnace by two axial induced draught fans (IDF) operating in parallel through a single flue gas duct. Afterwards, the flue gas duct divides into two trains upstream of the GAH's. Subsequently, the flue gases pass to the GAH's which are cooled down by the heat transfer to the combustion air to approximately 125 degrees Celsius at full load. Subsequently, the flue gases are de-dusted through the pulse jet fabric filter (PJFF) in each train. Downstream of each IDF a double-bladed shut-off damper is installed.

Downstream of the IDF both trains are connected to the common duct where cleaned flue gases are directed to the atmosphere through the chimney. A failure of the area system leads to an insufficient combustion air supply to the burners and an insufficient drying and transport of pulverised fuel. Failure at the flue gas systems leads to an insufficient distribution of the flue gases to the chimney. As a result, the boiler load shall be decreased on a failure of one lane or the boiler will shut down in the event of a failure of both lanes of the system. The IDF is driven by the asynchronous squirrel cage induction three-phase electric 15kV AC motors.

The size of the motors is a first, in the client fleet power plant.[18] emphasises that the induction motors are advanced electro-mechanical devices used to transform electrical energy into mechanical energy. [7]describes the induction motors as reliable for the driving of pumps and fan loads at the power generating station. [19]emphasises that the failure of the motor will have an impact on managing the plant produced flue gases. [20]Describes alternatively that the commissioning stages are there to check and set all the equipment before the plant is ready for synchronisation to the national grid and handover by the contractor. [21] further emphasises that commissioning is an essential function of new plant and modification projects and has a considerable impact on the completion and success of the project. [21]Further describes the importance of the correct application of the commissioning process for the new installation of equipment and has the benefits of reducing the risk of equipment damages.

2.3. Induced draft fan

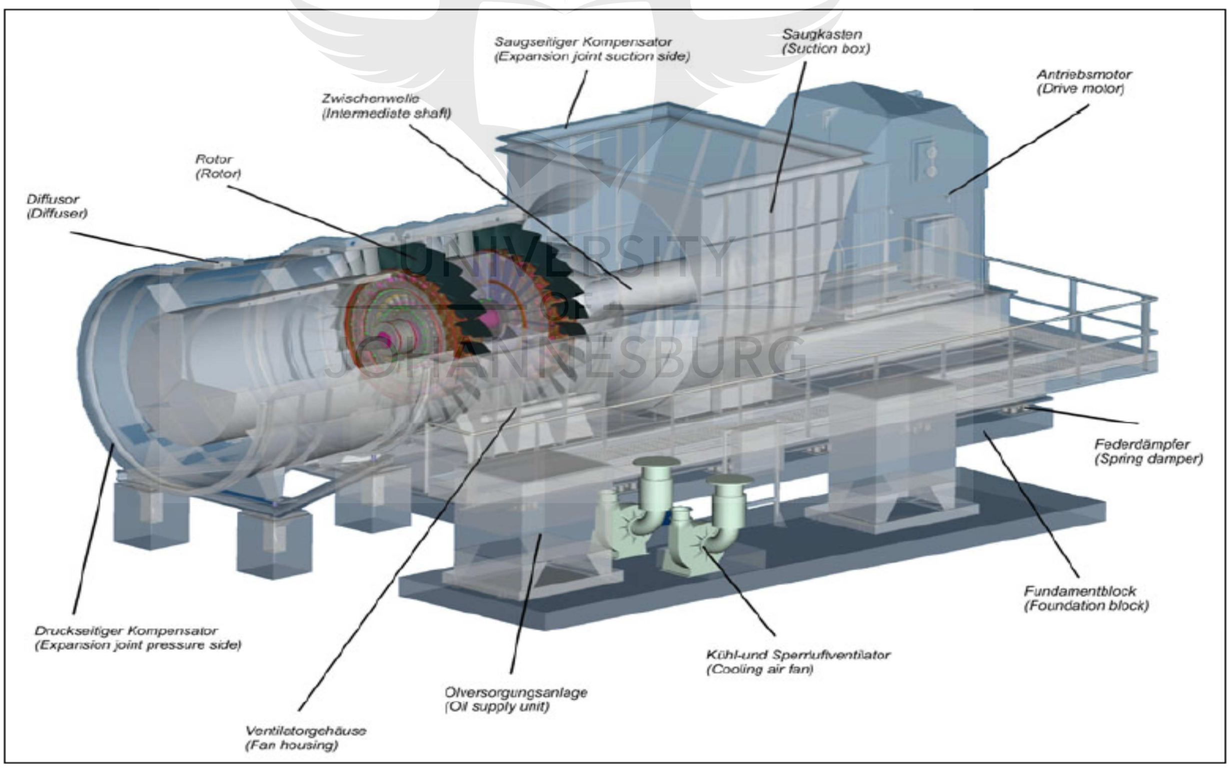

Figure 4: Induction fan component list [1]

The thermal power station consists of 6 boilers, and each boiler consists of two lanes with each lane equipped with an IDF. All 6 boilers are equipped with the flue gas desulphurisation, and the IDF will discharge the flue gas flow out of the steam generator over the gas-air heater through the pulse jet fabric filter, and flue gas desulphurisation and into the stack. The IDF is located downstream of the pulse jet fabric filter and is situated at the basement level. The equipment is supplied by TLT- Turbo GmbH as an axial type fan. The IDF has the following working parameters;

2.3.1. Boiler air and flue gas system

[22],[23]Describes the importance of boiler air and flue gas systems as part of the firing system. The air system supplies the combustion air to the firing system via the burners, and the flue gas system supplies the flue gases to the chimney via the gas air heater and flue gas treatment. In addition to the air and flue gas ducts the required equipment for measurement and control of the air and flue gas.

1) Forced draught fan (FD Fan)
2) Primary air fan (PA Fan),
3) Induced draught fan (ID Fan)
4) Steam air heater (SAH)
5) Gas air heater (GAH)

The study will focus on IDF motor operations and failures.

2.3.2. Induced draught fan

[14],[15],17]detailes the boiler IDF as a fixed speed axial type fan. The variable blade-pitch is used for throughput control. The adjustment of the blade pitch is affected by the hydraulic blade adjustment system. In addition to the hydraulic blade adjustment system, the IDF comprises an oil unit hydraulic system an oil unit lubrication system a drive unit, coupling and a rotor including the main bearing. The oil unit lubrication and the oil unit hydraulic system are part of the oil supply unit. The IDF facilitates the transportation of the full flue gases through the GAH and the PJFF to the chimney.

Therefore, the pressure loss from the duct system, including the individual components is to overcome. The oil unit lubrication systems ensure the lubrication of the fan and motor bearings with oil from the tank via a pipe system. The oil unit hydraulic system supplies the oil to the essential hydraulic blade adjustment system through a pipe system from the oil tank and enables the control of the blades, in addition to that the further operation at different boiler loads. The pump drives and oil tank heating are connected to the DCS with a specific power supply AC (for the daily) and DC (for emergency) use. The sealing air system consists of air fans, inlet filters, valves and piping systems. In addition to that, it avoids the access of the flue gas to the bearings and the hydraulic section, and the heat from the flue gas will be discharged by the sealing air.

Table 1: IDF operating parameters [1]

Mass flow	544,6 kg/s
Volume Flow	796,16m3/s
Temperature upstream fan	137 degrees Celsius
Total Pressure Increase	100,7 mbar

2.4.Induction AC electric motors

According to [24], the AC induction motor consists of a magnetic circuit connecting the mixture of two electrical circuits that are positioned in two primary components of the device. The static portion is the rotor's stator and spinning portion.

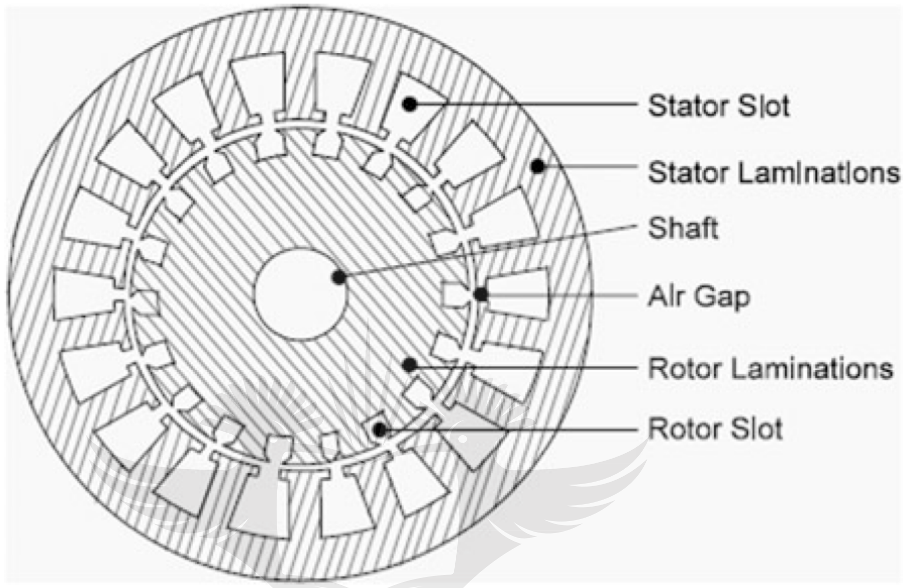

Figure 5: Magnetic Circuit of the stator and rotor of an induction motor [25]

[24] defines induction motors as extremely durable, needing low maintenance and comparatively high frequency. Furthermore, [24] emphasises that induction motors are prone to many kinds of faults in power plants or other manufacturing settings. The importance of commissioning assists the construction team to identify any abnormal or signs of failure before handing over the plant to the client. The handover of a motor that has not been pre-checked will have an impact on the production shutdowns of the plant and links with the costs regarding lost production time and maintenance costs of the Thermal power station to meet its set flue gas disposal process. The motor selection to be used for specific functions is vital for the consistency in applications.

The different types of electric motors are listed in figure 6 below

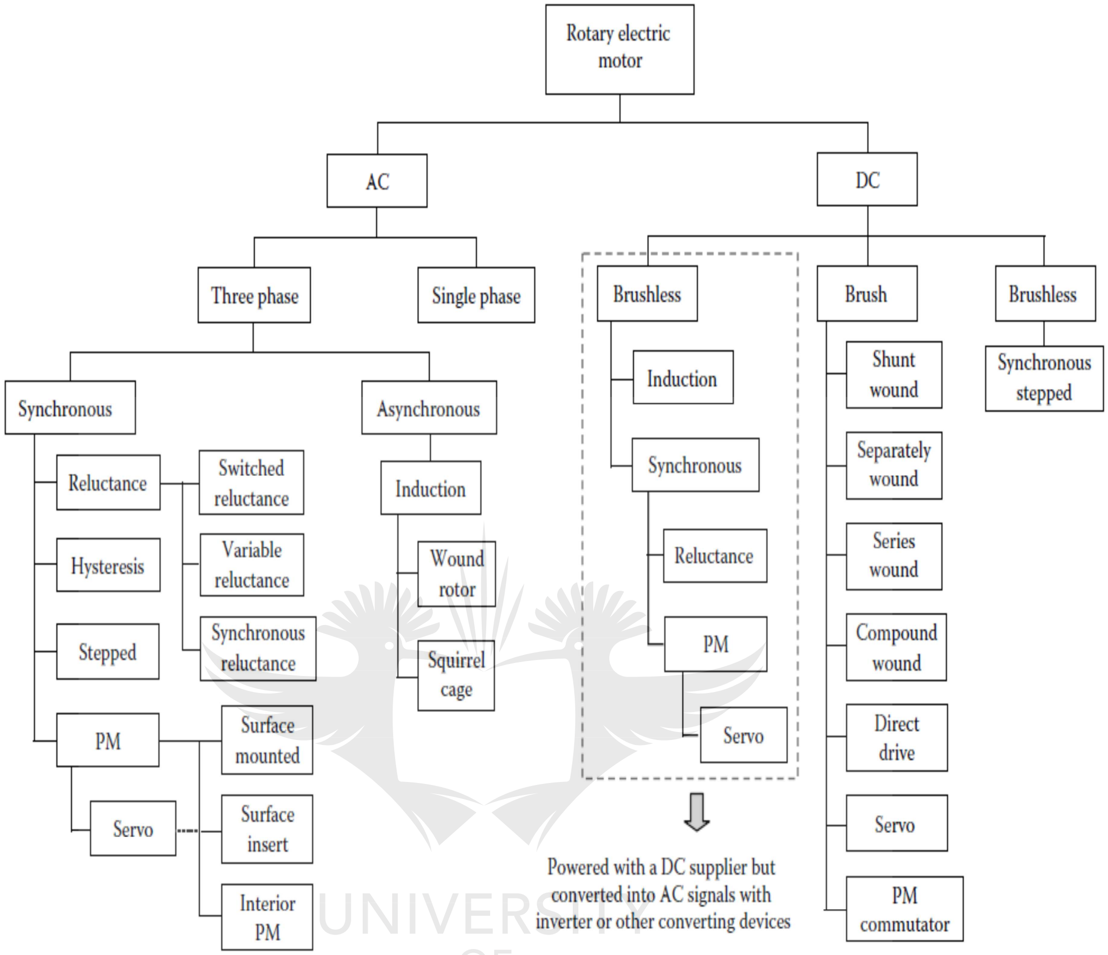

Figure 6: Types of induction motors [26]

The thermal power station had selected the AC three-phase asynchronous induction squirrel cage motor due to its robust performance within the power industry.

2.4.1.Induced draft fan MV motor data

Table 2: Induced Fan MV Motor Data [1]

Parameter	**Value**	**Unit**
Rated Voltage	15000	V
Rated Power	10200	KW
Nominal Torque	130370	Nm
Motor Mass Complete	47000	Kg
Nominal Current	463.6	A
Startup Current	2085	A
Phase Voltage	3 Phase	
Rated Speed	745	Rpm
Power factor	0.87	
Fault Capacity	0.25	S
Efficiencies	97.4	%
Frequency	50Hz	Hz
Frequency Tolerance	2.5	%
Insulation Motor Type	VPI	
Insulation Class	F	
Temperature Limit	120 B	
Start Mode	Direct-on-Line	
Degree of Protection	IP65	
Number of Poles	8p	
Motor Cooling Type	Water	
Direction of Rotation	Clockwise	
Lubrication Type	Oil VG68	
Voltage drop	15%	%
Voltage Unbalance	Maximum 2%	%
Motor Lifetime	35	Years
Rotor cage design	Single	

The failed motor detailed as per the table 2 above and the motor has rated power of 10200 KW and with rated voltage of 15kV AC and the speed of 745 rpm and with the fault capacity of 0.25 s. The motor design life is 35 years.

2.5.The Starting method of induction motors

The three-phase induction motor is described as the most use electric motor for use in power plants; the essential characteristics are the high current load on supply with the use of direct-on-line starting.

[27]describes the DOL(Direct on- line) start of the ancient techniques used for three-phase asynchronous engines; the stator coil is immediately linked to the power supply with a simple changing method. [27] The DOL is used to prevent unnecessary voltage falls in the supply line owing to elevated beginning temperatures. There are safety mechanisms inside the DOL starter which protects the motor as well as the operator of the motor.

2.6. Switchgear protection settings for induced draft fan motor

[28],[29]describes the failure protection of the breaker circuit as required by the failure clearance system and is not feasible to duplicate the circuit breaker protection component for practical or economic purposes, to allow for the use of breaker failure protection. Furthermore,[28],[29] points out that if the original circuit breaker does not move for secure components, the fault failure function issues the replacement pass to adjacent circuit breakers. It is performed by either evaluating the load or analysing the residual journey signal to detect an inability to split the cable through the lock. The Thermal boiler two switchgear is using ABB REM 630 feeder protection and control systems. The REM630 provides the short circuit, overcurrent, unbalance and thermal overload protection, and it provides support based on the IEC 61850 standards for substation communication. The protection settings are to supply the fastest possible fault clearance with accurate grading to allow the affected section of the plant to be isolated correctly. The devices use the feature to define the fault place and then calculate the network fault range.

Table 3: IDF Motor Protection Settings [1]

Relay	**Relay Function**	**VT Ratio**	**CT Ratio**			
ABB REM360	Motor Protection	15000/110	600/1			
Motor Information						
Motor Rating	10200	KW	**CT Phase**	600/1		
Motor Full Load Current	463.3	A	**CT Ground**	50/1		
Motor Rated Voltage	15	kV	**VT Ratio**	15000/110		
Motor Power Factor	0.87	pu				
Motor Efficiency	0.974	pu	**Fault Levels**	Three Phase Fault	17.071	kA
Motor Starting Current	2779.8	A		Single Phase Fault	360	A
Motor Starting Time	24	seconds				
Motor Stall Hot Time	15	seconds				
Motor Stall Cold Time	25	seconds				
Motor Number of Start/Hour	3					

[30],[31]argues that the second nondirectional earth faults are designed to safeguard and distinguish earth fault defects in networks that separate or earth the neutral point via a resonance coil or small force. It also covers strong, grounded networks and earth fault safety for multiple power-system-connected components. The safety of the motor stall is most important for protecting the motor from excessive increases in temperature since the motor gets a high stream in the stall phase, which increases stator windings.

[30],[31] emphasises that the motor thermal overload protection (MPTTR) is designed to restrict the heat engine amount to predetermined levels during unusual motor working circumstances and prevent early engine assembly loss. [28]Furthermore, it emphasises that in the event of any internal faults the present entry and exit of the windings are distinct, resulting in a differential flow which is then used as a basis for producing the operating message. Because of this concept, the differential item fails during apparent failures.

2.7. Induction motors and faults

[25] describes the induction motor as a characterised electromechanical device converting electrical energy into mechanical energy.[25] Emphasises that the induction motor is an asynchronous motor composed of two primary components, i.e. stator and rotor. The squirrel cage induction motor consists of operating bars, short-circuited between end chains. Compared to a slip ring induction motor, the squirrel cage induction motor is easy, economical and stiff. This induction motor is defined as possessing steady velocity with constant voltage and steady power supply frequency.

2.7.1. Stator winding faults

[25]emphasises that the stator winding faults shall be due to the failure of insulation of the stator winding and described as the inter-turn short-circuit faults. The different lists of stator winding faults are described as follows;

a) Turn to turn fault – the short circuit faults between two turns of the same phase
b) Coil to coil – the short circuit between two coils of the same phase
c) Phase to phase - the short circuit between turns of two phases
d) A short circuit between turns of all three phases
e) Coil to a ground fault – the short circuit between winding conductors and the stator core
f) Open circuit fault - when the winding gets a break

[25],[32],[33]describes the different types of the stator winding as per figure 7 below

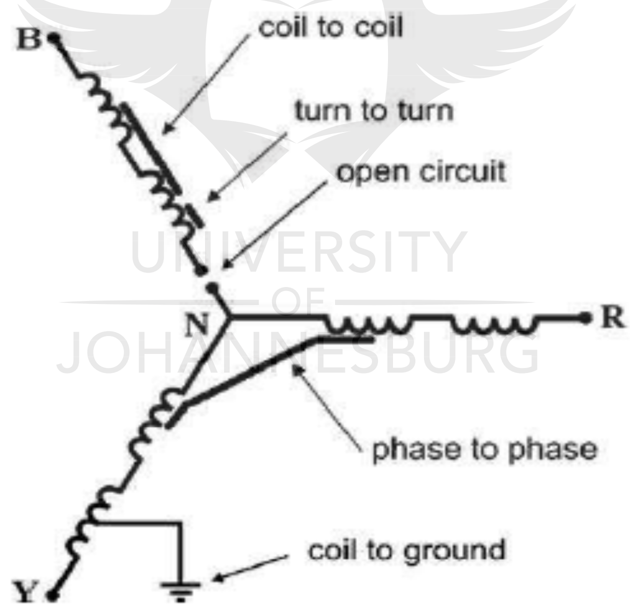

Figure 7: Star-connected stator showing different types of stator winding fault [33]

2.8. Stator winding faults causes and effect

[34]Describes the product of isolation as the most critical and susceptible to big equipment for operations.[34]Highlights the need to prevent damages to equipment during the completion procedure.

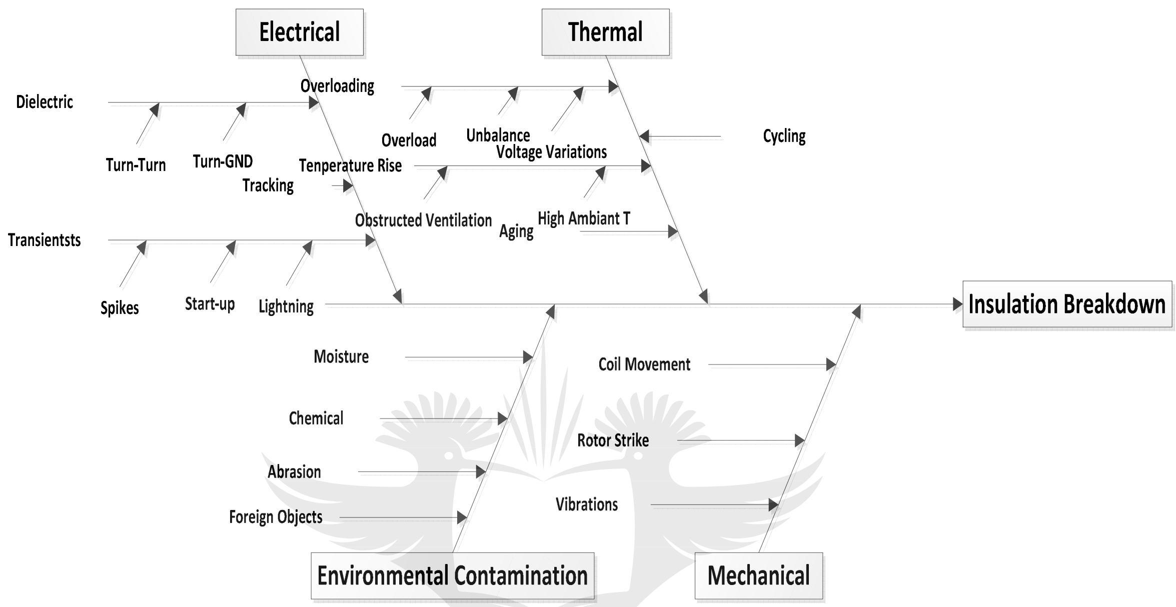

Figure 8: Insulation failure mechanism [33]

[34]describes that the motor stator winding mechanism was subjected to thermal, electrical, mechanical and environmental stresses during the operating process. Using the cause and effect diagram is a structured method of recording problems and improvement effects, it highlighted the current stator insulation failure, being highlighted at the horizontal line with the potential causes described with branches and sub-branches.

2.8.1. Thermal stress

[25],[33]describes the thermal stress being caused by overloading, which effects and reduces the life of the stator winding insulation. The cause of this stress is due to the supply of unbalance voltages and not having the required ventilation to the induction motor.

[25],[33]describes the sector thumb principle that says that a 10 % fold rise in temperature above stator coupling temperature boundaries will decrease the insulation lives of the motor by 50 per cent. [33]Furthermore describes the impact of the rise in temperature due to the machine operational environment and insulation life expectations as per table 4 below.

Table 4: Effect of the rise in temperature [25]

Ambient in °C	**Insulation life in hours**
30	250,000
40	125,000
50	60,000
60	30,000

2.8.2. Mechanical faults

[25],[33], describes the source of mechanical stress owing to the motion of the coil and rotor touching the stator. The mechanical stresses portray the displacement of the coils within the holes that harm wire insulations. The rotor that hits the stator may occur owing to distinct events and contribute to the following conditions.

a. Phase to ground faults will appear due to the stator sheet damage to winding insulation during the start-up period. The faults can gradually occur over the years.

[25]Narrate that, as a result of rotor misalignment, deflective shaft or errors, the rotor could strike the stator. The open-circuit fault will occur due to the high vibration of the stator winding and lead to the equipment being disconnected.

2.8.3. Electrical faults

[35]describes that electrical faults destroy electrical insulation and will decrease the lifespan that leads to winding faults. [35] emphasises the connection between the lives of the insulation and the tension applied to the winding.

[25]describes that the static voltage decreases the running lives of the stator and may trigger turn-to-turn or turn-to-earth failures in severe instances. [35] emphasises that short-circuit failures in motor windings may happen through immediate overvoltages attached to windings. The overvoltages will describe the following as per[35]**;**

1) The overvoltage's of the supply grid can be 3.5 times the rated voltages with recorded short rise time and can damage the motor windings.
2) The overvoltages create damage to the winding insulations
3) Overvoltage during starting will have an impact on 2 to 5 times the standard voltages rise time.

2.8.4. Environmental faults

[18],[25],[33],[35] describes the stresses of the environment are as a result of environmental pollutions. The impact of the environmental pollution increases the difficulties of keeping the motor dry and clean and [18],[24],[33],[35] describes the following impact to the motor regarding the environmental stress;

1. Reduces the heat transfer and the life of insulation
2. Causes erosion and bearing failure
3. Causes electrical insulation failure with the result of turn-to-turn or turn to- ground faults.

2.9. Influence of unbalanced voltages supply

[36],[37],[38]describes the operation of the induction motor with an unbalanced feed voltage that could lead to the destruction of the motor. [39]describes the unbalance voltage as the phenomenon of the three-phase voltage supply and that unbalance voltage supplies can cause excessive losses, overheating, noise, vibration, torsional pulsations, and slip.[36],[40] Emphasises the danger of using an induction motor that is supplied with unbalancing voltages is not appropriate and can harm the motor. The impact of unbalanced voltages will be primarily recognised that the rotor losses will be higher than the stator losses due to the rotor current having more significant deviations that the other. [36],[40] emphasises that the risk of providing the induction motor with unbalanced voltages will have a significant impact on the decrease of the motor torque.

Furthermore,[36][40] information the effect on metal yields of unbalanced voltages and the smallest effect on mechanical failures. The higher rise in unbalancing voltage on the induction motor will reduce the motor's effectiveness and performance. [41]Further elaborates the effect of adverse temperatures on one or more stage causes owing to unbalanced voltage. Moreover, finally[41]re-established the thumb law that states 3.5 % of voltage unbalance can trigger a 25 per cent rise in temperature.

2.10. Electric Motor Type Test

According to [42], electric motor testing is regarded as highly recommended to ensure the customer receives the stated efficiency integrity and performance. The testing is deemed to be key to the early detection of faults, confirm reliability during operations and assures the motor design output. The type tests and routine testing standards that the induction motor is designed under are carried out as per the agreed code of standards with the customer.

2.10.1 Medium voltage motor type tests

According to [42], the type tests by EN / IEC 60034 shall be carried out after manufacturing of the motor. The first motor of each size and type manufactured shall be type tested to prove compliance with the ordered performance. At the client discretion, type test certificates may be accepted in place of the type test for other identical motors of the series.

As a minimum the following tests shall be performed;

a) Impulse voltage test according to EN 60034/VDE 0530 part 15
b) Measurement of starting current and starting torque
c) Measurement of torque as a function of speed (speed torque test can be carried out to prove the pull-out torque)
d) Measurement of the time of inertia according to the deceleration procedure
e) Power factor and slip
f) Losses and efficiency during the individual loads (25%, 50%, 75% and 100%)
g) Temperature rise test and load test

2.10.2. Medium voltage motor routine tests

[42]Describes the routine tests by EN / IEC 60034 shall be performed on each motor. As a minimum the following tests shall be performed;

a) Winding resistance test
b) Insulation resistance test
c) Verification of temperature indicators
d) High-voltage test according to EN 60034/VDE 0530 part 1, section 17
e) Measurement of vibration severity according to EN 60034/VDE 0530 part 14
f) Functional test of accessories
g) Measurement of no-load characteristic
h) Measurement of short-circuit characteristic
i) Over-speed test, according to EN 60034/VDE 0530 part 1, section 2. The evaluation value for rolling bearings according to the shock pulse method (SPM)
j) Measurement of shaft voltage
k) Measurement of insulation resistance of the monitoring equipment
l) Noise measurement according to EN 21 680 part 1 for no-load operation
m) Partial-discharge measurement for all motors
n) Loss factor measurement on all (option) fully completed MV motors.

2.10.3. Medium voltage motor insulation resistance (IR) and polarization index testing

[4]Defines insulation resistance (IR) as the ability of electrical insulation to withstand direct current. Direct quotient voltage of negative polarity divided by current across machine isolation corrected to 40 ° C and drawn at a given time(t) from the beginning of voltage implementation. [4]Describes the polarisation coefficient as a variety in the value of insulation resistance with time. The isolation strength quotients at the moment (t2) split by the isolation force at the moment (t1). If the moment is not stipulated, we suppose 10 min and 1 min respectively

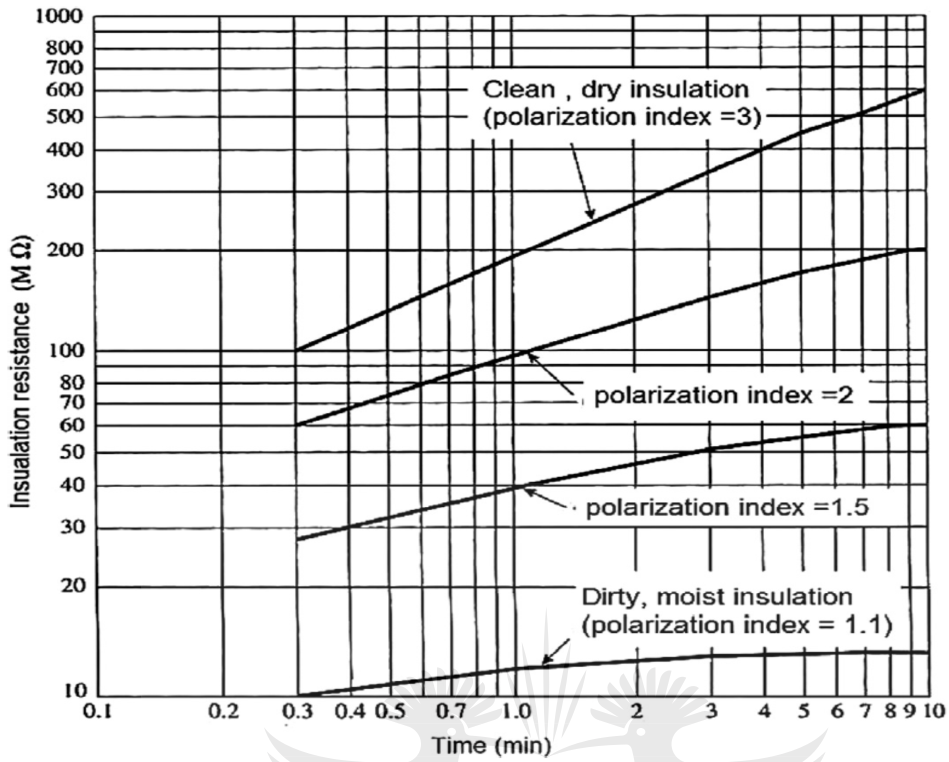

Figure 9: Recommended minimum insulation [43]

The test will detect any insulation windings where potential shorts to the ground can be addressed. The tests are conducted with the use of the 5000 V DC megger as per the motor rating of 15000V AC. According to [4]the insulation resistance of any electrical motors/machines depends typically on the insulation materials and condition stored, and it changes based on the surface area and temperatures that it operates.

The IR results determine the presence of winding faults to the ground or other windings and indicate whether the insulation is healthy (IR > acceptable minimum limit). The IR test results are dependent on temperature, and all results must be corrected to the same reference temperature (use 40°C as per IEEE Std.43-2013).[4] Emphases that the low values of insulation resistance (IR) are often due to contamination of insulation with moisture. If it is found to be the case, the client shall be advised to perform a dry out procedure on the motor. After drying out, the test shall be repeated, and if it stills fails, then the client shall be advised to replace and repair the motor. Also, it is recommended to compare the IR values for the various windings or coils against each other. The highest permissible difference between the IR scores of windings or coils in the same motor is 10percent.[43]Defines that the polarisation index (PI) is conducted to determine the situation of the motor insulation. PI testing requires time for insulation molecules to polarise from their random orientation to resist current flow and is defined as the ratio of 10 minutes isolation resistance to the 1-minute isolation resistance and PI provides the conditions of the motor windings as per figure 10 below.

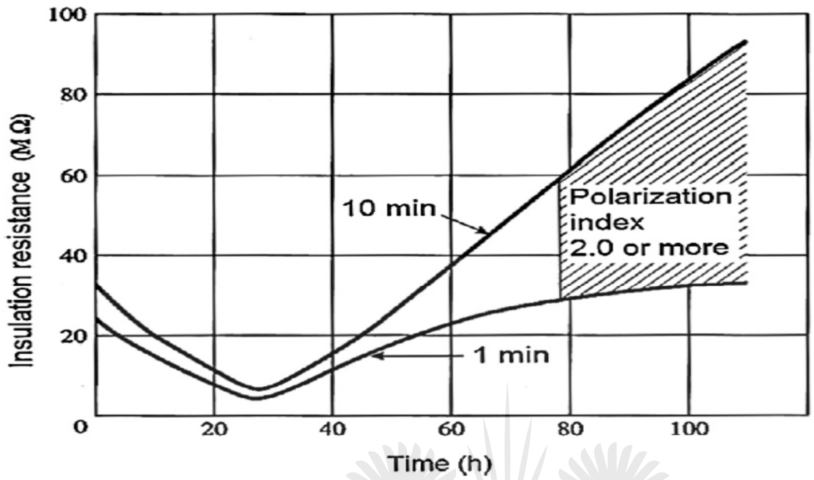

Figure 10: Polarization and insulation resistance[43]

[4]Concludes that the results will determine the contamination of the insulation due to dust or moistures with low PI and a low value will determine damages or contamination with moisture or dust. As recommended by the industry, the IDF motors are class F insulation then the reading of PI shall be higher than 2.0 as the minimum requirements.

2.11. Medium voltage induction motor commissioning

[12]describes the commissioning as the most critical operation, which includes the site acceptance test and factors the acceptance procedures that include pre-commissioning, cold commissioning and hot commissioning. Commissioning is the process of putting into service an item of plant which has been successfully inspected and safety cleared by the required contractual and performance requirements. Therefore covers all checks, adjustments, trial runs and tests of equipment, components, sub-systems, systems and of the whole plant which are necessary to achieve operational reliability of the complete supplied scope after installation. The completion of works has to be handed over to commissioning to commence with the process.

2.11.1. Induction motor pre-commissioning

[12] defines the pre-commissioning which, at and during the building or assembly stage, allows the manufacturing unit to be transferred to the initial charging stage. It comprises all activities and testing before applying energy, excluding all power supplies required for pre-commissioning. These activities are witnessed or executed by commissioning staff, which may be carried out parallel to construction and assembly.

- Visual inspection and system checks by piping and instrument diagrams (P&IDs), arrangement drawings, single line and cabling diagrams
- Adjustment of dampers,
- Adjustment of pressure relief and control valves
- Calibrating of transmitters
- Alignment of flame scanners and other monitoring equipment
- Pressure testing and flushing
- Internal cleaning
- Statutory tests as required by the inspection authority

2.11.2. Cold commissioning

[12] emphasises that the practice of verifying and adjusting for service, an item or section of the plant which has been completed, successfully inspected, safety cleared and pre-commissioned.

Characteristics for this phase is the lack of operating medium or fuel in the systems, energising takes place temporarily, and equipment and systems are not ready for continuous operation. While the components or section of the plant is safety cleared, the permit-to-work system is in force. The energising of the plant is to be carried out by the client's operating staff assigned to this task. The cold commissioning phase includes:

I. Function tests of motors, drives and actuators and other electrical consumers, e.g.
    - Visual inspection whether the supplied and installed equipment and components comply with the applicable standards and design documents
    - Connection check of external wiring

- Earthing measures inspection
- Inspection of safety devices
- Insulation test of power, control and instrument cables
- Insulation testing of motors and drives
- Trial runs of motors with DCS operation from the control room where two directional operations are required
- Stroking of electrical, pneumatic and hydraulic actuators
- Checking adjustment, calibration and parameters of transmitters, devices and components
- Loop-checks from tapping point up to the I/O terminal point in the junction box or the stand-alone control cubicle
- Checking the rotation of motors, drives and electric actuators,

II. Function tests of equipment, components, sub-systems and systems for

- Checking of equipment, component and system protection (Switchgear in test position)
- Checking of sequence programs and interlocks
- Checking of signal exchange, messages, warnings and alarms
- Boiler and turbine protection

III. Preparation of equipment, component sub-systems and systems for service of

- Filling with lubricants (oil, grease)
- Flushing of lubrication oil and hydraulic systems
- Filling with operating medium (air, nitrogen, chemicals, water, fuel oil, coal)
- Commissioning of heaters, trace heating, agitators and filters

2.11.3. Induction motor hot commissioning

[12] describes the startup as a process of putting into service an item or section of the plant which has been completed and successfully inspected, safety cleared and pre-commissioned. Characteristics for this phase is the presence of an operating medium and fuel in the systems the release of equipment and systems for operation and their readiness for continuous operation. The release for hot commissioning is permitted with the client's safety clearance certificate and requires:

- Completion of all mechanical, electrical, instrumentation and control equipment
- Completion of cold function tests.

I. Commissioning and operation of components up to function groups, commissioning and operation of:
   - Sub-systems, systems and function groups
   - Check the direction of rotation
   - Function check of interlocks and protection circuits and devices (devices, circuits, logic)
   - First start-up of E, I&C equipment and components via remote and local operator station with activated power supply
   - Test of single and sequence control functions
   - Check of analogue control functions
   - Start-up of E, I&C equipment and components via remote and local operator station with live process media
   - Re-adjustment, re-calibration and optimising of control circuits and measurements by the operating parameters
   - Combined function groups
   - Function test programs/sub-groups and group controls carried out by DCS operation with circuit breaker and switchgear insert of main drives isolated and in the test position.
   - Test of application of automatic functions and in compliance with the purpose (alarms, trips and interlocks, etc.).

II. Commissioning and operation of sub-group and group controls

- Commissioning of sub-group controls, group controls, and systems with operating fluids/ consumables/fuels, with the full effectiveness of all signal paths, release and protection interlocks, with checking of different parameters, limit values and simulated values.
-

2.12. Root cause analysis of induced draft fan motor failure

[44]describes the root cause analysis as a method of identifying the cause of the failures[44]Describes RCA techniques as step-by-step analyses of the failed motor and its sub-systems. The RCA focuses on different areas that are deemed to have acted upon the failure of components of the motor conducting the FMECA will show the RCA of the failure.[45] describes the RCA as a system for any equipment failure key for corrective action and adds valuable information for the designers, OEM and clients for research and further development.

[45]confirms that the RCA has six steps to follow as be figure 9 below

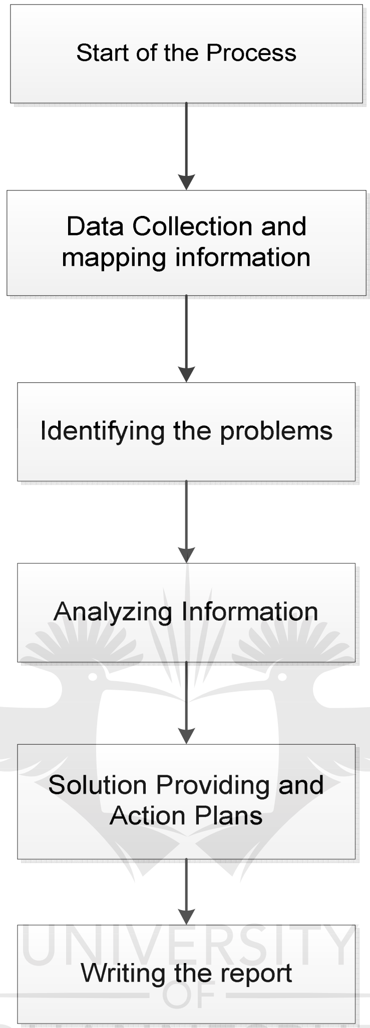

Figure 11: The process of root cause analysis[45]

[45],[46]describes the RCA as the process of identifying the causes of failures and the proposed prevention method for future operations. The methods selected will include the FMECA, FTA, RBD (reliability block diagram). [46]Emphasises the FMEA as the lead method to use for failure identification and focuses on a single failure mode of the system, and then the process focuses on failure causes and modes.[46] It furthermore describes the FTA methods as a backward process for RCA analyses for the systems and its causes of failures. The fishbone diagram using the backward method focuses on the procedurally and hierarchically by using predetermined categories for analysis.

[47]decribes the new dimension of introduction, using the 4M, i.e. man, machine, materials and methods and establish a way of linking the reliability, availability and maintainability process. Concerning "man" a lack of training will lead to the wrong setting of equipment and will have an impact on production efficiency. Table 5 below [44]lists the methodology summary for the RCA of the motor failure based on the combinations of all potential causes that lead to the methodology that deals with failure mode or class and failure patterns.

Table 5: Summary of methodology for analysis[44],[48]

Motor Component	Failure Mode and Class	Failure Pattern
Stator Winding	Turn to Turn	Symmetrical
	Phase to Phase	Single phase
	Phase to Ground	Nonsymmetrical and groudend
	Coil to Coil	Nonsymmetrical and groudend
	Open Circuit	Nonsymmetrical and groudend
Rotor Assembly	Shaft	Thermal
	Bearing	Magnetic
	Lamination	Residual
	Squirrel Cage	Dynamic
	Ventilation System	Mechanical and Environmental
Ball Bearings	Fatigue Spalling	Thermal Vibration Noise
	Fretting	Lubrication Qulaity
	Smearing	Lubrication Qulaity
	Skidding	Mounting/fits
	Wear	Contamination
	Lub. Failure	Mechanical Damage
	Electrical Fitting	Electrical Damage
	Fluting	Load Pattern
	Cracks	Load Pattern
	Seizures	Load Pattern
Shaft	Overload	Ductile
	Fatigue	Brittle
	Corrossion	Beach Marks
		Chevron marks
		Ratchet marks
		Cup/cone
		Shear Lips
		Fretting

2.13. Failure mode effect and criticality analysis of induced draught fan

[49]describes the failure mode effect and criticality analysis (FMECA) semi-qualitative device layout assessment method, but contains a tool to determine the seriousness of the default. Any prospective error is classified by the seriousness of its impact in order to restrict high-risk incidents by suitable corrective measures. [50]emphasises that the FMECA is essential as a design aid when considering modifications or upgrades to a system. [51]Describes the FMECA as the tool to assist in the maintenance plan and also describes the criticality as a base for engineering maintenance to have on the influence of reliability. Principal contractor design and Build contract allow that all design changes should not adversely affect the system's reliability or compromise safety and therefore potential failure modes and causes associated with the design changes should be thoroughly analysed with the client approval. [52],[53] stresses that while the goal of the FMECA is to define all types of error within the framework of machine architecture, its first goal is to define all the disastrous and critical failing opportunities soon so that layout adjustment can eliminate them or minimise them as soon as feasible.

FMECA is the sequel of reliability, availability and maintainability (RAM) study and meant to detail safety and reliability issues for selected components. In consequence, the RBD that is one result of the RAM study serves as a starting point for the FMECA. [54] describes the system under consideration is subject to the failure mode effect and criticality analysis and is carried out subsequently to a RAM study. It is the objective to refine the system such that relevant information for risk assessment and maintenance can be deduced from the results of the analysis. [53]Details the purpose of FMECA as primarily:

1) To recognise those errors that have undesirable impacts on device efficiency, security and activities
2) To provide an efficient technique for assessing the impacts of the suggested modifications to the structure
3) To improve the sustainability of the scheme (by identifying regions of danger or non-compliance for sustainability)

4) To determine the importance or criticality of each failure mode and each failure mode and the impact on the reliability or safety of the system.
5) Develop design enhancement proposals for mitigating error types .
6) Support the creation of an efficient repair scheme to mitigate or decrease device errors ;

2.13.1. Failure causes

The following failure causes were chosen [55], and the failure causes describe by the principal contractor design team and approved by the client.

Table 6: Failure causes[55]

Failure Causes	
1	Inherent defect of a component
2	Incorrect Operation
3	Failure mechanism (wear)
4	External force

Table 6 above describes the identify failure causes below as the industrial norm

1) An inherent defect to a component is, for example, a manufacturing fault or material weakness. In this case, the failure does not occur due to continuous wear or operating conditions but predominantly due to the inherent defect.

2) Failures can occur due to inappropriate operating conditions, which may result in the electronic interference of the control system using safety trips or interlocks but may also result in accelerated wear of a component. Eventually, the component may fail due to excessive wear. Several failure mechanisms can affect a component. In the study, only the most dominant factor is indicated.

3) Failure mechanisms which generally refer to wear in its different forms such as erosion, corrosion, abrasion, thermal shock, most components subject to continuous wear are wear parts and therefore subject to regular maintenance.

4) The failure due to external force means that the component is damaged by some influence which does not originate from the process itself.

Such an external force could be almost anything but is limited to sensible events within the typical vicinity of the plant such as accidents and inappropriate use of equipment.

2.13.2. Failure mode effect and criticality analysis of induced draft fan

[3]describe the ID fan as part of the flue gas system which ensures the boiler when under pressure, discharges the flue gas from the boiler via the gas-air heater and pulse jet fabric filters to the chimney. The risk assessment for the aspects is not always the same. In this case, the worst value was chosen. All considerations are made assuming that defined maintenance procedures are adhered to and that the process is run at normal parameters. This compliance of the prescribed procedures is called good working practice. The risk ranking used by the principal contractor, OEM and client is as per table 7 below.

Table 7: Risk Assessment of FMECA induction draft fan[3]

Failure Ref No.	Failure	Cause of Failure,Failure Mechanism	Prptective Measures	Consequences of Failure and Mitigation Measures	Risk Rank	Comments and Recommendations
1,1	Drive Unit Fails	Winding damage or Electrical failure	Regular Maintenance and inspection, ensure sufficient cooling	Failure of drive unit causes the ID fan to fail. Shut down of ID fan causes one lane operation of	4	Temperature of the windings will be monitored
1,2	Cooler Fails	Flange connection leaking. Vent fails due to Electrical Failure	A. Regular maintenance and inspection. B. Ensure sufficient cooling water supply. C Ensure operation	Delayed shut down due to over temperature at drive unit of ID fan. Shut down of ID fan causes one lane operation of plant	2	The delay time depends on the boiler load and is typically in the range of minutes. The temperature at the windings of the drive unit will be monitored
1,3	Couplings Fails	Material fatigue, wear, overload	Regular Maintenance and inspection . Replace coupling	fan to fail. Shut down of ID fan causes one lane operation of Plant.	2	Spring elements can be replaced without change of hole coupling during standstill. Rotational speed of fan shaft will be monitored.
1,4	Hydaulic oil supply system fails	Oil tank Leakage. Pump fail by electrical failure.Filters clogged	Regular maintenance and inspection. Replace Filters	The load range of plant operation is limited	3	If differential pressure over the filters increasess too high, then the system is automatically switched over to the redundant filters. The pumps are redundant with automatic switchover to other pump if pressure too low.
1,5	Pre- Heater Fails	Winding damage or Electrical failure	Regular Maintenance and inspection, ensure sufficient cooling	If the oil temperature is too low the ID fan can not be started	2	Oil tank temperature monitored
1,6	Operation of ID fan beyond stall line	Specific operation of ID Fan	Operate fan only at designated load range. Regular maintenance and nspection of stall warning	The ID fan will be shut down by excessively high vibrations. This will cause one lane operation of the plant	3	Actual operation point of fan will be monitored by stall warning device in DCS. Stall probe detects operation beyond stall line.
1,7	Oil Pumps Fail	Electrical failure cable loose or broken. Bearing damage	Regular Maintenance and inspection. Replace Pump	If the oil temperature is too low the ID fan can not be started	3	Pumps are redundant with automatic switchover to other pump if pressure too low.

2.14. The fault tree analysis of stator failure

[33]describes the construction of the fault tree to identify all possible causes to the induction motor failure; it will identify and establish the formation of the FTA to the cause of the failures. The FTA serves as a means for describing component failures, more precisely the root of these failures. The cause analysis is done systematically using fault trees which spares the necessity to compose long descriptive texts. Using a fault tree, the critical information is available at a glance. Thermal IDF motor is new and started to fail during the commissioning period, and the insulation failed prematurely at the first startup process as shown in figure 12 below

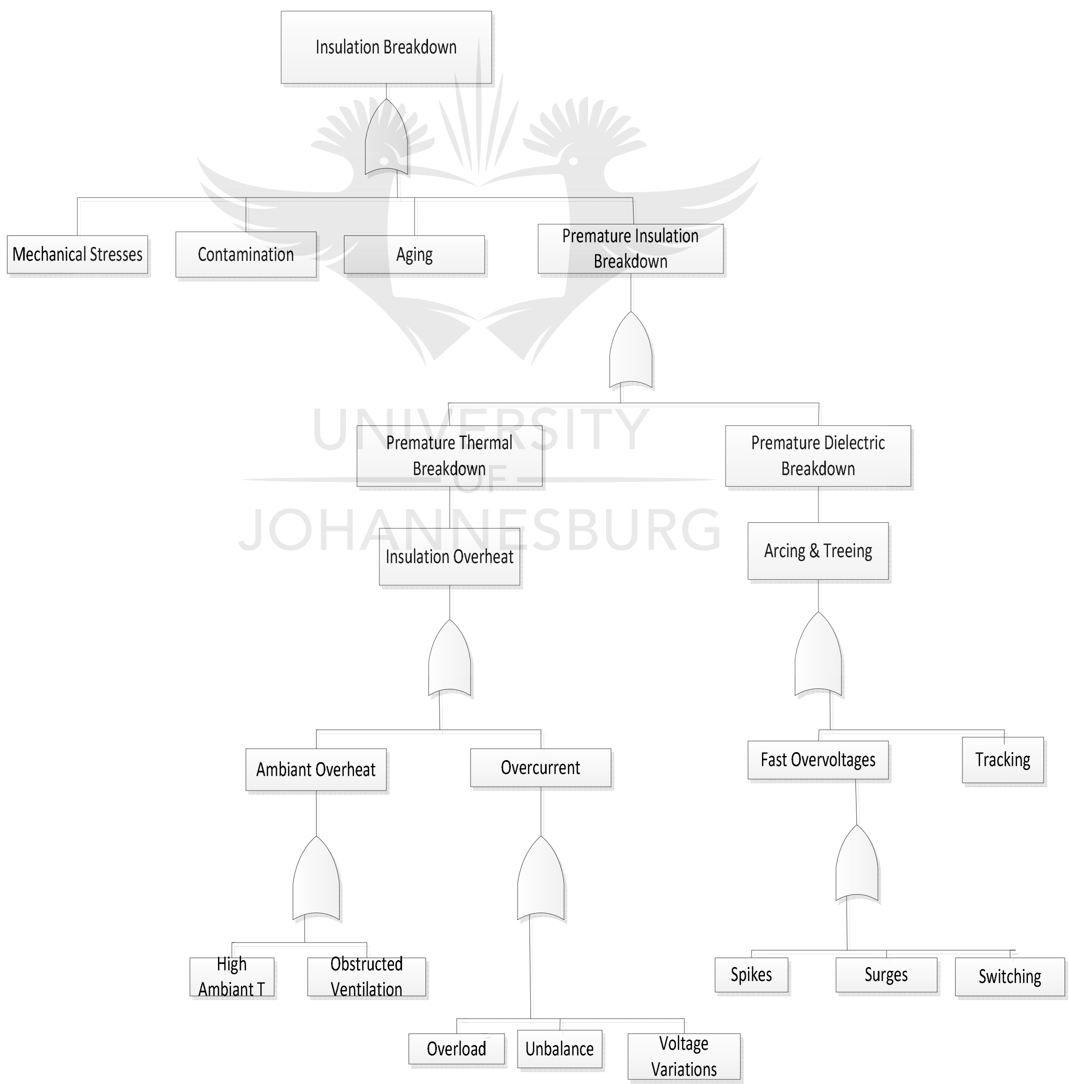

Figure 12: Fault tree analysis for stator insulation breakdown [33]

2.15. Induced draft fan motor reliability block diagram

According to [49], the approach chosen for this study is based on abstraction. In other words, to keep the system, tractable components were lumped together in subsystems. Those subsystems by themselves comprise several components which can sometimes be labelled by reliability data. The detail is lost when all the reliability data is incorporated into one single set of data for the subsystem and not for its components. As a result, system boundaries can differ from those used in other parts of engineering. This circumstance must be considered when estimating the reliability data for a single block of the RBD. Furthermore, the accessibility is described as the probability that at a specified moment, the element or unit will be in its working state. Reliability is not equivalent to accessibility, although accessibility is a feature of an element or system's accuracy and maintenance.

[49] Defines that maintainability is the comparative and moment savings with which a faulty element or scheme can be returned to a particular situation when servicing is done. Decreasing downtime owing to maintenance increases the maintenance of the element or scheme. The system's quality and accessibility are subordinate to the quality and accessibility of each element of that unit. These components may be combined in complex configurations, including redundancy built into the system. [49],[56]define the block that represents each component in a so-called RBD. Each element of the scheme in an RBD is linked in sequence and column and is also a graphic depiction of how the parts of a scheme are reliably linked depending on the functional dependence between the elements. [49]Argues that device loss of any element in a sequence setup, whereas loss of an element in a simultaneous (redundancy) setup may not simply end in device loss principal contractor detailed the corresponding RBDs shown in figure 13 below.

The systems/components shown in level 3 of the RBDs are described in more detail

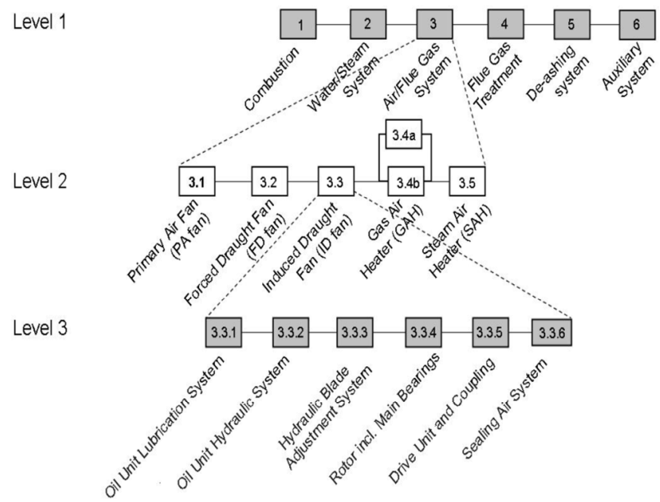

Figure 13: Reliability block diagram for the air/flue gas system [3]

2.15.1. Induced draft fan (3.3)

The ID fan is a fixed speed axial type of fan. The variable blade-pitch is used for through-put control; the adjustment of the blade-pitch is affected by the hydraulic blade adjustment system. In addition to the hydraulic blade adjustment system, the ID Fan comprises an oil unit hydraulic system, an oil unit lubrication system, a drive unit and coupling and a rotor including main bearings. Therefore the pressure loss from the duct system, including the individual components, is to be overcome.

2.15.2. Drive Unit and Coupling (3.3.5)

The system drive unit and coupling comprise an electrical driving motor and coupling. The coupling comprises two halves which connect the motor shaft with the fan shaft using an intermediate shaft. The motor is equipped with sleeve bearings which are lubricated by the oil unit lubrication system.

2.16. Conclusion

The IDF discharges the entire flue gas through the GAH and the PJFF to the chimney. Therefore the pressure loss from the duct system, including the individual components, is to overcome. The challenges of the induction motor failures experienced at Thermal power station boiler 2. Stator coil failures are linked to the stator coupling error and are defined as short-circuit intervertebral faults. The reasons for mechanical stress are owing to the spiral and rotor motion, which hit the stator.Testing is deemed to be the key to early detection of faults and confirm the reliability during the operations and improves the motor design output. Commissioning is the process of putting into service an item of plant which has been successfully inspected and safety cleared by the required contractual and performance requirements.

Failures can occur due to inappropriate operating conditions, which may result in the electronic interference of the control system using safety trips or interlocks but may also result in accelerated wear of a component. Eventually, the component may fail due to excessive wear. Several failure mechanisms may affect a component. In the study, only the most dominant factor is indicated. The RCA is used as the process of identifying the causes of failures and the prevention method for future operations. The methods selected will include the FMECA, FTA and Fishbone diagrams. The FMECA is essential as a design aid when considering modifications or upgrades to a system. The fault tree serves as a means of describing component failures more precisely the root of these failures. Chapter 3 will give direction on research design and methodology in assisting the investigation of the cause of the IDF motor failure during commissioning.

3. Research design and methodology

3.1. Introduction

The possible causes of the Induction motor failure during commissioning in the engineering and construction industry are brought to light in chapter 2. In the power station industry, as is the same with other construction industries, there is a combination of electrical, instrumentation, civil works and mechanical professionals. The questionnaires are designed for the respondents to help provide an understanding and verification of causes of Induction motor failure during the commissioning phase. To obtain the industry challenges, the South African power systems industry is experiencing, structured questioners were sent to construction managers, commercial managers, project managers, commercial teams and other representatives. The following companies were involved with power projects in thermal power station: OEM, principal contractor, contractor and client

The purpose of this study is to provide a balanced and progressive approach to improve the process of selecting an appropriate strategy to manage integration between the construction team, commissioning and client handover. The research problems have been established as the based on the practical problems facing the power station industry and to answer questions to promote the improved check sheet during the commissioning process and construction industry with tested methods to study the works. The investigation of the problem does not always guarantee a solution to the problem, but it will clear the way for commissioning and the OEM to employ other methods to solve problems they encounter. [57]Describes the RCA as an expedient manner of consideration and analysing the serious adverse event. Furthermore describes the RCA primary function to focus on system-based factors that increase the possibility of an adverse event while preventing the culture of blaming other team members for the incidents.

3.2. Investigation and chosen research tool

The main aim is to understand the causes of failures on equipment after all the factors and acceptance tests are achieved and acceptance by all parties The research case study selection looks at the following;

- Understanding the impact of the current risk assessment and study for thermal power station
- Root cause analysis of Motor failure during commissioning concerning the RAM study and FMECA methods.
- The data will include collection from the principal contractor database and records from DCS and switchgear systems from the client.

The data collection method was chosen as per to [13] focus on survey questioners and company records of all four parties(OEM, principal contractor, contractor and client).[13]Describes the use of sampling methods, the accuracy of results and low costs. A qualitative research strategy has been chosen to obtain detailed information about the involvement of the commissioning process over the years and a possible forecast for the future. The focus groups will be personally interviewed with assistance from the questionnaires that are going to be sent to those selected for the survey. The commissioning process in the industry is exceptionally detailed, but this research will concentrate only on a power project in the thermal power station. The chosen method of study is based on Figure 14 below

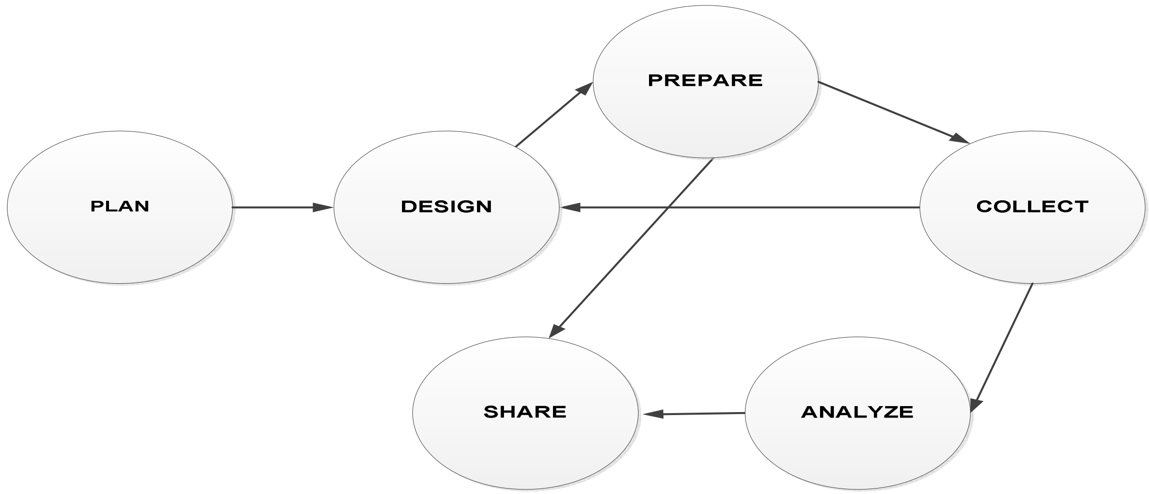

Figure 14: Research framework of the case study. (Source: adapted from [58]

[58]describes a figure 14 schedule for a case study investigation by defining and understanding research issues and strengths and constraints. The layout stage relies on identifying the assessment device and the probable trigger in the research and also identifies processes for maintaining the performance of the situation research. [58]emphasises the importance of the design of the case study, to follow the four significant tests;

- Construction validity - identification of operational measures that match the concepts
- Internal validity - focusing on the broader problem of inferences
- External validity – checking the neighbourhood theory
- Reliability - the objectivity will come to the final or same findings with previous researchers

The emphases of preparation will focus on the preparation of sound structural questions with selected candidates, not allowing bias or pre-empting of answers.

3.3. Research methodology

According to [59], the information used for this research project is base on information accumulated through the data gathering method and the use of an empirical survey. The survey consists of questionnaires and interviews with the focus group. The respondents of this study were chosen based on their involvement with current thermal power projects. The experienced project managers of international projects and some of the other leading manufacturers of motors will also participate and feed into the study. The integration and involvement of the project management, construction, and commissioning management teams in various construction projects will also add value to the study.

The opportunity for the project managers to provide a personal level of understanding, as per their experiences in the construction industry, will add further value to this research study. Firstly, a literature review was carried out with a focus on information found in journals, case studies, various topical books and seminars to determine the reasons documented for the premature failure of IDF motors during the commissioning phase. Secondly, the study was conducted using questionnaires and structured interviews with representatives of the OEM, principal contractor, contractor and client involved in thermal power station projects.

3.4. Research limitations

The research study is limited to the thermal power station in Mpumalanga as the only power station in South Africa using 15KV AC MV motors with FGD.[60] describes that It is necessary to understand the causes of induction motor failures and the proposed approach to manage the inevitable failures at unit 3 to unit 6. The research questions and the focus group are limited to the main problem addressed by this research study.

Further study is, however, possible to investigate challenges not mentioned in this research report. A further limitation of this research study is the accuracy of the answers provided by the focus group in the questionnaires and interviews. The scope is limited to only the boiler contractor's scope of works for supply, installation and commissioning of boiler induced draft fan motors. However, the design study method will be used to bridge the gap between the information required to conclude the study. There will be a limitation on the participant of the study and will have limitation based on the current skills in the commissioning of power plants in South Africa to back up the study. The client is client generation and assumes responsibility for the successfully commissioning of the plant.

3.5. Research survey structured

The newly developed questionnaire and teamed with the use of personal interviews, with these in place the study was conducted using the questionnaires and structured interviews conducted with representatives of the OEM, principal contractor, contractor and client all involved in the thermal power station project. The design research of the study will be limited to the evidence of the already supported literature review from previous researchers. The focus of the questionnaires is to gather the following information:

- The personal details and background of selected participants in the study
- Types of similar projects involved with the study
- How testing of the FAT and SAT were conducted
- The lessons learned from Units 1 and 2 and how to implement them for units 3 to 6 in the future
- To demonstrate the process of managing project integration between the OEM, construction, commissioning teams and the client during the project life cycle
- The proposal of the correct procedure to follow in future projects.
- To relate the findings of the literature review to the industry at today's level of views.

3.6. Area of Study

[59] emphasises the area and the location where the study was conducted, where the area of study for this research is the thermal power station located in Witbank, Mpumalanga province, South Africa

3.7. Data Collection

The research questions are required to address the guidelines for answering the structured interview questions with representatives of the OEM, principal contractor, contractor and client, which were involved in thermal power station project. The test records from the OEM and principal contractor preservation teams gathered during the five years via the preservation process records and all test results conducted after SAT. The DCS records before and after the IDF motor failure. The company representatives had been requested to sign a consent form stating that they had an understanding that their involvement is voluntary as per the attached Appendix D.

3.8.Data analysis

[60]describes the data analysis process involving the review of information generated from completed questionnaires into manageable sections and drawn into conclusions. The queues data collected will be in graphical formats with the questionnaire conclusions. According to [58],[60] list of suggestions will be taken when using qualitative research for data analysis;

- State study issues
- Collect background data to assist in comprehending the context, ideas and theories in question.
- Suggest multiple definitions or responses to issues or issues depending on this data
- Use these to guide the quest for proof that could help or contradict the responses.

- Continue to seek appropriate proof. Eliminate contradictory perspectives or responses, abandoning, possibly, one or more than the proof supports.
- To guarantee precision and consistency, cross-examine the reliability and origins of proof.
- Carefully verify the logic and legitimacy of the findings of the statements.
- In case of more than one hypothesis, select the most solid situation

The detailed data analysis will be presented in chapter four as research findings.

3.9.Research ethics

The research respects the ethical standards set by recognised global research ethics. The research team will be informed of the process to be followed during the research activities. The respect and recognition of all participants are deemed more important than the study itself. The volunteers and their participant's companies were duly informed about these voluntary activities and will not jeopardise their current positions or standards in their jobs, and it is for the benefit of all companies involved for the completion of the project on time. The importance of clear guidelines by the OEM together with the client on the equipment release to the site for completion. The research will have confidentiality for all participants, the data and materials obtained for the research will be destroyed after completion of the study, and the recommendations will be shared to all that request the findings and future recommendations and improvements of the process. The researcher and the company had agreed to keep the name confidential for this report.

3.10. Conclusion

This chapter focuses on research methods used to gather the data required to answer the research problem: An examination of the causes and effects of the IDF motors failing prematurely during the last commissioning stages. The opportunity for the project managers to provide a personal level of understanding, as per their experiences in the construction industry, will add value to this research study. The questionnaire was chosen with the use of personal interviews; the study was conducted using questionnaires and structured interviews with representatives of the principal contractor, which are involved in thermal power station projects.

There will be a limitation on the participant of the study and limitations based on the current skills in the commissioning of power plants in South Africa to back up the study. The client is KET and assumes responsibility for the successful commissioning of the plant. The research problems have been establishing as the top ten facing the power station industry-and to answer the questions in order to promote the improved check sheet used during the commissioning process and the construction industry with tested methods to study the works. The next chapter presents the findings of the study and case study analysis, the DCS and switchgear start and trip curve report with associated temperature measurements.

4.Data analysis and discussion of findings

4.1. Introduction

The current research focuses on the RCA for the un-predetermine failure of IDF motor during commissioning and will also access the processes, the tracking of the commissioning processes and integration between the parties to the completion of the task at hand and the closing of the current information gap. The questionnaire was chosen and with the use of structured questions with managers, engineers and technical staff of the principal contractor, OEM, client and subcontractor which are involved in thermal power station projects. The study targeted the team that was involved from concept design until commissioning. The DCS switchgear start and trip curve were analysed to determine at chapter 5 as part of case study analysis with the possible cause and also the functionality of the protection system to the fault detection. The questionnaires were sent to forty-seven potential targets that were directly involved with the OEM, principal contractor, subcontractor and client until the commissioning of the IDF motors. They were only thirty-five responses, confirming a 75% response rate as per table 8 below.

Table 8: The response rate to the structured questioners

The targeted number of participate	The actual number of response	Response Percentage
47	**35**	**75%**

4.2. Data analysis

The structured questionnaires were focused on addressing the following questions;

1. How was the motor handled from the time it left the factory until it was put into service?
2. How many times was the motor started before this event, what was the cumulative running time of the motor before the failure, did the failure occur on start-up or when the motor was at full speed?
3. The motor was manufactured six years before being installed and commissioned, was the winding completely dry and were the polarisation Index| (PI) and insulation resistance tests conducted?
4. What was the condition of the switchgear that operated this motor, was the motor protection set up correctly, was there any other equipment failures at the time of the motor failure and were there any power surges at the time of the failure?
5. Was the motor safety clearance certificate available from the clients commissioning?
6. Was the commissioning engineer at duty trained to perform the task?

Section A has specified the confidential information concerning the participant's qualification, background, work experience and involvement at the thermal power station and has assisted the researcher with valuable information that has a positive influence on the study

4.2.1. Section A: Background or demographic information

4.2.1.1. What is your highest educational qualification?

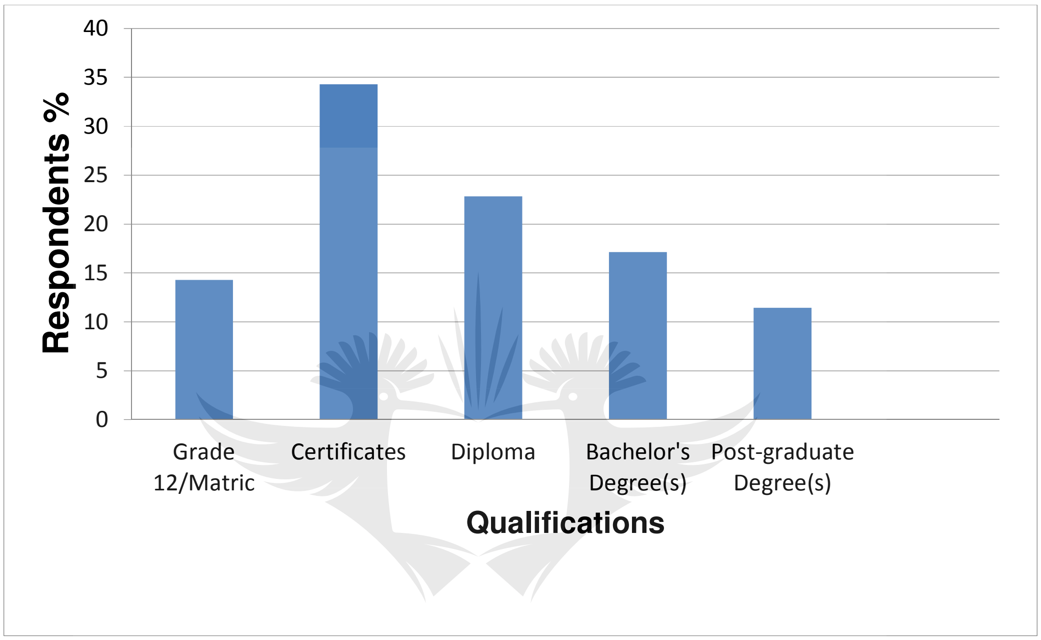

Figure 15: Highest educational qualification

Figure 15 detailed the respondents are within the specific mix of qualifications with the highest being 34 % being national certificates. This shows the level of equivalent qualification within the thermal power station during the construction and commissioning of the plant. 21 % were recorded for the national diploma, followed by 17 % with bachelor's degrees and 14 % Matric certificates that are working as semi-skilled employees and finally 11 % with post-graduate degrees. The balance of educational background gives the research a positive impact on the study and valid information for the investigation of the causes of IDF failure during the commissioning phase of the project. The experienced employees from the principal contractor, OEM and client give the balance of their skills; know-how and lessons learn knowledge for future boiler commissioning process.

The summary of profile in numbers are tabulated in table 9 below and showing the list of candidates qualification responses. This regarded as essential to identify the level of experience of the team working after the IDF motor.

Table 9: List of candidates qualification

Candidates highest qualifications	No. Of candidates
Grade 12	6
Certificates	12
Diploma	7
Bachelor's Degree(s)	6
Post- Graduate Degree(s)	4

4.2.2.2. How long have you been working at the thermal power station?

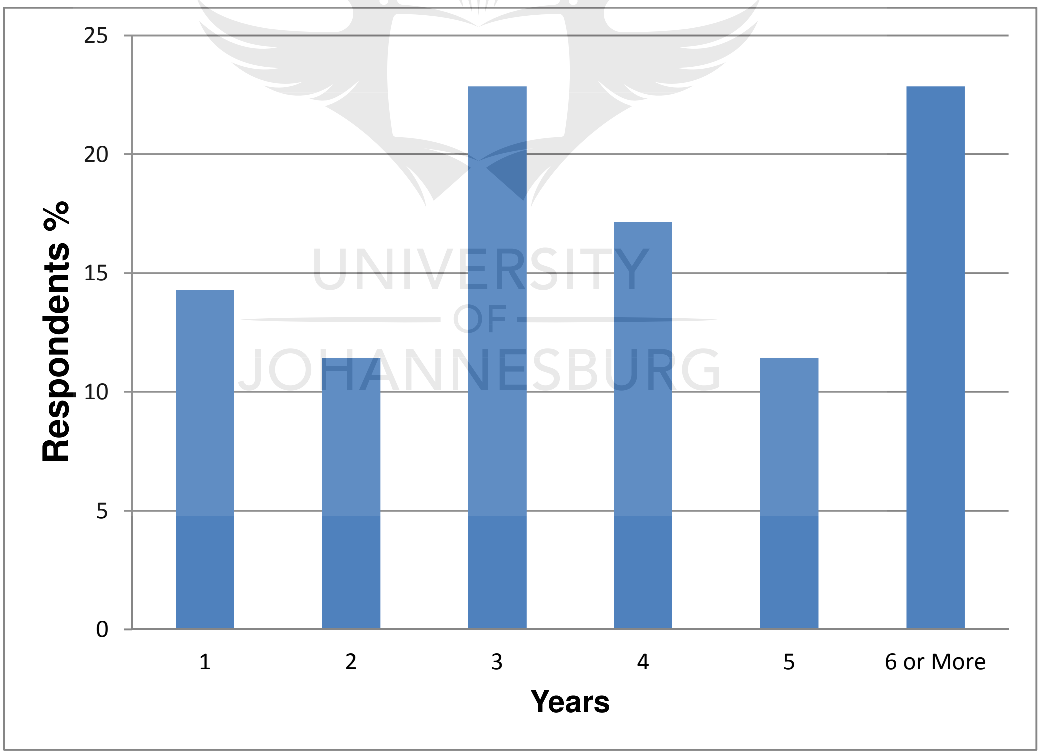

Figure 16: Working experience

Figure 16 above details, the respondents who have 3,4,5 and 6 or more years, with a combined working experience of 64% having working experience and able to provide valuable information for the study. It also indicates that 36% of participants have less work experience, respectively, of about one and two years. Principal contractor commissioning has to embark on training of the commissioning teams by arranging practical training to increase the experience and awareness of their workforce. The experience mix between the client and contractors shows that the team is capable of construction and commissioning of the plant. The graph indicates that the principal contractor and the client had an experienced workforce to enable the thermal power plant to be commissioned as per the client operational requirements.

Table 10: The years of working experience of candidates

Numbers of Working Experience	**No of Candidate**
1	5
2	4
3	8
4	6
5	4
6 or More	8

4.2.2.3. What is your job title?

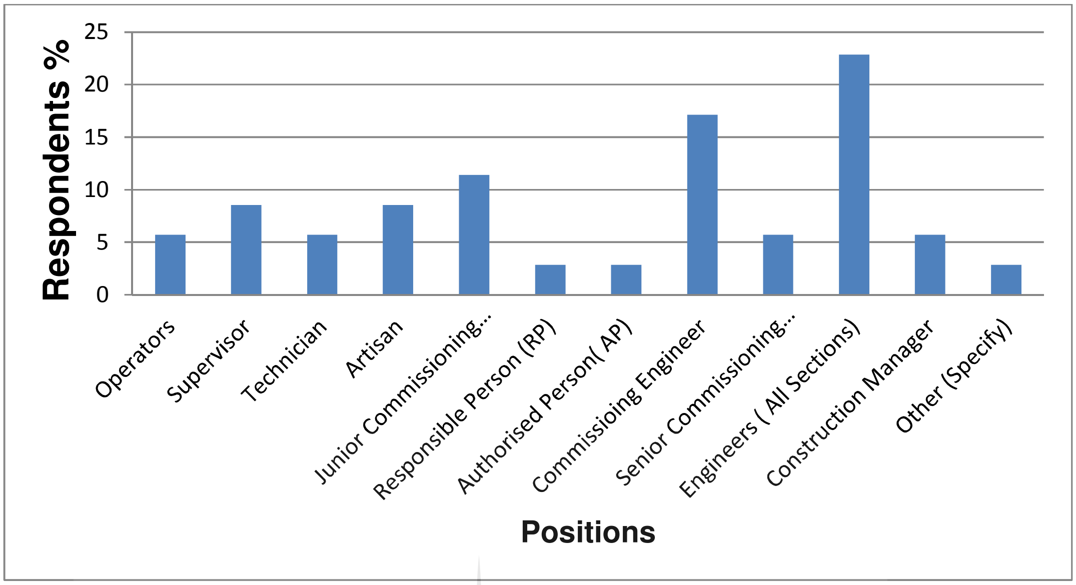

Figure 17: Participants position or job title analysis

Figure 17 above indicates the job title representatives of the respondents to the study which indicates 34 % is made up of commissioning engineers and other discipline engineers to give balance for the support of the remaining 66% that deal with supervision, technicians and artisan, operators, responsible person and construction management. The commissioning engineers and other discipline managers lead the construction of the IDF and commissioning before handing over to the client. The results show that the team responsible for the construction and commissioning has vast experience which complements each section to achieve the completion of the Thermal boilers and handover to the client for operations.

Table 11: The role of candidates that responded

The role	No of candidates
Operators	2
Supervisor	3
Technician	2
Artisan	3
Junior Commissioning	4
Responsible Person(RP)	1
Authorised Person(AP)	1
Commissioning Engineer	6
Senior Commissioning	2
Engineers(All disciplines)	8
Construction Manager	2
Others (Specify) – HSE	1

4.2.2. Section B: This section will cover questions related to the causes of IDF motor failures during the hot commissioning phase.

Question 1: *How was the motor handled from the time it left the factory and until it was put into service?*

No	Questions	Yes (%)	No (%)
1	Was preservation done at the factory?	100	0
2	Were the bearings free to rotate and operated as intended?	100	0
3	Were the storage conditions acceptable?	100	0
4	Was preservation done at the project site?	100	0
5	Were the space heaters connected to construction power?	100	0
6	Was transportation of the IDF from the factory to site performed according to the OEM guidelines	100	0
7	Was the motor OEM checklist supplied with the motor to site?	57	43
8	Was FAT completed at the factory?	100	0
9	Was SAT completed on the project site?	100	0
10	Did the IDF motor passe all type tests?	100	0
Mean		**96%**	**4%**

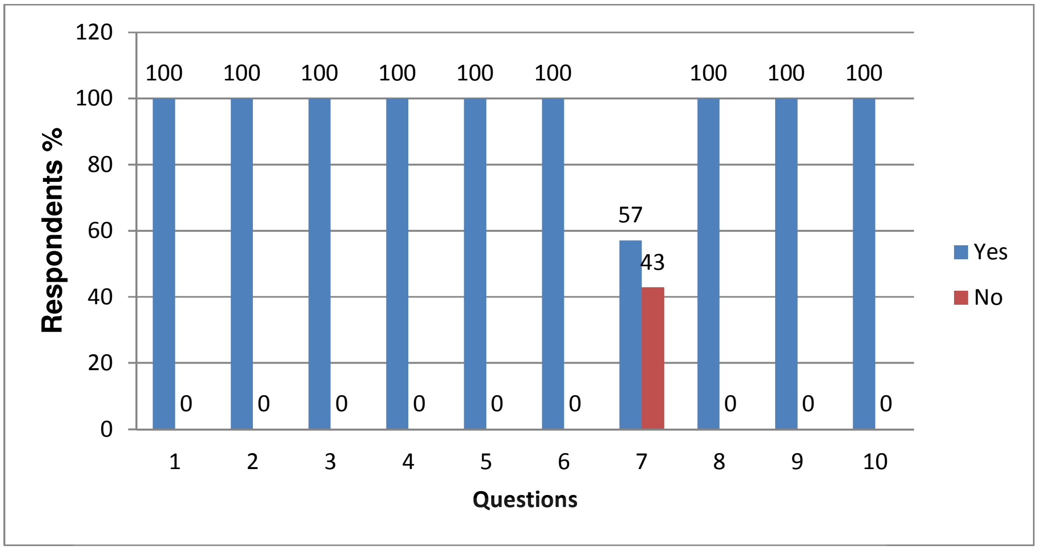

Figure 18: Research Question 1

The most critical questions are ranging at 100% from Q1, Q4, Q5 and Q9 due to the importance of the preservation of the IDF motor when not in operation and the basic requirements from the OEM to maintain the guarantee of the motor by following their set requirements to guarantee operations. It is also clear from the list that the motor checklist was not available for all team players to evaluate. The cause of this is due to the team members from a different organisation, not having direct access to the databases and being able to answer the question accurately. The preservation of the IDF motor can be confirmed as 96% of responses from the participants and all protocols being adhered too. [33].[35],[43] describes the maintenance history of motor preservation as the first area to look at the potential failures. [43] emphasises that the failure mode and pattern can be identified by looking at the appearance and the maintenance history of the motor. The motor is still new then the maintenance history will not be considered for this study, and only physical appearance applications will be looking at it. The objectives of this question were to look at the motor handling protocol from OEM premises and installation at the project site

Question 2: *How many times was the motor started before this event, what was the cumulative running time of the motor before the failure, did the failure occur on start-up or when the motor was at full speed?*

No	**Questions**	**Yes (%)**	**No (%)**
1	Was the motor in service during the failure?	0	100
2	Did the motor archive the full speed?	78	22
3	Was the voltage balanced between phases?	43	57
4	Did the IDF fail on start-up?	0	100
5	Is the motor sitting idle before starting?	100	0
6	Was the starting DOL?	86	14
7	Was the IDF motor on-load?	11	89
8	Was the IDF commissioned at load?	20	80
9	Is the operating sequence followed during starting?	96	4
10	Was maintenance performed?	12	88
Mean		**58%**	**42%**

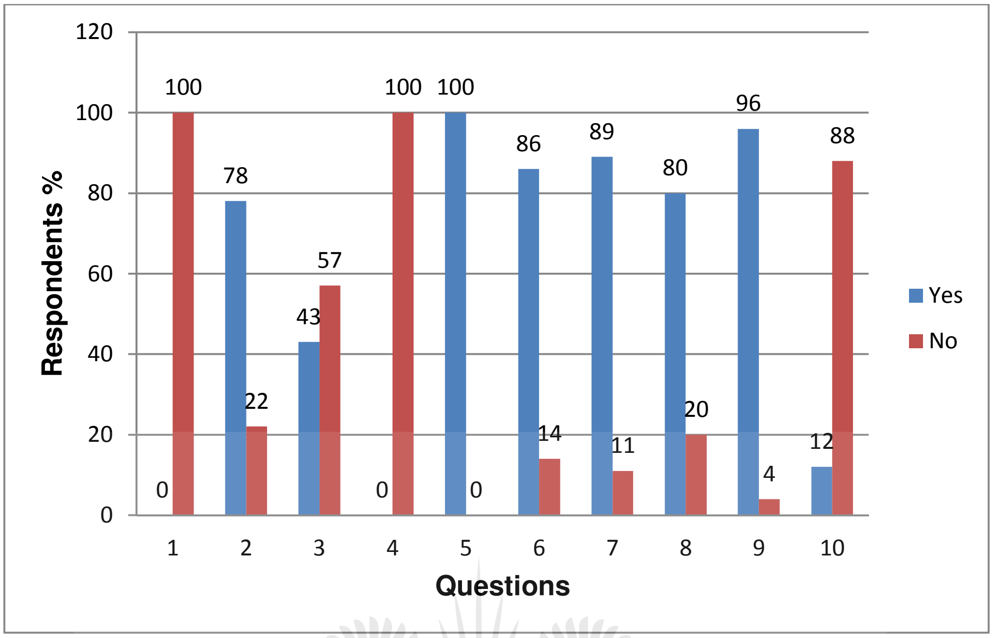

Figure 19: Research Question 2

Figure 19 above describes that 100% of participates agree that the motor was never used before failure on the 23 June 2017. However, concerning Q2, the respondents are 78% sure that the motor had reached the maximum speed due to the use of DOL starting methods that reach maximum speed within seconds. The balance of the voltage is showing the split between 43 % yes and 57 % due to the lack of information sharing between the parties and the use of different databases. Q4 confirms that the IDF motor did not fail on start-up but 2 minutes after starting with the motor archiving full speed. The understanding of Q6 described the motor reaching the maximum speed of 750rev/min due to the direct on Line starting process. The question Q7 and Q8 wanted to identify the knowledge of operations taking place during the commission, and it seems the majority of the respend agreed that the was not on load. Q9 look at the operation sequence as per the client requirements for starting the new motor and 96% of the responses show the knowledge that it was followed. Regarding [37], [43],[45] the maintenance history is one of the five RCA methods required to identify the failures, and we can confirm that 88% confirm that there was no maintenance to the motor that failed due to being new.

Question 3: *The motor was manufactured six years before being installed and commissioned, was the winding completely dry and were the polarisation index| (PI) and insulation resistance tests conducted?*

No	Questions	Yes (%)	No (%)
1	Does the IDF motor exhibit any foreign materials?	5	95
2	Are rotor cooling passages free and clear of clogging debris?	100	0
3	[61] Were the polarisation index (PI) and insulation resistance (IR) tests conducted at the factory at three-month intervals?	95	5
4	[61] Were the polarisation index (PI) and insulation resistance (IR) tests conducted at the thermal project site at three-month intervals?	100	0
5	Had the OEM guaranteed expired?	90	10
6	Were bearings rotatable and worked as designed?	86	14
7	Is the motor properly installed, fitted, paired?	96	4
8	Were storage conditions acceptable as per the OEM's guidelines	93	7
9	Were the correct lubrication procedures utilised?	85	15
10	Were the PI and IR results acceptable?	96	4
Mean		**85%**	**15%**

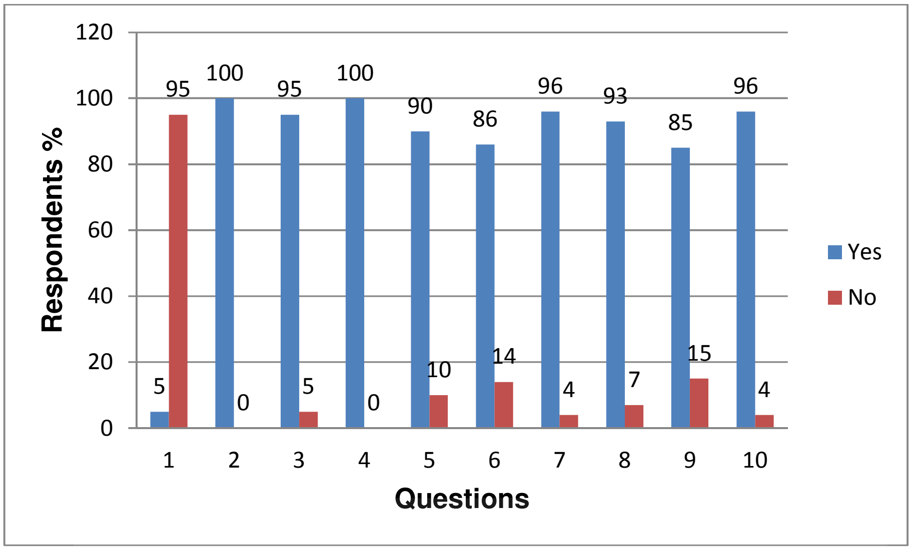

Figure 20: Research Question 3

The findings of figure 20 above show that the team has an understating of the process to be followed for the long term storage of the MV motor as per the OEM recommendations. Q3 95 % and Q4 100% of the respondents have an understanding of the importance of Polarization Index and insulation resistance test intervals as per the OEM. 86 % of the respondents know the motor guarantee, as stated in the contract agreement. Q5 responses show that there was some knowledge about the motor guaranteed that expired before the motor was put in service. The IDF has a 5-year guarantee but only commissioned after six years on site. 96 % of the respondents agreed that the motor installation and coupling were done correctly and acceptable to the client. Q6 86%, and Q8 93% of respondents confirmed that the motor conditions were monitored according to OEM requirements and check monthly as per the long term preservation process. Q7 is very important as if the motor not fitted according to the standard that will experience vibrations, and it will have a failure during operation. Q9 85 % confirm the knowledge of the lubrication to be used on the IDFmotor skid as per the OEM recommendations. Q10 96 % confirm that the PI and IR results were acceptable because they will not have to be suction for the test if not meeting the requirements.

Question 4: *What was the condition of the switchgear that operated this motor and was the motor protection set up correctly and was there any other equipment failures at the time of the motor failure?*

No	Questions	Yes (%)	No (%)
1	Was the IDF motor uses DOL?	58	42
2	Was the bus bar insulation resistance conducted on the Switchgear?	40	60
3	[43] Was the voltage balanced between phases?	30	70
4	Were all requirements for earthing protection in place?	90	10
5	Was the supply voltage 15KV AC?	80	20
6	Was the switchgear power cut immediately after failure detection?	30	70
7	During the failure, was the motor rotating?	100	0
8	Have any other unsuccessful devices on the request?	0	100
9	Did the IDF motor fail on starting?	0	100
10	Did the IDF motor fail while operating?	100	0
Mean		**53%**	**47%**

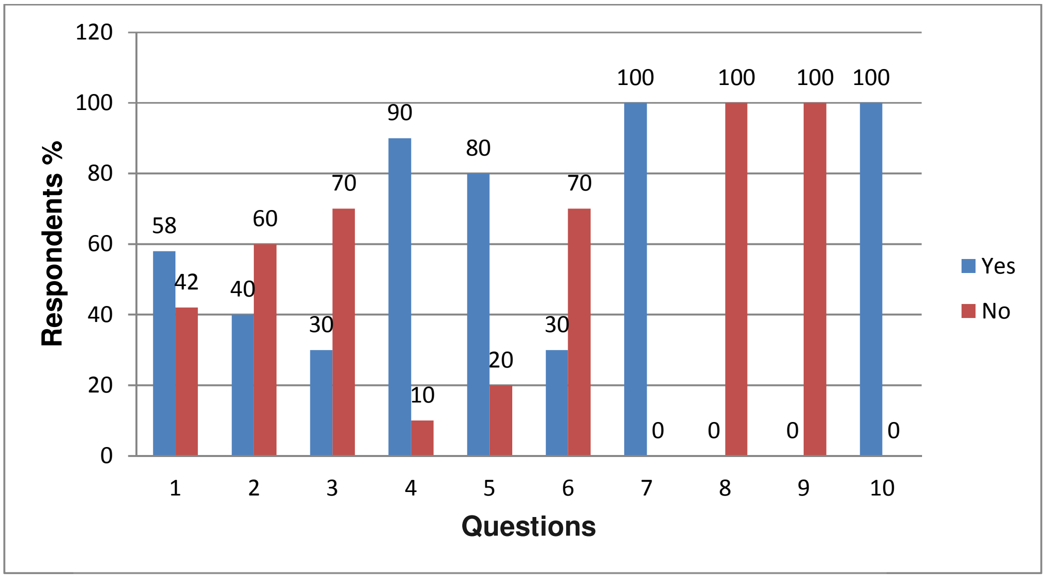

Figure 21: Research Question 4

Figure 21 above shows that the respondents do not have full knowledge of the IDF motor starting requirements as the result is almost 50%. The Integration of information between client and subcontractors is not managed well and regarding information sharing because of the use of different databases for the information. Principal contractor installs and commissions the IDF motor, and the client installs and commissions the switchgear that drives the motor. The Q3 70% response in voltage balance also results due to a lack of information from the client switchgear subcontractor to the IDF motor subcontractor The 30% of responses for Q6 has acknowledged that the switchgear trips on time but 70% disagree on this answer due to the limited sharing of information and impact on an integrated project like thermal power station. All parties require 100% participation to achieve 100% of the plant commissioning ready for operations by the client. The client will have to close the gap by supplying all required information to interfacing subcontractors. Q9 100% confirm that the motor did not fail at the start but during operations and answering Q10 at 100%.

Question 5: *Was the motor safety clearance certificate available from the client commissioning?*

No	Questions	Yes (%)	No (%)
1	Was safety clearance certificate received?	100	0
2	Was IDF motor under commissioning phase?	90	10
3	Was cold commissioning achieved?	90	10
4	Is the commissioning quality inspection performed?	100	0
5	Does the IDF motor posses the attributes of Client expectations?	90	10
6	Was the client AFI process requirement successfully circulated and understood throughout personnel?	90	10
7	Were all open items closed?	80	20
8	Equipment grounding and bonding systems are in place?	100	0
9	Was the IDF motor ready to be safely energised?	95	5
10	Were the method statement and risk assessment available?	78	22
Mean		**91%**	**9%**

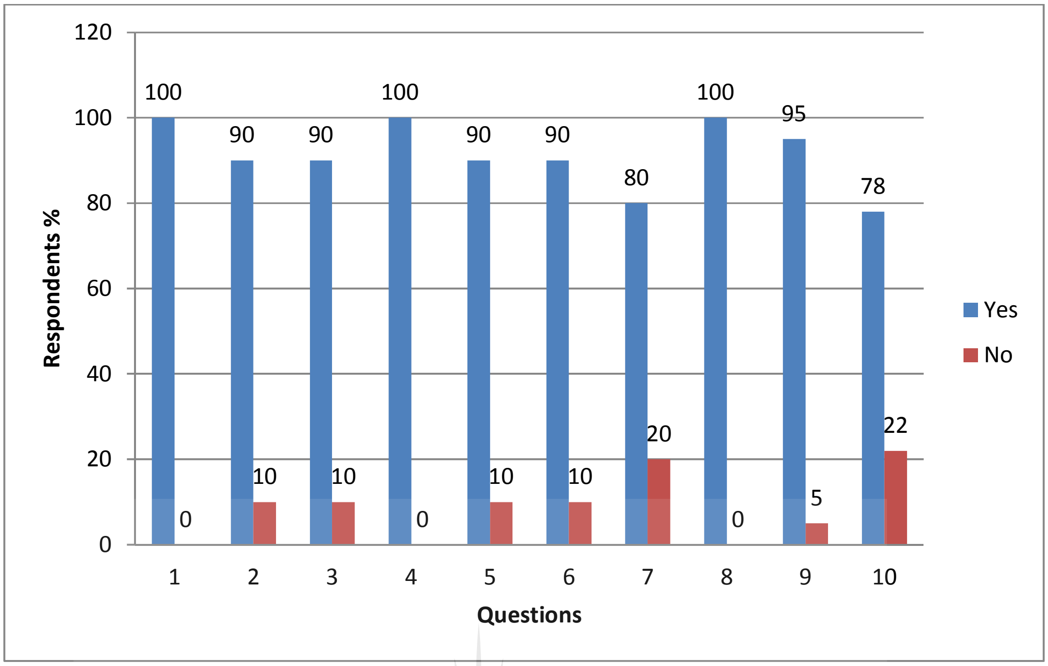

Figure 22: Research Question 5

Figure 22 results indicate that 91% of the respondents have an understanding of the client safety clearance process, allowing them to manage the construction and commissioning phases. The commissioning process requires the method statement and risk assessment to be approved by all parties before commencement of construction and commissioning of the plants. The respondents confirm that all parties followed the application for inspection (AFI) process. The process of commissioning is done when all the major category A and B open items are closed, 80% of the respondents confirm that the A and B items were completed, and 20% indicates a lack of understanding on the category A and B requirement which were concluded to be the operators, technicians and artisans.Q8 shows 100% due to the first requirements by the client to make sure all the equipment are safely grounded before suction test can be performed.Q9 The readiness question had been answered at 95% showing the understanding of the client process to run the equipment during commissioning. Q10 78% agreed that the risk assessment and methods statement were in place for the contractor in their scope area but not the overall one for the operators of the equipment.

Question 6: Was the *commissioning engineer on duty trained to perform the task?*

No	Questions	Yes (%)	No (%)
1	Do you have commissioning experience?	40	60
2	Did you have a PSR?	20	80
3	Have you conducted hot commissioning?	30	70
4	Was the switchgear protection set correctly?	30	70
5	Were there signs of overheating or smell of smoke?	60	40
6	Were the method statement and risk assessment available?	70	30
7	Did you verify the safety clearance of the switchgear?	20	80
8	Was the client Integration commissioning party in place?	20	80
9	Was access to the control room granted to the principal contractor?	20	80
10	Was the communication process in place between all parties?	10	90
11	Was there any vibration encountered by the motor?	10	90
Mean		**33%**	**77%**

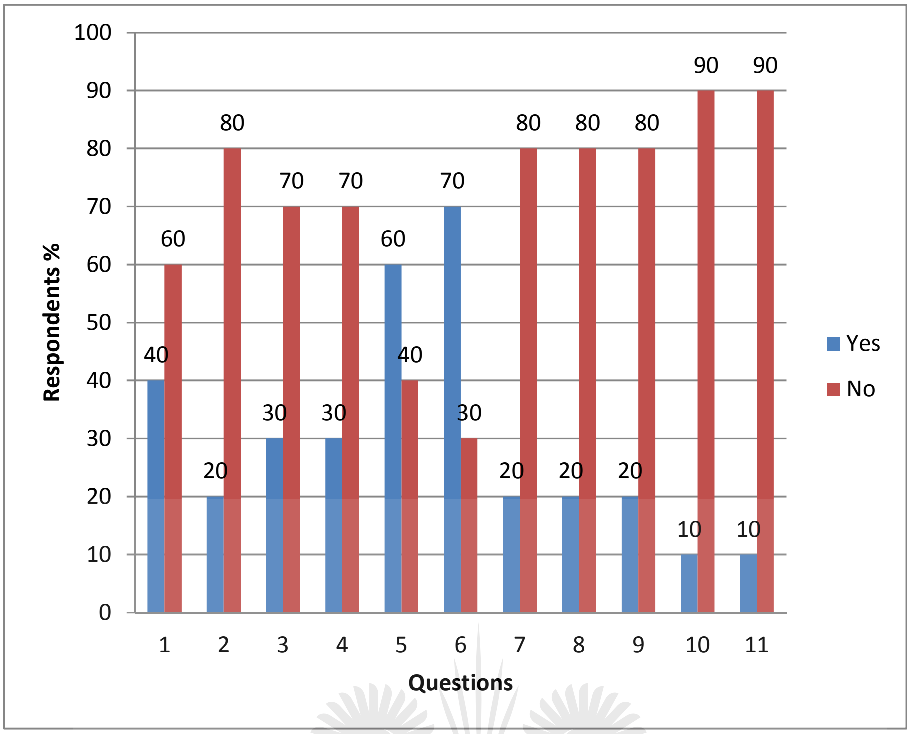

Figure 23: Research Question 6

Figure 23 above summarises the respondent's lack of experience on commissioning due to 33 % of 35 respondents having commissioning experience based on figure 16 above. The commissioning of the motors was predominantly conducted by the OEM themselves but at thermal power station commissioning is not part of their scope of works. The lack of information for switchgear setting confirmation is the worrying factor with relation to the integration of systems by the client. The lack of knowledge on the switchgear safety clearance also raises a concern on the commissioning team that will be monitoring the performance of motor within set parameters. The clear communication within all parties lacked, based on the 90% "no" answer recorded from the respondents and the client will have to improve on the currently available information of systems and the principal contractor will have to generate a check sheet that demands specific information from the client before commissioning activities can commence. The IDF motor failure cost will be for the contractors due to the principal contractor's handover of a fully commissioned plant to the client. 90% confirm that there was no vibration encountered by the motor before failure.

4.3. Conclusion

The difficulties of communication and sharing of information between the subcontractor and the client have been deemed difficult and the client to close the gap with the use of documentation that integrates all subcontractor requirements to achieve the contractual requirements and handover to the client. Client subcontractor installs the switchgear that operates the IDF motor, which is installed and commissioned by the principal contractor. The client process of AFI and safety clearance of the plant has been achieved as the first start to commissioning the equipment on site. The commissioning of equipment was done by the OEM, but things have changed, and the subcontractor is installing and commissioning the plant only with technical advice from the OEM. The communication between the parties, including commissioning, has been raised as a concern that the client must close the current gaps in the sharing of integrated equipment information. Further analysis will be conducted in chapter 5, looking at the DCS records and RCA by using FMECA and FTA tools.

5. Case study of induced draft fan motor failure

5.1. Case study A: Data analysis of distributed control system report and switchgear curve

The DCS report shows the start and trip curve as per the following figure 24,25, and 26, with the analysis as follows. The motor PI was tested on the 25 May 2017 (see attached Appendix D) and found in order with less than 10 GΩ. The motor was started on the 13 June 2017 at approximately 15:42:51 without a load as per client requirements for the MV motors to be meggered and hot commissioned within 28 days from the last PI reading. The motor failed approximately 2 minutes later. The DCS curve 20HNC20AN001 (see figure 24) shows the motor starts at approximately 15:42:52 shown in yellow. The nominal motor current is 463.6 A with the startup current approximately 2085A as per design.

The DCS rage is set for 600A max. After the run-up, the motor, current drops to a no-load current of 134 A. After approximately 2 minutes the current goes off the scale, and approximately 1 second later the switchgear cuts the power off. The DCS values should be a guideline as to the more specific and individual voltage and current and are recorded in the switchgear log. The startup of the motor has been recorded in the switchgear log and reflected in figures 25 and 26. According to the technical specifications, the motor requires a nominal voltage (15KV) for approximately 4 seconds to start. However, the switchgear recording system only recorded 3 seconds after the failure. The switchgear records 1 second before the trip has been detected. At the start of the DCS recording the motor is found to be running unbalanced L1 =2000A, L2 = 1000A andL3= 1200A. The switchgear protection system has detected this imbalance “IDMT NPS STRT”, but the system did not react. The motor tripped on “DIFF INT BLKD” differential current based from the current transformer (CT). The indication of failures in the IDF motor is a fault resulting in an imbalance in the supply current and finally ensuing in a winding failure resulting in a differential current to the phases causing arcing which leads to the U phase being completely burned.

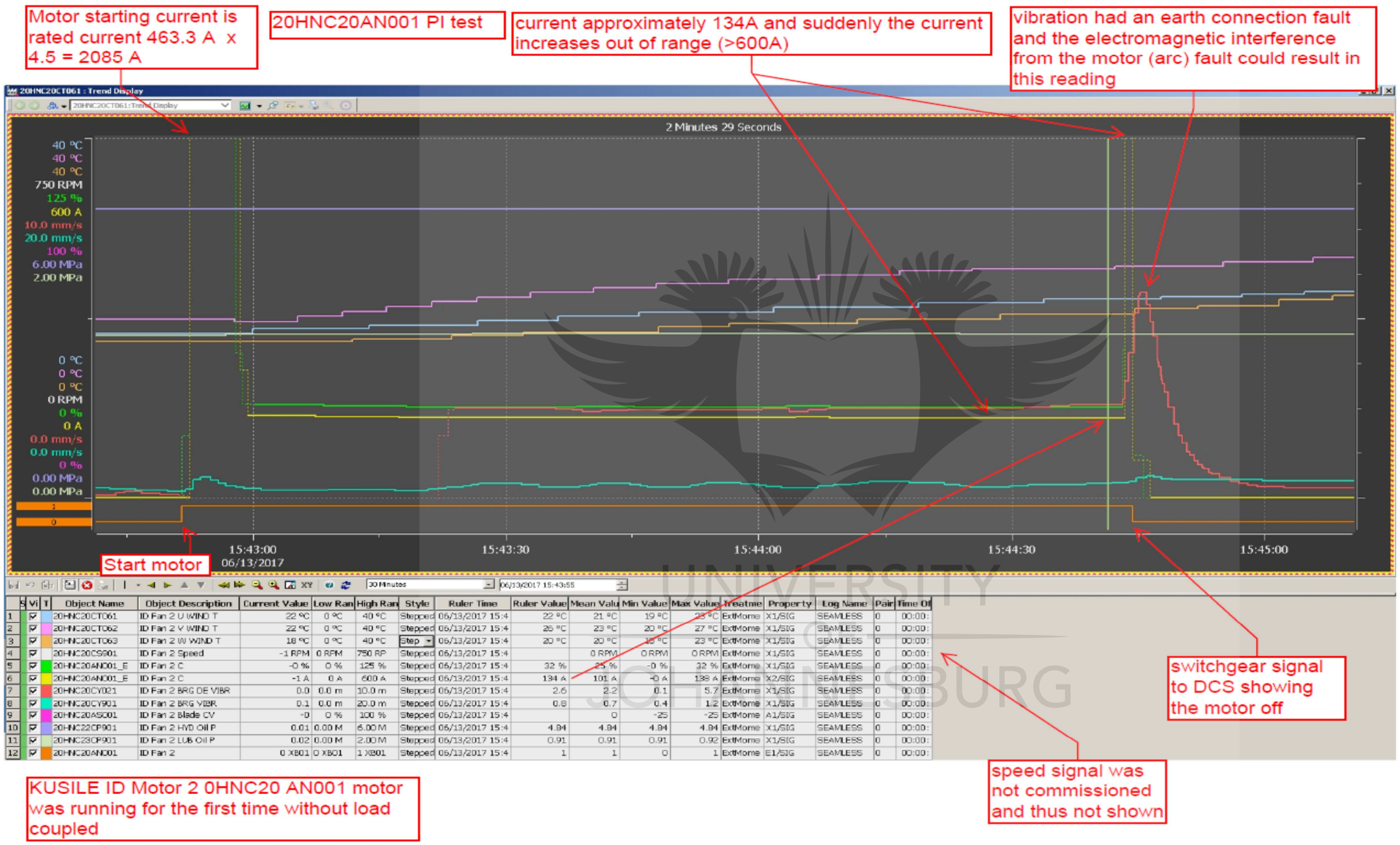

Figure 24: Distributed control system curve shows the DCS operation summary of the ID fan motor from start to the time of failure

	Time in ms	Measuring Signal	Instantaneous	R.M.S.	2.Harmon.	5.Harmon.	Phase
Cursor 1:	0.0	BrkSidCurr_L1	-1.2355 kA	1.5979 kA	0.00828 kA	0.01508 kA	-142.8°
Cursor 2:	60.0	NSideCurr_L1	-0.2666 kA	2.3936 kA	0.3266 kA	0.08887 kA	-161.2°
C2 - C1	60.0	NSideCurr_L1 - BrkSidCur	0.9689 kA	0.7957 kA	0.3183 kA	0.07379 kA	-18.45°

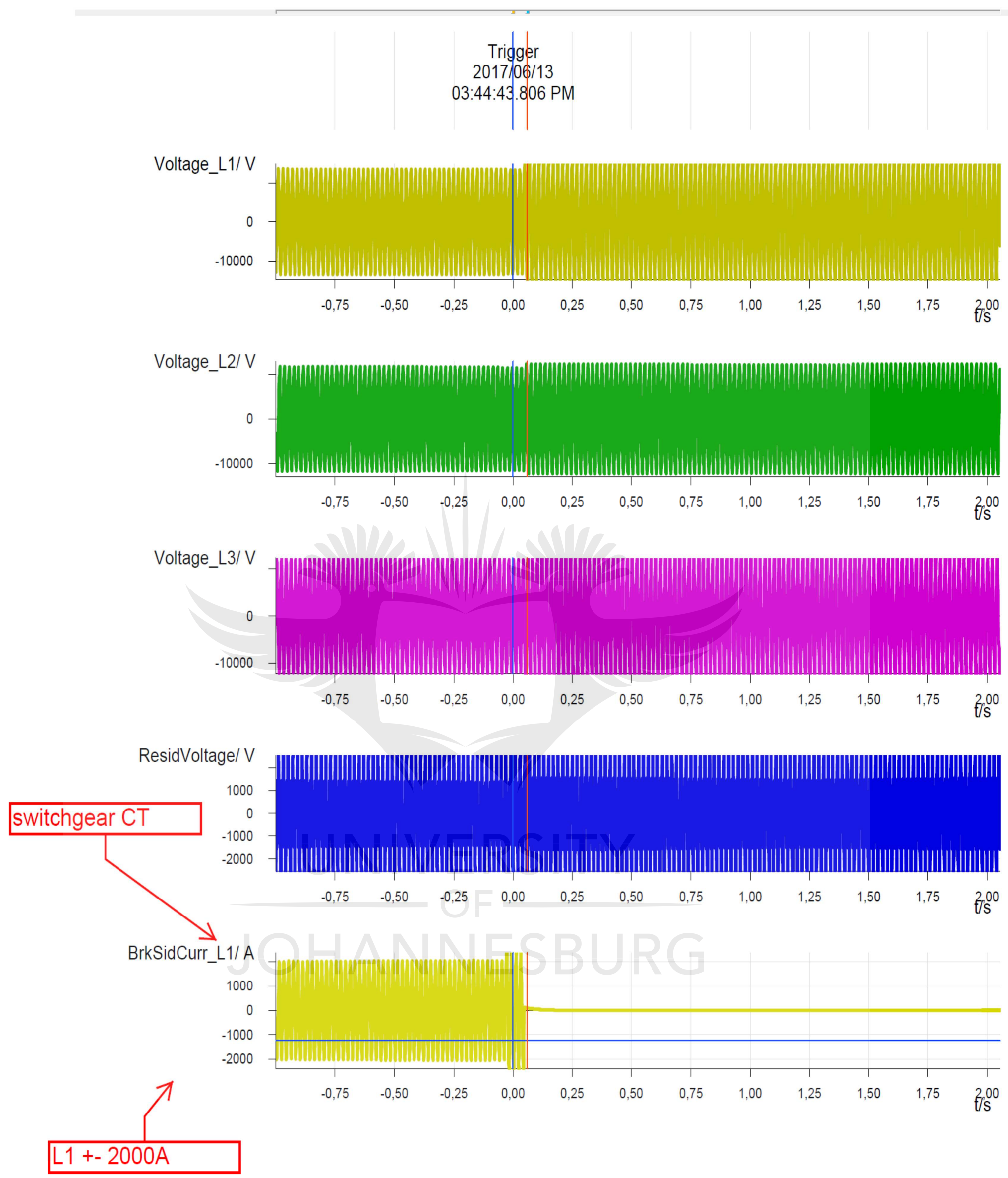

Figure 25 above and Figure 26 below shows the switchgear current transformer reading from DCS report show the motor was running unbalanced with L1 =2000A, L2 = 1000A and L3= 1200A

Figure 25: Switchgear trip curve 1

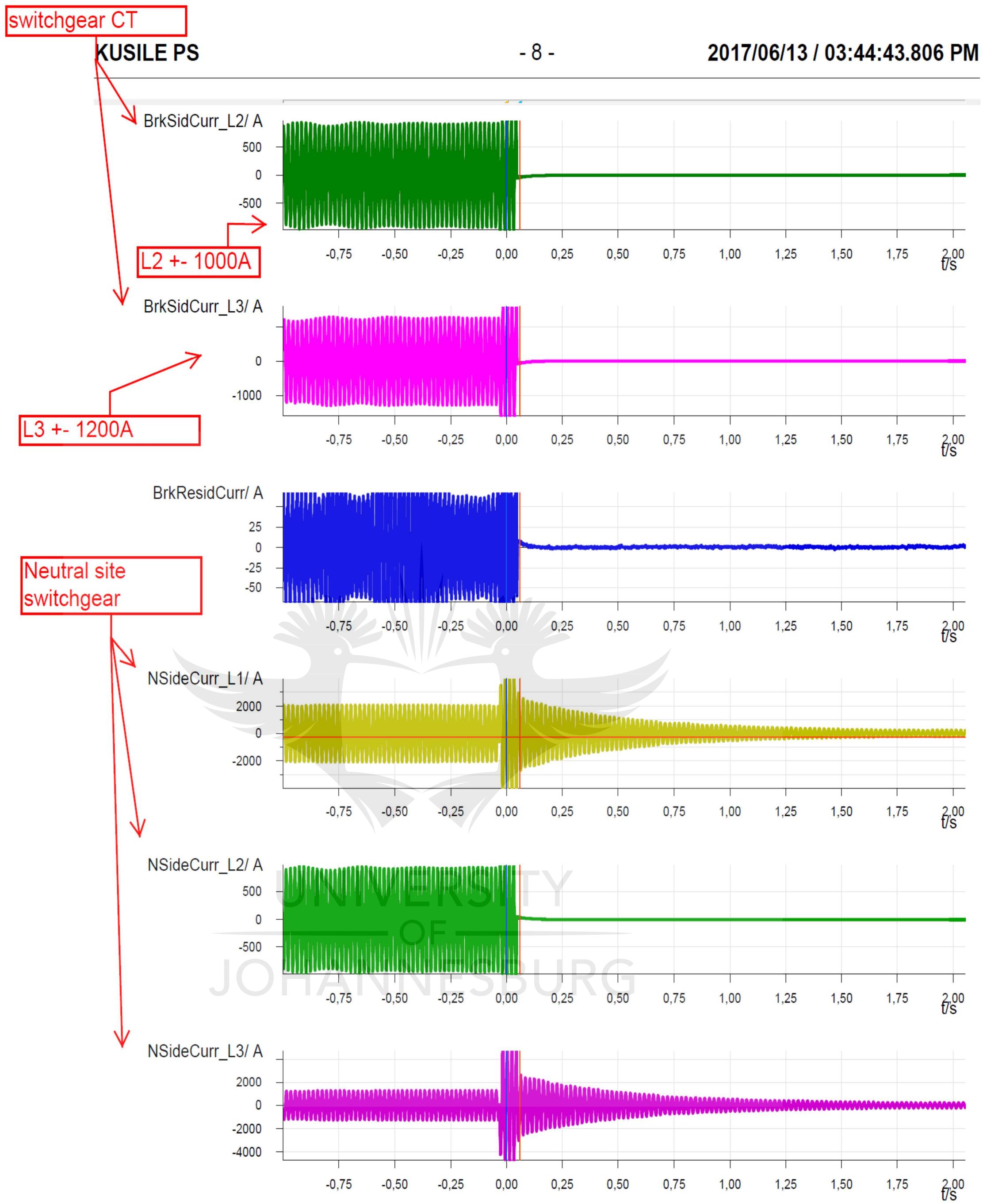

Figure 26: Switchgear trip curve 2

5.2. Case study B: FMECA analysis

[43],[45] describes the failures can be the reason for design flaws, manufacturing defects, incorrect installations lack of protection and maintenance issues. The selected categories of failures are linked being electrical and mechanical as per the attached table below;

Table 12: Potential failure list per discipline [43]

Mechanical Failures	**Electrical Failures**
Bearing and Lubrication	End winding series and lead connections
Lack of motor maintenance and protection	Winding failures in the slot or end turn
Motor cooling enclosures	Magnetic wedges
Rotor or rotating mechanical components	Rotating rectifiers for Induction machines

5.2.1. Failure Mode Analysis

During failure analysis, the OEM has been requested to further investigate by opening the motor and looking at all possibility of the motor failures. The knowledge and experience of the OEM had contributed a lot in identifying the potential failures based on physical assessment of the equipment. [43],[45] further emphases the impact of component failures and overall equipment failures. See attached photos detailing the damages after the opening of the motor.

Figure 27: Blown away section [63]

Figure 28: Damage from underneath [63]

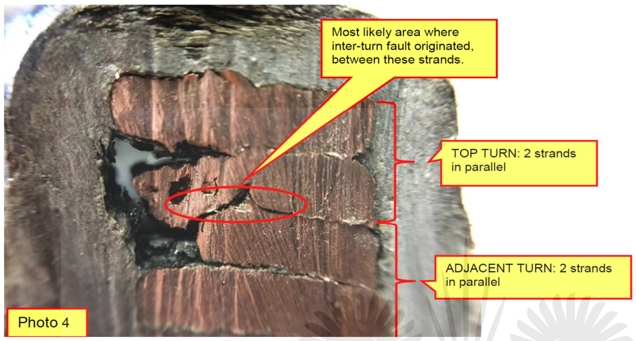

Figure 29: Deformed strands [63]

Figure 27, 28 and 29 from OEM gave their physical prediction of the motor failure based on the photos taken above.

Table 13: Possible modes for motor failure [43],[45]

Functional failure (Loss of function)	Cause of failure(Failure mode)
Stator winding	Turn to turn
	Phase to phase
	Phase to ground
	Coil to coil
	Open circuit

5.2.2. Effect Analysis

The reliability analysis has the way of looking at the effect of the failure modes. Each failure analyses will have an impact on the safe operation of the IDF motor and will have to look at the impact and their consequences. Table 14 describes the failure effect of the IDF motor base on impact versus failure effect.

Table 14: Failure Effect analysis

Functional failure (Loss of function)	**Impact**	**Failure effect**
Stator winding	Workforce	Failure of the motor has a high impact on the Workforce and can lead to fatality
	Replacement equipment cost	The rewinding of the damage phase has the following cost: labour **R678k** and materials **R 2,500k** and rigging equipment **R 287k** **Total cost: R 3,465k**
	Functionality of Equipment	The impact on these fans is less due to the redundancy of the system at reduced generation
	Environment	The impact on the safe discharge of gases to the FGD due to the single operations and creates an impact on the Fan running

5.3. Case Study C: FTA Analysis

[33] Emphasises that FTA serves as a means for describing component failures, more precisely the root of these failures. The root cause analysis is done systematically using fault trees, which spares the necessity to compose long descriptive texts. Using a fault tree, the critical information is available at a glance. The IDF motor is new and started to fail during the commissioning period, and the insulation failed prematurely at the first start-up.

5.4. Conclusion

The case study failure conclusion was drawn based on data analysis confirmed in the structured questionnaires and subsequent analysis of the DCS and switchgear start and trip curves relating to the design parameters. The respondents have a balanced experienced that gives the outcome of the study a positive impact on the validation of causes that lead to the failure of IDF motor during the commissioning phase. The study confirms that the motor preservation procedures were managed as per the OEM's recommendations. The IDF motor failed approximately 2 minutes after starting and had reached the maximum speed of 750 to the selected DOL starting benefits for large motors. The mandatory testing during the commissioning phase of the new motors was done.

The motor was commissioned after the lapse of the supplier's guarantee of 5 years. Moreover, the risk has shifted to the principal contractor to ensure that all contractual requirements are managed. The DCS records show the motor is running unbalanced L1 =2000A, L2 = 1000A andL3= 1200A. The switchgear protection detected the imbalance "IDMT NPS STRT", but the system did not react. The IDF motor fault is resulting in the unbalanced supply of current, resulting in winding failure which ensues in a differential current between phases causing arcing, which causes the U phase to be completed burned out. The next chapter concludes the study and recommends further research. Furthermore

[43],[45] describes the RCA as the step by step way od checking the failed motor and its system.

[43] describes what had been noted all the years as the critical steps for root cause analysis methods;

1. Failure mode
2. Failure Pattern
3. Appearance
4. Application
5. Maintenance history

[37],[43],[45] had given the indications that with the general motor appearance, they are usually indicated the cause of the failure. OEM had supplied all the appearance of the damaged equipment, and it can concur with [43] indication of the failure cause.

6. Conclusion and Recommendations

6.1. Introduction

The study focused on the investigation of the IDF motor failing during the last stage of construction. The importance and relevance of the study are due to the high cost for the replacement of damaged MV motors and the delay to project completion by 18 weeks at the cost of R54 million per month. The conclusion and recommendations are drawn from the results and findings of the study in addition to the literature reviews. Finally, the study recommends principal contractor commissioning and construction to develop and improve the current inter-phase check sheet before the commencement of commissioning and not entirely relying on the client for the information. Chapter 1 had highlighted the background of the study, problem statement, benefits of the study, research questions, research methodology, research design, de-limitation of the study and assumptions. Chapter 2 focused on the literature from different sources to assist the process of investigating the causes of the induction motor failures. The theories would assist in the interpretation of the current testing records and the one to be determined in chapter 3; chapter 4 summarises the data collected, chapter 5 case studies as well as elaborates the conclusions and recommendations.

6.2. Conclusion

The research has identified the importance of process-driven systems during the commissioning of the IDF motor and contributed to determining the causes of the boiler 2 induction draft fan motor failures during the hot commissioning phase. The current site integration process between different suppliers and contractors on the thermal power station will require improvements. There are no papers that support the correct way of commissioning due to the function being managed by the OEM companies and not the construction team. The IDF transports the full flue gas through the GAH and the PJFF to the chimney.

The testing is regarded as key to early detection of faults and confirms the reliability during the operation and improves the motor design output. Commissioning is the process of putting into service an item of plant which has been successfully inspected and safety cleared based on the contractual and performance requirements. Failures can occur due to inappropriate operating conditions, which may result in electronic interference of the control systems safety trips or interlocks but may also result in accelerated wear of a component. Eventually, the component may fail due to excessive wear. Generally, several failure mechanisms affect a component. In the study, only the most dominant factor was indicated. Concerning the study, certain shortcomings have been identified and should be addressed through further studies. The improved integration of the systems can be achieved with the right communication tool from the client. It allowed completing an investigation of the cause and effects of IDF motors failing prematurely during the commissioning stages.

The opportunity for the project managers to gain knowledge and provide a personal level of understanding as per their experiences in the construction industry and especially at the power plant failure management. The client assumes responsibility for the successful commissioning of the plant. The conclusion was drawn based on data analysis confirmed on the structured questionnaires and analysis of DCS and switchgear start and trip curves concerning the design parameters. The respondents have a balance of experienced that gives the outcome of the study a positive impact on the validation of the causes of IDF motor during the commissioning phase of the plant. The study confirms that motor preservation procedures were managed as per the OEM recommendations. The difficulties of communication and sharing of information between the subcontractor and the client have been deemed difficult and the client to close the gap with the use of documentation that integrates all subcontractor requirements to achieve the contractual requirements and handover to the client. Client’s other contractors install switchgear that operates the IDF motor which is installed and commissioned by principal boiler contractor.

The communication between the parties involving commissioning has been raised as a concern to the client to close the current gaps and sharing of integrated equipment information. The IDF motor fault is resulting in the unbalanced supply of current and finally, winding failure resulting in a differential current between phases causing arcing, which results in the U phase being completely burned out. The next chapter concludes the study and recommends further research. The following findings identified as the main factors that contributed towards the failure of IDF during the commissioning phase;

- Lack of structured communication during the interface of different contractors. The checklist for the commissioning procedure is valid only to the contractor, and there is no coordinated check sheet for the switchgear, control and IDF contractor.
- 90% of the respondents acknowledge a lack of communication by all parties and with 70% of the construction team not aware of the Switchgear protection settings.
- A shortage of experienced commissioning engineer's that are trained to look at all areas of their process.
- A construction delay contributes to the failures of the equipment if the Preservation process is not stipulated by the manufacturer and the procurer.
- Through analysis of this first design motor by the manufacturer, the 15KV motor failures that were recorded resulted in additional insulation areas, and further Insulation materials were used on later equipment with no failures recorded on 31KV AC test at 1 minute.

6.3. Research objectives findings

6.3.1. How was the motor handled from the time it left the factory and until it was put into service?

From the case study and structured questioner conducted it describes the importance of the preservation of the IDF motor when not in operation, the primary process from the OEM to maintain and guarantee the motor by following their set requirements to guarantee operations. It is also clear from the study that the motor checklist was not available for all team players to evaluate. The preservation of IDF motor can be confirmed as followed as per the 96% of responses from the participants and that all protocols had been adhered to. The objective was to determine the understanding of the team on the long term preservation of the motor from OEM, warehouse to project site before commissioning.

6.3.2. How many times was the motor started before this event and what was the cumulative running time of the motor before the Failure and did the failure occur on start-up or when the motor was at full speed?

From the case study, the results describe that 100% of participates agree that the motor was never used before failure on the 23 June 2017. However, with the second part of the question, the respondents are 78% sure that the motor had reached maximum speed this deduced by the induction motor speed vs time curve analysis and with the use of DOL that reaches the maximum speed within seconds. The accumulative runtime of the motor recorded to be 2 and 29 seconds and the motor had been confirmed failed during the full speed regarding DCS records in figure 24.

6.3.3. The motor was manufactured six years before being installed and commissioned, was the winding completely dry and were the polarisation Index| (PI) and Insulation Resistance tests conducted?

The objective of the study was to look at the involvement of the team, confirm understanding of the processes to be followed for the long-term storage of MV motor as per the OEM recommendations. It was concluded that 85% of the respondents had an understanding of the importance of polarisation index and insulation resistance test intervals as per the OEM. It was shown that 86 % of the respondents knew of the motor guarantee as per the contract agreement.
It was further shown that 96 % of the respondents agreed that the motor installation and coupling were carried out correctly and acceptable to the client. The motor PI and IR result as per the appendix A of motor routine test certificates on cage induction motor is within the design and operation limitations.

6.3.4. What was the condition of the switchgear that operated the motor and was the motor protection set up correctly and was there any other equipment failure at the time of the motor failure?

The survey response from the participants shows a lack of information between all involved in the commissioning of the motors; results show that the respondents have minimal knowledge of the IDF motor starting requirements as the results show at almost 50%. The protection setting of the switchgear response is not answered with confidence because the principal contractor is responsible for installing and commissioning the IDF motor and the client to install and commissioning the Switchgear that drives the motor. There were no other equipment failures.

6.3.5. Was the motor safety clearance certificate available from the client commissioning?

The survey results indicate that 91 % of the respondents have an understanding of the clients' safety clearance process that manages the construction and commissioning phases. The respondents confirm that the application for inspection (AFI) process is followed by all parties. The understanding of the commissioning process is completed when all the major category A and B open items are closed this confirmed by the 80% survey response; the survey also confirms that 20% lack an understanding of the requirement, we can conclude that 20% of respondents are from the operators, technicians and artisans. The objective was to check the team knowledge of construction turn over for the commissioning process.

6.3.6. Was the Commissioning Engineer on duty trained to perform the task?

The survey summarises the results and shows the respondent's lack of experience of commissioning shown in the response percentage of 34% of 35 of the respondents have commissioning experience. The commissioning of the motors is predominantly conducted by the OEM themselves but at the thermal power station commissioning is not part of the OEM but of the contractor. The objectives were to look at the experience of the commissioning engineer performed the works. The setting of the switchgear that drives the motor will have to be verified before switching on the equipment, and DCS reports show that the supply current was not balanced. The running of the motor with unbalanced supply shows that settings were not conducted as per the set specification of the motor.

6.4. Recommendations

The figure 30 below detailed the proposed process diagram to be used by significant contractor construction and their subcontractors and commissioning will manage the integration with the client to be involved in all process until the plant in on service.

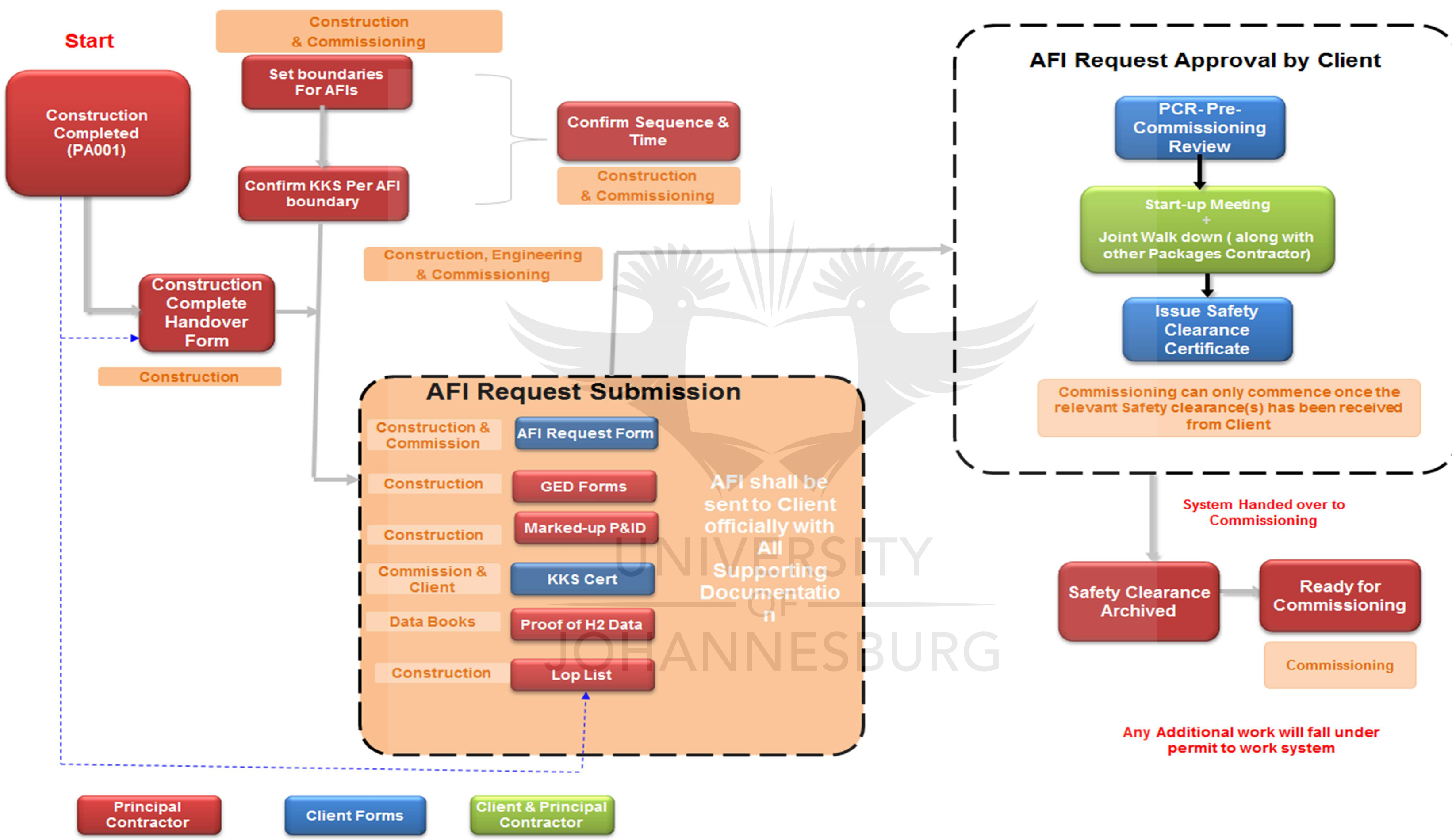

Figure 30: Construction to Commissioning Integrated process [1]

The following recommendations are suggested for the limited equipment failures during the final stages of construction;

- Lessons learnt to be shared with commissioning and across the more extensive principal contractor business.
- The preservation of MV motors from the OEM and suppliers on-site shall follow the OEM guidelines.
- PI and IR measurements to be conducted according to the OEM's recommendations and heaters to always be on during the construction period.
- The commissioning procedures to be revised to accommodate the integrated scope that is managed by other interface contractors.
- The extension of motor guarantees needs to be secured with the OEM to reduce the risk of failures before handing over to the client due to construction delays.
- The setting of the switchgear needs further investigation of why it detected the unbalanced current but failed to react and allowed the motor to run for 2 minutes until it failed. Further investigation of the system to check for phase unbalance and why the protection systems fail to shut down the motor before failure.
- The client to monitor ABB REM630 feeder protection and control systems settings during commissioning phases and protection settings are to supply the fastest possible fault clearance with accurate grading to allow the affected section of the plant to be isolated correctly

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8. Appendix

8.1. Appendix A - Motor routine test certificate on cage induction motor

10/27/2011 9:53

TESTED BY ACTOM LARGE MOTORS:
MOTOR ROUTINE TEST CERTIFICATE ON CAGE INDUCTION MOTOR

Customer	: HITACHI POWER		Date of test	: 12-10-2011	
Customer Reference	: BRA 460023		Power	: 10200	kW
Serial Number	: DOO4972-02		Voltage	: 15000	V
Frame	: UL190/315		Current	: 463.3	A
Frequency	: 50	Hz	Speed	: 745	r/min

Stator Winding Resistance at 21.6 ℃

U - V : 0.12300 Ω
U - W : 0.12300 Ω
V - W : 0.12300 Ω
Resistance per phase @ 20.0 ℃ 0.06223 Ω
(Star Connected)

Insulation Resistance at 5.0 kV

Before High Voltage Test
Stator : 2220 MΩ (1 min)
23400 MΩ (10 min)
PI : 10.541

After High Voltage Test
Stator : 2660 MΩ (1 min)
39800 MΩ (10 min)
PI : 14.962

Insulation Resistance per Phase [MΩ] at 5.0 kV (1 min values)

Stator - Before High Voltage Test:

U -Phase	V-Phase	W-Phase
8750	7800	7200

Stator - After High Voltage Test:

U -Phase	V-Phase	W-Phase
9100	9150	8750

High Voltage Test (Power Frequency - 50Hz)

Stator:
U-Phase : 31 kV for one minute
V-Phase : 31 kV for one minute
W -Phase : 31 kV for one minute
Internal Star : N/A kV for one minute

Temperature Detector Continuity

Winding Detectors: (RTDs)		Bearing Detectors: (RTDs)			Air Temperature Detectors: (RTDs)		
1:	119.7 Ω	1:	121.1 Ω	DE	Cool Air DE	1:	113.5 Ω
2:	120.0 Ω	2:	121.8 Ω	DE		2:	113.6 Ω
3:	120.6 Ω	3:	121.5 Ω	NDE			
4:	120.3 Ω	4:	121.3 Ω	NDE	Hot Air Middle	1:	119.5 Ω
5:	119.6 Ω	5:	Ω	DE		2:	119.5 Ω
6:	120.0 Ω	6:	Ω	DE			
7:	Ω	7:	Ω	NDE	Cool Air NDE	1:	112.5 Ω
8:	Ω	8:	Ω	NDE		2:	112.4 Ω

Routine Test Certificate - Cage Motor
BLM 166
Page 1 of 2
Version 1.70
20 July 2011

9/11/2011

TESTED BY ACTOM LARGE MOTORS:
MOTOR ROUTINE TEST CERTIFICATE ON CAGE INDUCTION MOTOR

Insulation Resistance above 1090 **MΩ at** **500** **V (Y/N)?**

All Winding Detectors: Y   All Bearing Detectors: Y   All Air Temp. Detectors: Y

Bearing Insulation at **500** **V**

Drive End : 332 MΩ
Non Drive End : 332 MΩ

Shaft Voltage

Measured voltage : 2.727 V (Earthed)
Measured voltage : 4.381 V (Unearthed)

Heaters

Resistance : 24.3 Ω
Power : 2000.0 W
Voltage : 230.0 V
Current : 9.47 A
Insulation R : 5250.0 MΩ

Bearing Temperatures After **4:00** **Hours**

Drive End #1 : 51.9 ℃
Drive End #2 : 53.3 ℃
Non Drive End #1 : 52.4 ℃
Non Drive End #2 : 52.6 ℃
Ambient Air Temp. : 25.2 ℃
Oil Temperature : 53.0 ℃
Water Temperature : N/A ℃

Vibration [mm/sec (rms)]

	Drive End	Non Drive End
H	0.65	0.58
V	0.62	0.42
A	0.48	0.44

Air Gap Measurement in mm

DE	1 :	4.6	NDE	1 :	4.6
	2 :	4.6		2 :	4.6
	3 :	4.5		3 :	4.5
	4 :	4.5		4 :	4.5

Locked Rotor Test at **1.29** **Times Full Load Current** 1)

Voltage (V)	Current (A)	Input Power (kW)	Unsaturated Starting Torque (p.u.)	Unsaturated Starting Current (p.u.)
4369	598.2	566.10	0.57	4.43

No Load Run at Full Voltage 2)

Voltage (V)	Current (A)	Input Power (kW)
15000	123.5	133.0

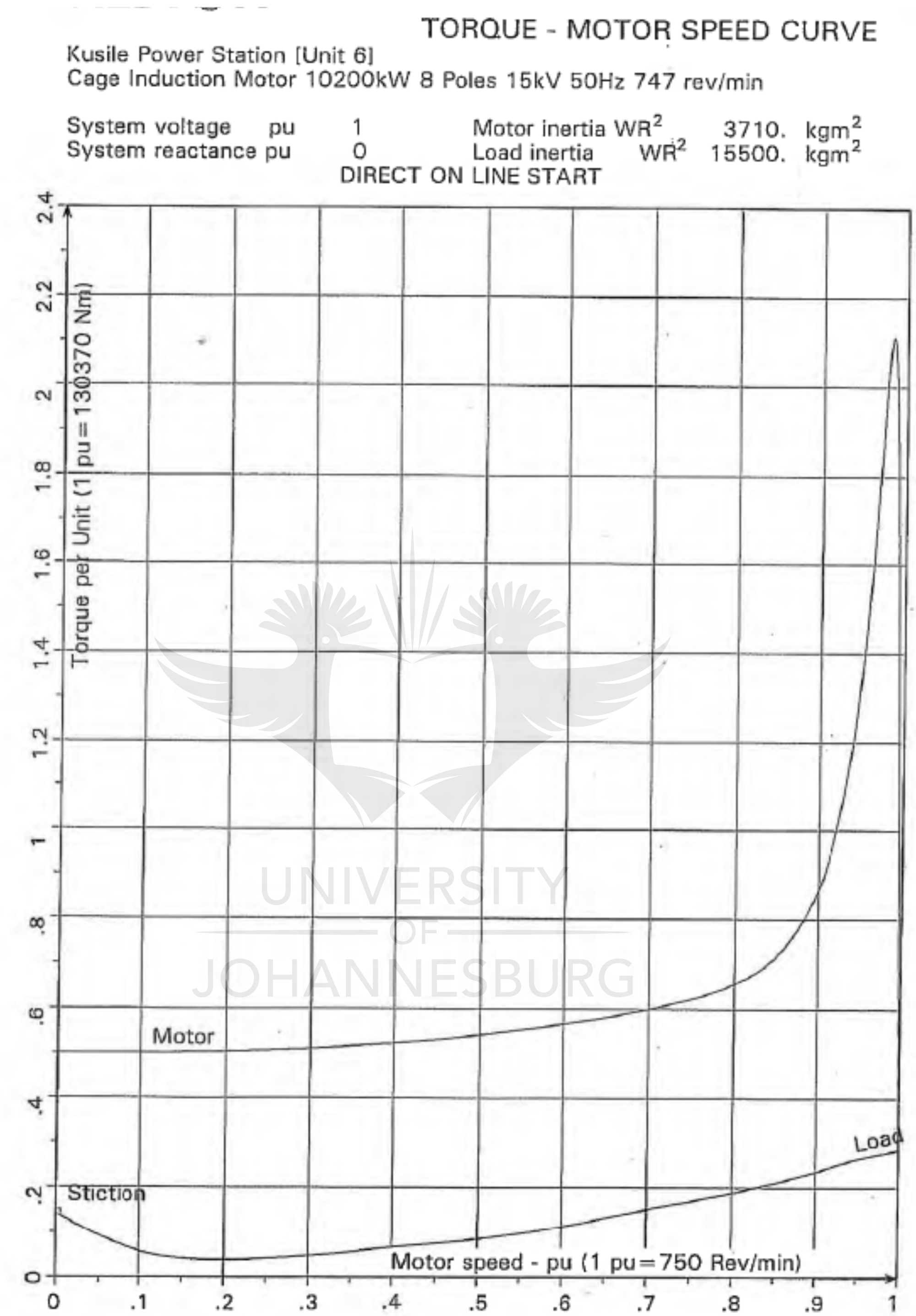
Remarks : 1) Locked Rotor test performed with stator winding λ connected.
2) No-load Run performed with stator winding Δ connected and measured values converted to line values for 15kV star.

Tested By : REINHARD, KHALA, WERNER, CHRIS

Approved By : [signature]   Date : 9/11/2011

Witnessed By : ____   Date : ____

8.2. Appendix B – Cage induction motor torque – motor speed curve



8.3. Appendix C – Cage induction motor speed vs time curve

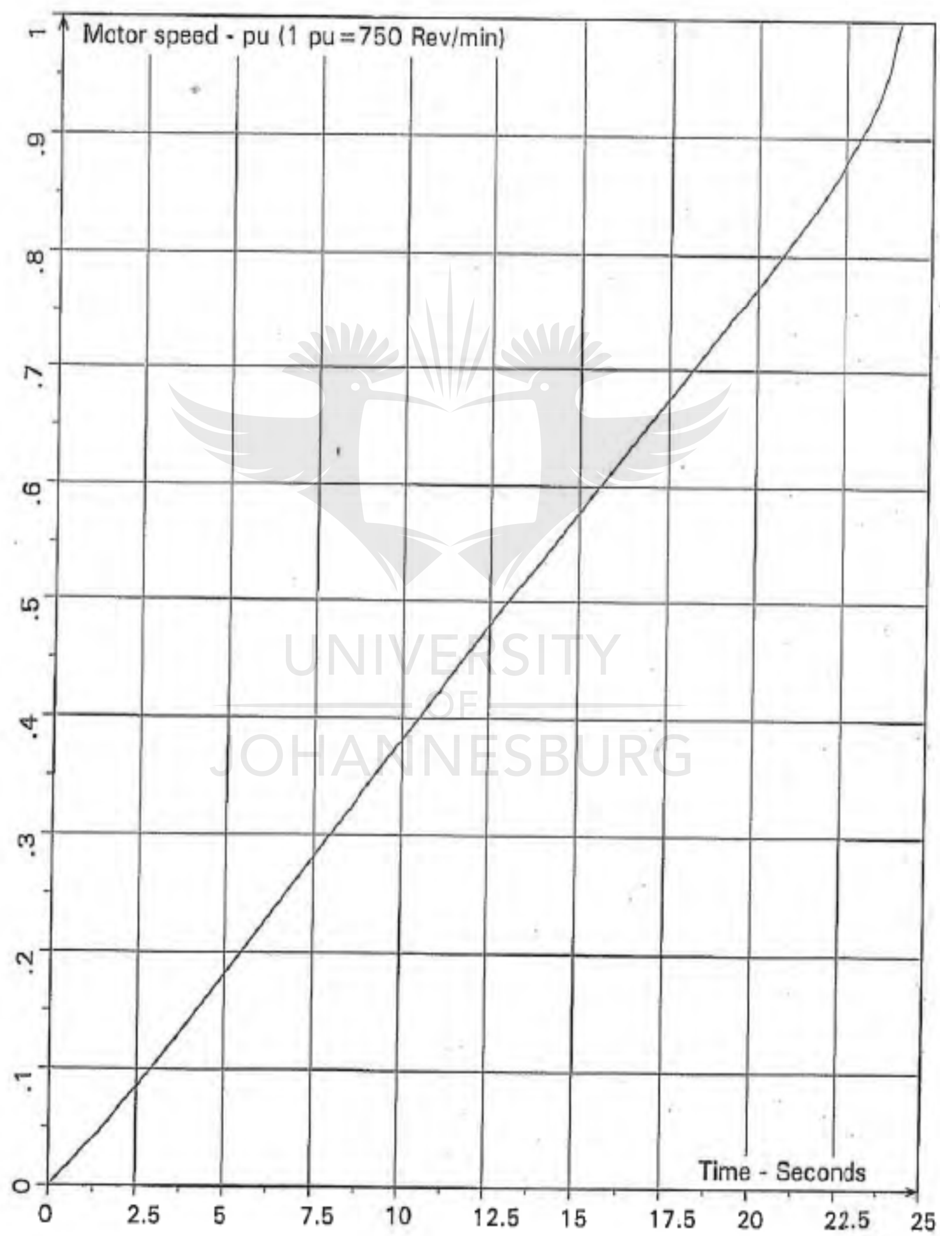
MOTOR SPEED v TIME CURVE

Kusile Power Station [Unit 6]
Cage Induction Motor 10200kW 8 Poles 15kV 50Hz 747 rev/min

System voltage pu	1	Motor inertia WR^2	3710.	kgm^2
System reactance pu	0	Load inertia WR^2	15500.	kgm^2

DIRECT ON LINE START

Stall Time From Cold = 25Sec and From Hot = 15Sec



8.4. Annexure D: Questionnaire introductory letter

Dear Colleagues,

Research structured questionnaire introductory letter

Research Topic: Root cause analysis of the unpremeditated failure of induced draft fan motor during commissioning: Degree: M.Eng(Engineering Management)I am studying towards a master's degree in engineering management (M.Eng) with the University of Johannesburg and carrying out the case study research on the investigation of a 15kV AC induced draft fan motor failure during hot commissioning; the research method requires completion of the questionnaires as attached below.

Research Objectives:

The objective of this research is to provide answers to the question above and to identify the causes of medium voltage motor failure. The introduction of processes and techniques to support the principal contractor construction and commissioning teams to identify the potential challenges that will have an impact on the completion of the boilers as this type of failure will delay the project by 18 weeks. You are kindly requested to complete the attached questionnaires, and that there are no right or wrong answers, your responses will be significant for the success of this research. Your responses will be anonymous, and identity is not mandatory. For any clarity on the questions do not hesitate to contact me on the email and numbers provided below.

Thank you for participation and co-operation

Yours Faithfully

Tinyiko Makondo

Tel: +2711 260 4581

Cell: +2783 968 4844

Email:tinyiko1@icloud.com or e_makondo@za.mhps.com

8.5. Annexure E: Structured questionnaire

The purpose of this study is to investigate the causes of the induction fan motor failure during commissioning at the thermal power station boiler 2 line 2. Please review the attached questions and complete truthfully with an X in the relevant box. The results of the study will be confidential. The research questions to be answered are for the thermal power station in conjunction with the IDF motor failure during commissioning: The photos supplied are to assist on the methodology flow diagram checklist with the photos showing the consequential damages of the motor and systems.

Section A: Background Information

1. **What is your highest educational qualification?**

Grade 12/Matrix	
Certificates	
Diploma	
Bachelor's degree	
Post-graduate degree	

2. **How long have you been working at the power station?**

One year	
2 Years	
3 Years	
4 Years	
5 Years	
6 Years or more	

3. What is your job title?

Operator	
Supervisor	
Technician	
Artisan	
Commissioning engineer	
Responsible person(RP)	
Authorised person(AP)	
Senior commissioning engineer	
Engineers(All Disciples)	
Commissioning engineer	
Construction manager	
Other(Specify)	

Section B: This section will cover questions related to thee causes of IDF motor failures during the hot commissioning phase. Please mark the relevant box by(X).

4. **How was the motor handled from the time it left the factory and until it was put into service?**

No	Questions	Yes (%)	No (%)
1	Was the preservation done at the factory?		
2	Were the bearings free to rotate and operate as intended?		
3	What were the storage conditions acceptable?		
4	Was the preservation done at the thermal site?		
5	Were the space heaters connected to construction power?		
6	Was transportation of the IDF from the factory to site performed according to the OEM?		
7	Was the motor checklist supplied with the motor to site?		
8	Was FAT done at the factory?		
9	Was SAT done on thermal project site?		
10	Is the IDF motor passed all type tests?		

5. How many times was the motor started before this event and what was the cumulative running time of the motor before the failure and did the failure occur on start-up or when the motor was at full speed?

No	Questions	Yes (%)	No (%)
1	Was the motor in service during a failure?		
2	Did the motor archive the full speed?		
3	Was the voltage balanced between phases?		
4	Did the IDF fail on start-up?		
5	Is the motor sitting idle before starting?		
6	Was the starting DOL?		
7	Was the IDF motor on-load?		
8	Was the IDF commissioned at load?		
9	Is the operating sequence followed during starting?		
10	Was maintenance performed?		

6. **The motor was manufactured six years before being installed and commissioned, was the winding completely dry, and are polarisation index| (PI) and insulation resistance test conducted?**

No	Questions	Yes (%)	No (%)
1	Does the IDF motor exhibit any foreign materials?		
2	Are the rotor cooling passages free and clear of clogging debris?		
3	[61] Were the polarisation index (PI) and insulation resistance (IR) test conducted at the factory at three months intervals?		
4	[61] Were the polarisation index (PI) and insulation resistance (IR) test conducted at the thermal project site at three months intervals?		
5	Was the OEM guaranteed expired?		
6	Were the bearings free to rotate and operate as intended?		
7	Is the motor mounted, aligned and coupled correctly?		
8	Were storage conditions acceptable as per the OEM?		
9	Was correct lubrication procedures utilised?		
10	Were the PI and IR results acceptable?		

7. **What was the condition of the switchgear that operated this motor and was the motor protection set up correctly and was there any other equipment failures at the time of the motor failure and was there any power surges at the time of the failure?**

No	Questions	Yes (%)	No (%)
1	Was the IDF motor uses DOL?		
2	Was bus bar insulation resistance conducted on the switchgear?		
3	[43] Was the voltage balanced between phases?		
4	Were all requirements for earthing protection in place?		
5	Was supply voltage 15KV AC?		
6	Was the switchgear cut power immediately after failure detection?		
7	Was the rotor turning during the failure?		
8	Have any other equipment failed on this application?		
9	Did IDF motor fail on starting?		
10	Did IDF motor fail while operating?		

8. **Was the motor safety clearance certificate available from the client commissioning**

No	Questions	Yes (%)	No (%)
1	Was safety clearance certificate received?		
2	Was IDF motor under commissioning phase?		
3	Was cold commissioning archived?		
4	Is commissioning quality inspection performed?		
5	Does the IDF motor possess attributes of client expectations?		
6	Is client AFI process requirement successfully circulated and understood throughout personnel?		
7	Were all open items closed?		
8	Equipment grounding and bonding systems are in place?		
9	Was the IDF motor ready to be safely energised?		
10	Was the method statement and risk assessment available?		

9. Did the commissioning engineer at duty train to perform the task?

No	Questions	Yes (%)	No (%)
1	Do you have commissioning experience?		
2	Do you have PSR?		
3	Have you conducted the Hot commissioning Before?		
4	Was the switchgear protection set correctly?		
5	Are there signed of overheating or smell of smoke?		
6	Was the method statement and risk assessment available?		
7	Did you verify the safety clearance of the switchgear?		
8	Was client integration commissioning party in place?		
9	Was the access to control room granted to the principal contractor?		
10	Was communication processes in place between all parties?		
11	Was there any vibration encountered by the motor?		