FOREIGN MATERIAL EXCLUSION (FME) FAILURES OF LARGE TURBO ALTERNATORS

by

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ELECTRIC POWER AND ENERGY SYSTEMS

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DECLARATION

I Amesh Narain Singh declare that

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ABSTRACT

Synchronous turbo alternators form the basic building block of a generation scheme. Turbo alternators are highly susceptible to foreign material ingress. In industry this phenomenon is on the rise. We evaluated the effects of foreign materials on the generator and condition monitoring equipment. The sources of foreign materials and methods to reduce ingress were investigated. We further evaluated industry best-practices on foreign material exclusion.

Information is scarce, as no classic research material is available on foreign material exclusion. We therefore used industry foreign material exclusion best-practices and expert opinions were gathered. Eleven global incidents of foreign material exclusion failure were investigated. The areas of interest were: types of foreign material, area of ingress, condition monitoring response, component damage, root cause and prevention.

We point out that turbo alternators are vulnerable to foreign material ingress mainly due to weak foreign material exclusion practices. We categorised the foreign materials and their effects on the operational parts of the turbo generator. We found that the air gap was the most susceptible to ingress. We identified the Generator Core Monitor as a possible solution to minimising foreign material damage.

PREFACE

This subject matter investigated in this dissertation was based on the practical experiences of engineers in the field of turbo alternators. Most of these engineers, due to non-disclosure agreements with their organisations, shared information with me on a selective basis and in all cases I was asked not to disclose the source.

In this dissertation the style that I have used for referencing is based on the Publication Manual of the APA, 5th ed.

Some of the work presented in this dissertation will be published in a modified form:

- For a paper to be presented at SAUPEC 2009.
- I have also been invited by EPRI's Jan Stein to present the findings of this work.

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List of Symbols

H_2	Hydrogen	
°	Degree	
I^2R	Power	W
°C	Degrees Celsius	
pH	"Power of hydrogen"	
X_a	Magnetising reactance	Ω
R_a	Stator resistance	Ω
X	Stator leakage reactance	Ω
X_s	Synchronous reactance	Ω
Z_s	Synchronous impedance	Ω
E_1	Air gap voltage	V
$V_1(V_t)$	Terminal voltage	V
I_f	Field current	A
I_a	Armature current	A

List of Abbreviations

MW	Mega Watt
FME	Foreign Material Exclusion
EdF	Électricité de France
FM	Foreign Material
GCM	Generator Condition Monitor
AC	Alternating Current
DC	Direct Current
RPM	Revolutions per Minute
Hz	Hertz
m	Meters
CRRs	Coil Retaining Rings
mm	Millimetres
OEM	Original Equipment Manufacturer
EPRI	Electric Power Research Institute
INPO	Institute Nuclear Power Operations
STAR	Stop Think Act Review
LPUC	Local Power Utility Company
FMI	Foreign Material Ingress
ICD	Ion Chamber Detector
GE	General Electric
CM	Core Monitor
TPP	Thermal Particulation Point
cm^2	Centimetres Square
EMI	Electro Magnetic Interference
PD	Partial Discharge
PTFE	Polytetrafluoroethylene
RTD	Resistance Temperature Detector

Chapter 1

Introduction

1.1. Introduction

The demand for cheap reliable electricity in the country has reached a peak. ESKOM experienced its record highest demand of 35 479 mega Watts (MW) on the 22nd of May 2007 (Maroga, 2008). With an installed capacity of 40 000 MW, the reserve margin is slim. Any risk to the reliability of the generating plant could lead to major outages, causing loss of generating capacity and subsequent rolling black-outs. For government to meet and sustain the goal of a six percent growth in the economy per annum from the year 2010 onwards, power supply reliability is paramount (Hill, 2008).

On the 26th December 2005, Koeberg Power Station in the Western Cape experienced a trip on their 900 MW Unit One Generator (Baker, 2006; Bamford, 2006; O'Connor, 2006). After much speculation and rumours of sabotage, the breakdown was attributed to a failure in Foreign Material Exclusion (FME) practices, where an 8cm bolt was left in the generator. The damage caused was significant and the repair costs were estimated to be in the region of R150 million (Helfrich, 2006). The repairs involved replacing a number of damaged stator bars and shipping in a replacement rotor from the French utility Électricité de France (EdF) after a request for assistance from former President Thabo Mbeki (Baker, 2006). This created a major power crisis and the Western Cape experienced rolling black-outs. The cost to the economy is estimated at R500 million (The Star, 2006).

This is not a unique phenomenon experienced by South Africa alone. An alarming trend in the American Nuclear Industry shows that FME failure incidents are on the rise. Most incidents can be attributed to poor FME procedures and standards (INPO, 2004).

In this study, the areas of concern will be FME failures, FME best-practices, effects of foreign material (FM) and methods to reduce failure, all pertaining to large hydrogen/water cooled turbo alternators. Failures of this nature are widespread and are a source of embarrassment to many utilities, making these failures classified as confidential and unspoken-of. The effects of these failures have far-reaching consequences, not only within the industry, but also economically and socially.

1.2. Motivation for this study

FME and related failures have always been an area of interest in the industry. To-date, there has not been any consolidated study on FM, its effects and prevention. No classical literature exists on the subject and the frequency of these incidents is increasing.

The practical and fundamental importance of this study, is to attempt an evaluation of FME failures, industry best-practices and to identify a possible solution.

1.3. Aims of this study

The aim of this study is to investigate the influence of FM on large turbo alternators. The various parameters of concern will be: FME standards and best-practices, types of foreign material, area of ingress, condition monitoring response, component damage, root cause and prevention. Ultimately a solution will be proposed after all the information is analysed.

1.4. Theoretical grounding

A turbo alternator in essence is an electromechanical device that converts mechanical energy into alternative current energy. During repairs, outages and commissioning these devices are highly susceptible to foreign material ingress.

Foreign material exclusion is a process where a system or equipment is protected by procedures and practices to prevent foreign material intrusion. FM can be described as any material that by quantity, nature or location was not accommodated in the intended design (Kerszenbaum, 1996; Lewis, 2007). A foreign object in the generator environment will lead to undesired operation and failure.

1.5. Document layout

A brief overview of the thesis layout is provided in this section. In Chapter 2 generator design and operation will be discussed. The understanding of the operation, construction and design of a turbo alternator will aid in the choice of parameters to be investigated. This is followed by the effects of foreign material as well as foreign material exclusion principles in Chapter 3. The need to follow industry best-practices will be highlighted in a benchmarking exercise of FME practices. In Chapter 4, the focus is on industrial FME incidents. Various events and parameters are investigated to gain a deeper understanding of FME failure. The reaction of condition monitoring equipment is also an area of consideration. All of the incidents investigated were classified and information regarding many of the incidents was scarce. A condition based solution is proposed in Chapter 5 to detect foreign material and minimise the consequent damage. The Generator Condition Monitor (GCM) is found to be able to detect thermal decomposition promptly coupled with the added advantage of using Gen Tags. The limitations of the GCM are also explored and an appropriate reaction philosophy devised. Chapter 6 provides a conclusion, followed by the appendices. Appendix A discusses the Doppler Flow Test that is used to detect blockages in stator bar hollow conductors and stator water chemistry is covered in Appendix B. The different generator monitoring parameters are briefly covered in Appendix C.

Chapter 2

Literature Survey

2.1. Introduction

The benefit of Alternating Current (AC) over Direct Current (DC) as a means of electricity distribution was only realized towards the end of the 19th century. The rapid growth of AC networks led to the demand for AC generators. Initially these were slow speed machines driven by reciprocating engines, but these later advanced to being directly driven by high-speed steam turbines, which become the forerunners of today's modern machines, (Finn, 2005; Hirsh, 2002)

In the remainder of this chapter, generator design and operation will be discussed.

2.2. The synchronous generator

The majority of generators used by power utilities are synchronous generators, also know as alternators. A DC current is supplied by the exciter to the rotor winding where a magnetic field is created. Concurrently the rotor is being rotated by either a steam turbine, gas turbine, diesel engine or a hydroelectric turbine. The rotating magnetic field of the rotor induces a current to flow in the stator winding. The rotor field rotates at synchronous speed relative to the stator. The power produced eventually feeds into the infinite bus, (Chapman, 2001; Fitzgerald, Kingsley, & Umans, 2006; Theraja & Theraja, 1997).

The generator may be designed using either a round/cylindrical rotor or salient pole rotor. In sections 2.2.1 and 2.2.2 a brief description of round/cylindrical and salient pole generators will be given.

2.2.1. Cylindrical/Round rotor generators

Cylindrical rotors are mainly used for high-speed applications where the rotor is required to revolve at a 1000 revolutions per minute (rpm) speed or more. Electrical networks commonly operate at 50 or 60 hertz (Hz), the former will result in the rotor rotating at

3000rpm and the latter 3600rpm. The cylindrical smooth surface of the rotor reduces energy losses due to the movement of air around the air gap between the rotor and stator, known as windage losses. The shape also results in a much more robust structure able to withstand high centrifugal forces.

Commonly referred to as turbogenerators, these high-speed machines can be driven by steam turbines or gas turbines. Units have been constructed in excess of 1800 MW, with dimensions ranging from 10 meters (m) in length and 5m in diameter. Such generators are almost always horizontally mounted and hydrogen cooled, (Klempner & Kerszenbaum, 2004; Stone, Boulter, Culbert, & Dhirani, 2004).

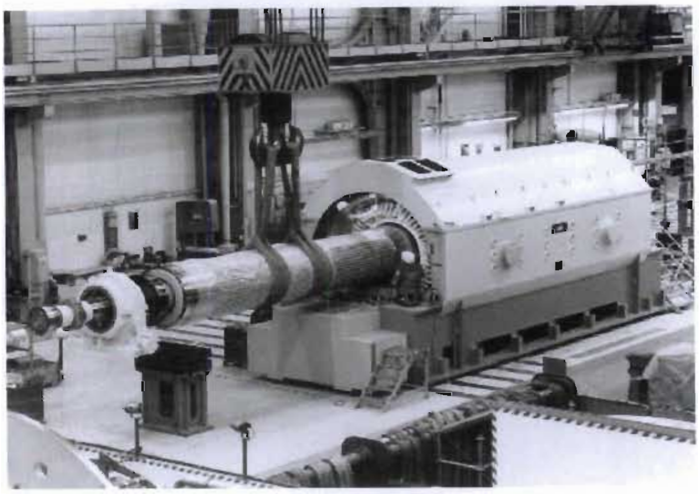


Figure 2-1: Cylindrical rotor generator (Alstom)

2.2.2. Salient pole generators

Salient pole rotors are generally used for smaller alternators and low speed diesel or water driven generators. In this instance the rotor shaft is composed of a number of individual magnetic field poles mounted to a rim. The field poles are evenly spaced around the rim and protrude into the air gap. This arrangement causes considerable turbulence in the air gap and can result in high windage losses. However the rotational speed of the rotor is considerably lower than 1000rpm, resulting in the losses being minimal.

A hydrogenerator rotor may consist of up to fifty pole pairs, as compared to one or two pole pairs of a turbogenerator, resulting in a large rotor, sometimes with a diameter in excess of ten meters. Units have been constructed up to about 800MW. Such generators are almost always vertically mounted, (Klempner & Kerszenbaum, 2004; Stone et al., 2004).

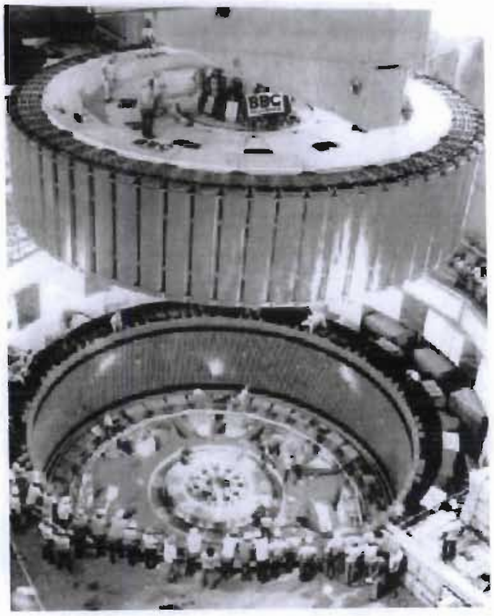


Figure 2-2: Salient pole generator (Coetzee, 2008)

This study will only focus on hydrogen/water cooled, steam driven horizontally mounted turbogenerators. In the next section, turbogenerators will be introduced and discussed in more detail including their design and operation.

2.3. Turbogenerators

Michael Faraday in 1831 discovered that when an electrical conductor is moved through a magnetic field in a direction perpendicular to the direction of the field, a voltage is generated in the wire. The amount of voltage generated is directly proportional to the active length of the conductor, the strength of the magnetic field, and the velocity of the conductor. This became known as Faraday's Law and is the basis for electromagnetic induction, the fundamental principle of electric power generation.

This law implies that there must be either physical movement of the conductor relative to the magnetic field or movement of the magnetic field relative to the conductor. Lenz's Law expands on Faraday's Law stating that the magnitude of the voltage generated at any instant is proportional to the number of coils and the rate of change of the magnetic flux threading these turns (Chapman, 2001; Fitzgerald, Kingsley, & Umans, 2006; Theraja & Theraja, 1997).

The turbogenerator is constructed of two main components, the rotor and stator. The rotor carries the excitation winding and transfers the torque from the turbine to the electromagnetic reaction at the air gap. The stator is the stationary part which consists of the core and armature winding which is capable of withstanding the produced torque.

Figure 2-3 is a schematic cross section of a three phase two pole generator. Both the stator and rotor windings are in slots, distributed around the periphery of the machine. The stator possesses three sets of windings phase A, B and C. In large generators the windings are always Y-connected as a fewer number of coils are necessary for a required terminal voltage than a delta-connected generator. The Y-connected generator also has a neutral point available for grounding. Grounding the generator stabilizes the power frequency voltages to ground and minimizes transient overvoltages during a fault condition. The accompanying wave forms illustrate the instantaneous three phase voltage induced as the generator rotor rotates. As the rotor is approaching the point in its rotation where the maximum positive voltage is produced in phase A the output will corresponding to the maximum positive voltage on waveform "a". As the rotor continues to turn the voltage in phase A will decrease to zero and then begins to increase in the negative direction as the magnetic field from the south pole of the rotor begins to cut across the A phase. Meanwhile the north magnetic field has begun to cut across phase B. The voltage in phase B reaches its positive peak and then decreases to zero. As the voltage in phase B begins to increase in the negative direction, the north magnetic field starts to cut across phase C creating the three phase output at the generator terminals that are 120 electrical degrees apart. The phasor sum of all three voltages will equal to zero at any instant.

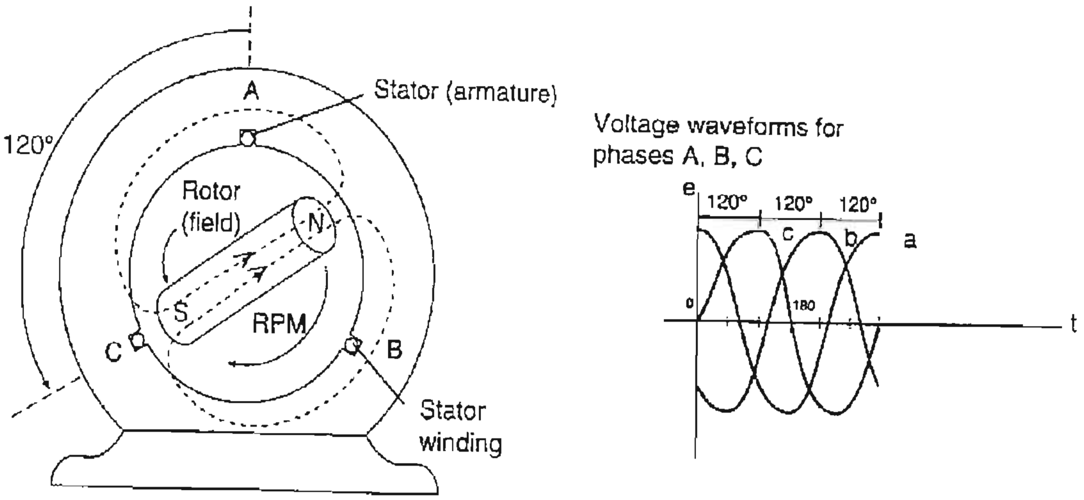


Figure 2-3: Schematic cross section of a generator and voltage output curves

The circuit diagram of a three phase Y-connected generator is depicted in Figure 2-4. The generator is being excited externally. The circuit shows the interconnections between the stator, rotor, sliprings and exciter rotor. The current from the exciter armature is collected via a commutator and brushes. This is then supplied to the generator rotor via two sliprings and brushes. The field voltage of the rotor is varied to control the field current of the synchronous generator. Refer to section 2.3.2.3 for more on excitation methods.

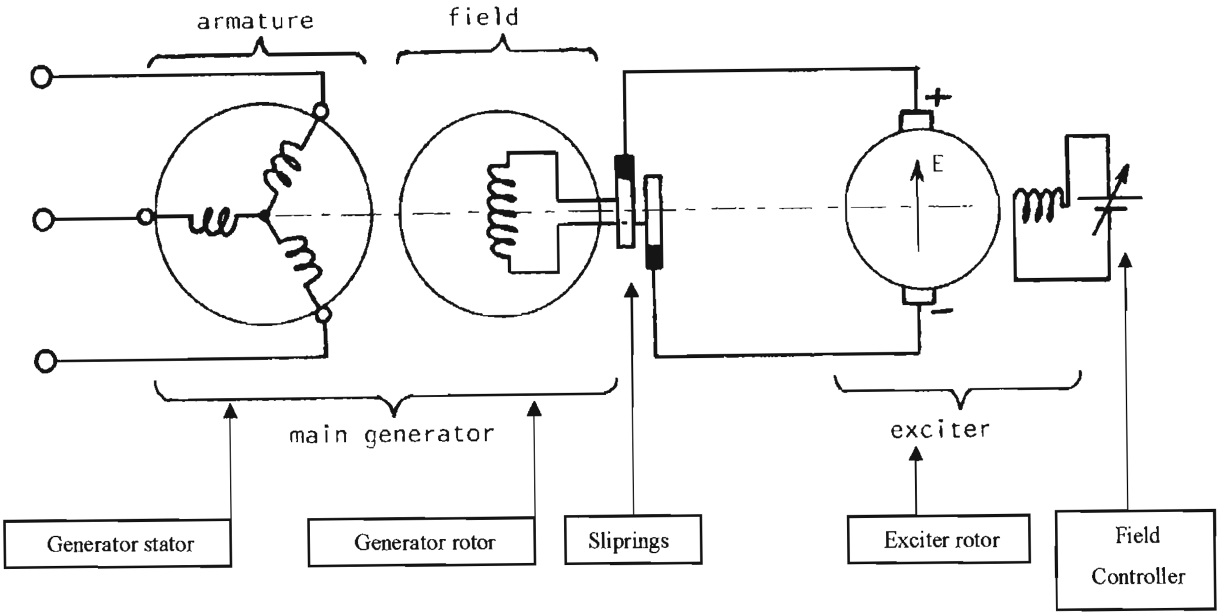


Figure 2-4: Turbogenerator circuit diagram (Coetzee, 2008)

The steady-state equivalent circuit in Figure 2-5 shows the air-gap and leakage components of synchronous reactance as well as air-gap voltage of a generator. The reactance X_a represents the magnetising or demagnetising effect of the stator windings on the rotor known as the magnetising reactance. R_a is the effective resistance of the stator. X represents the stator leakage reactance. The synchronous reactance (X_s) of the machine is the sum of X_a and X, being the total reactance of the machine. Z_s is the synchronous impedance of the machine. The voltage E_l is the internal voltage generated by the air gap flux commonly referred to as the air gap voltage. The terminal voltage is represented by V_l(V_t) and the magnetising voltage as E_m. The field current and armature current being I_f and I_a.

The generator voltage equation is as follows:

$$\overline{E}_m = \overline{V}_t + \overline{I}_a(R_a + jX_s) \tag{2.1}$$

The terminal voltage equation is as follows:

$$\overline{V}_t = -R_a\overline{I}_a - jX_s\overline{I}_a + \overline{E}_m \tag{2.2}$$

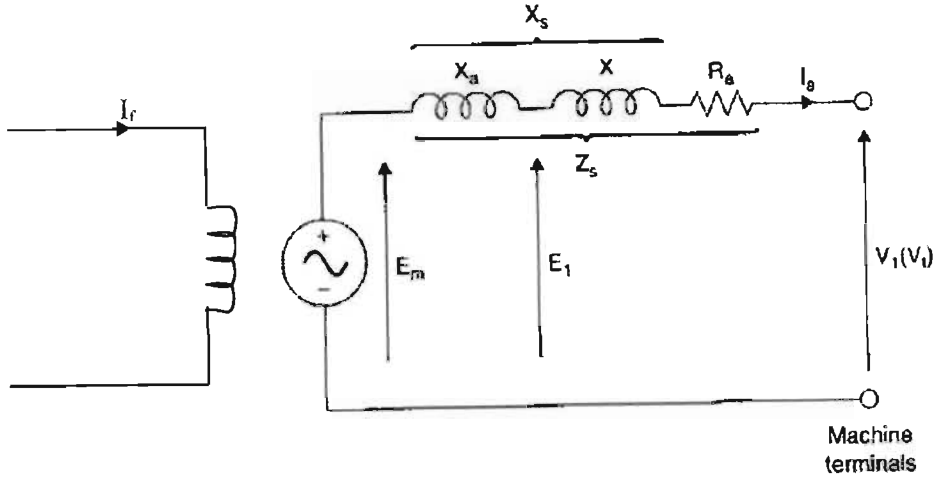


Figure 2-5: Steady state equivalent circuit

It should be noted that Figure 2-5 is a single-phase, line-to-neutral equivalent circuit for a three phase generator operating under balance three phase conditions and suffices to determine the steady-state performance parameters of a synchronous generator. (Chapman, 2001; Fitzgerald, Kingsley, & Umans, 2006; Theraja & Theraja, 1997)

2.3.1. Stator

The stator comprises of the frame, core, armature windings, connection terminals, slip ring brush gear and fluid supply circuits.

2.3.1.1. Frame

It can be seen from Figure 2-6 that the frame forms the outer casing of the generator. It is made up of a series of plates electrically welded together, which resembles a cylindrical tank, the ends of which have centrally located openings traversed by the rotor shaft ends. The frame is securely bolted to the foundation via mounts. The mounts not only support the stator mass, but must also be able to withstand radial and tangential forces due to high operating torques or sudden short circuits. Furthermore it provides support for the stator core and acts as a pressure vessel for the hydrogen cooling gas. Heat exchangers, known as hydrogen coolers, remove the heat absorbed by the hydrogen are also supported by the frame. The

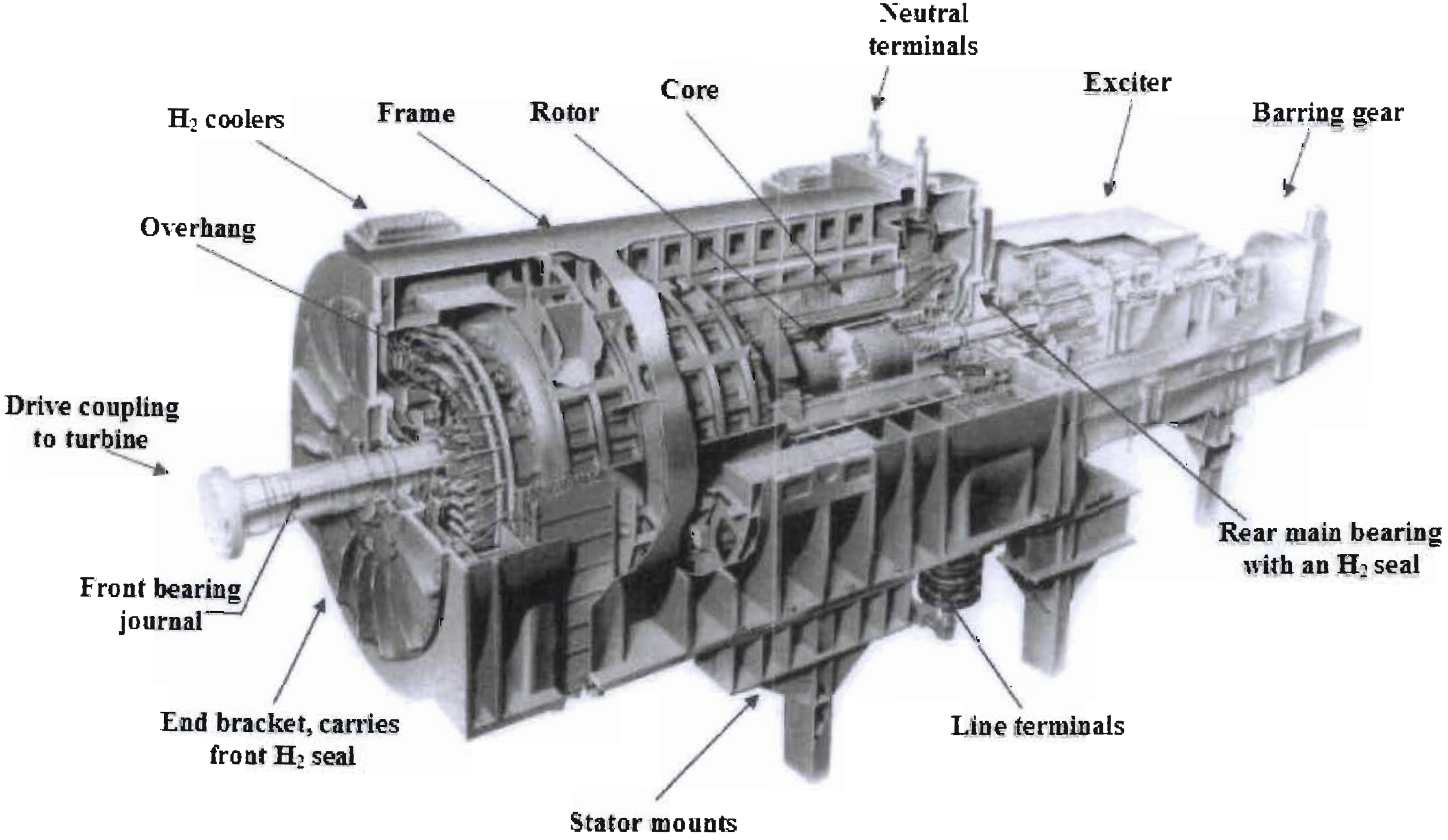


Figure 2-6: Cross section of a turbogenerator (Coetzee, 2008)

casing must also be able to withstand the pressure developed by an ignition caused by an explosive mixture of hydrogen and air, without catastrophic failure. Frame stiffness is an important consideration in generator design as it determines how well the core vibration is isolated from the foundation. Great care is taken to ensure that the natural frequencies of the core and frame are not near the 50Hz and 100Hz operational frequencies of the generator. The frame is internally reinforced by composite O-rings which are placed perpendicular to the shaft axis. These rings give the frame the necessary rigidity and also support the bars which hold the magnetic core.

Pathways within the frame structure connect the various elements of the cooling circuit which ensure optimum distribution of gas throughout. This would include the rotor fans, hydrogen coolers, stator core, air gap, rotor and stator terminals which all require forced gas cooling. The dimensions of these pathways are designed in such a manner that an acceptably low pressure drop is used to circulate the hydrogen gas.

The frame is also designed to withstand lifting and moving during manufacture, transportation and installation at the destined power station.

Figure 2-7: Turbogenerator frame (Siemens)

2.3.1.2. Core

The core provides a path for the magnetic flux from one rotor pole around the outside of the stator winding and back into the other pole. The core comprises of thousands of thin, low loss magnetic steel sheets which creates a low reluctance path for the magnetic field. The use of steel results in high energy losses which are referred to as iron or core losses. These losses are made up of two components: Hysteresis and Eddy current losses. Hysteresis losses occur when the electrons of the iron core are constantly being forced to align with the alternating magnetic field of the rotor. During this process the electrons vibrate and produce heat energy. The energy required to constantly change the polarity of the iron is known as Hysteresis losses. Eddy currents occur due to the iron being conductive. The magnetic field loop contained within the core induces circulating currents, known as Eddy currents.

The core sheets are punched in segments that are insulated and stacked in rings, to form an annular cylinder with longitudinal slots along the inner circumference to accommodate the armature and wedging system. The punching also makes provision for location notches and ventilation holes. The outer periphery of the core has dovetail slots which align with the keybars which locate the core in the frame. Grain-oriented sheet metal, whose magnetic properties are deliberately made different in the two perpendicular axes, is preferred as lamination material. The advantage is that flux in the circumferential direction behind the winding slots is arranged to coincide with the low loss orientation which enables the back of the core to operate at higher flux densities as opposed to non-orientated steel.

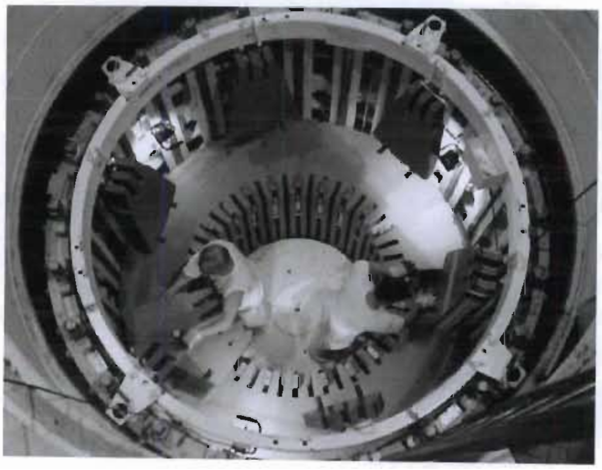


Figure 2-8: Stacking of a stator core (Siemens)

Slots for the stator winding bars extend radially from the bore. The tooth tips of the core experience the highest concentration of flux density. Some leakage flux in the end winding regions penetrates into the ends of the core. The axial component of this flux induces alternating voltages in the teeth, resulting in a current flowing around the teeth, causing losses. This effect is reduced by introducing radial slots which are punched into the teeth at the end of the core, referred to as Pistoye Slots. In effect, these slots reduce the Eddy current paths, minimizing losses. Stepping of the outermost laminations as well as flux shields or laminated press plates, are also used to divert the axial flux.

It is important that the core assembly has no resonances near the excitation frequency, and is strong enough to undergo minimum distortion, due to ovalisation caused by the rotating magnetic field of the rotor.

Figure 2-9: Stator core lamination plates (DTEC)

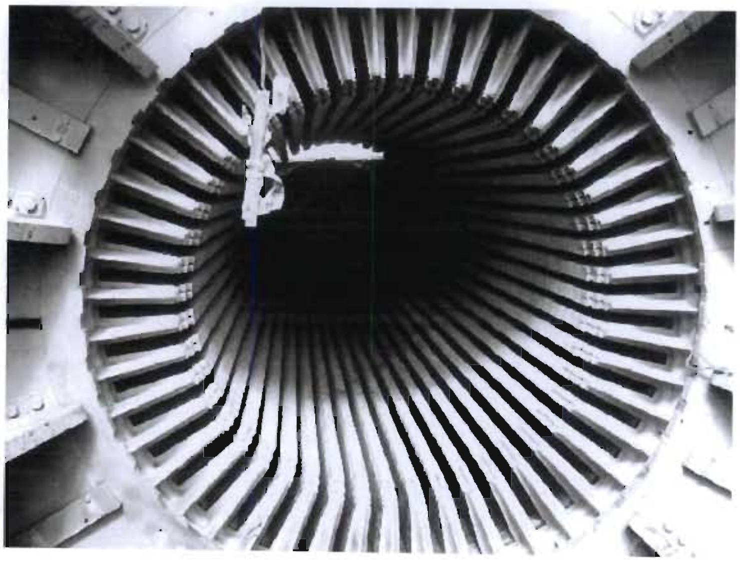


Figure 2-10: Stator core

2.3.1.3. Stator Winding

The stator winding is the noble part of the generator. It is composed of conductors wedged into the magnetic core. It is in this winding, that the electrical energy is generated, and it is from the winding that this energy must be channeled outside. There are two distinct parts to the winding: the straight part, which is within the core, and the end windings (or overhang), outside the core.

The conductors are made up of insulated copper coils, which are distributed around the inner bore of the stator in equally spaced slots in the core to ensure linkage with the flux of the rotor. The winding design in modern machines can either be a two layer lap winding (high speed generators), or a two layer wave winding (low speed generators). In both designs each slot contains two bars, one on top of the other. These are referred to as top and bottom bars (refer to Figure 2-13(b)). The conductors are pitched to minimize the harmonic content of the generated voltage (refer to Figure 2-11). The bars are bent where entering and leaving the slot ends. Top bars and bottom bars bend in opposite directions creating a structure called the winding basket as depicted in Figure 2-12. The bars are connected together in pairs at one end of the machine to form a turn. At the other end of the machine the bars are connected, so that the turns form phase coils which connect to the machine terminals. The phase coils are generally Y connected and designed to produce voltages that are 120° apart.

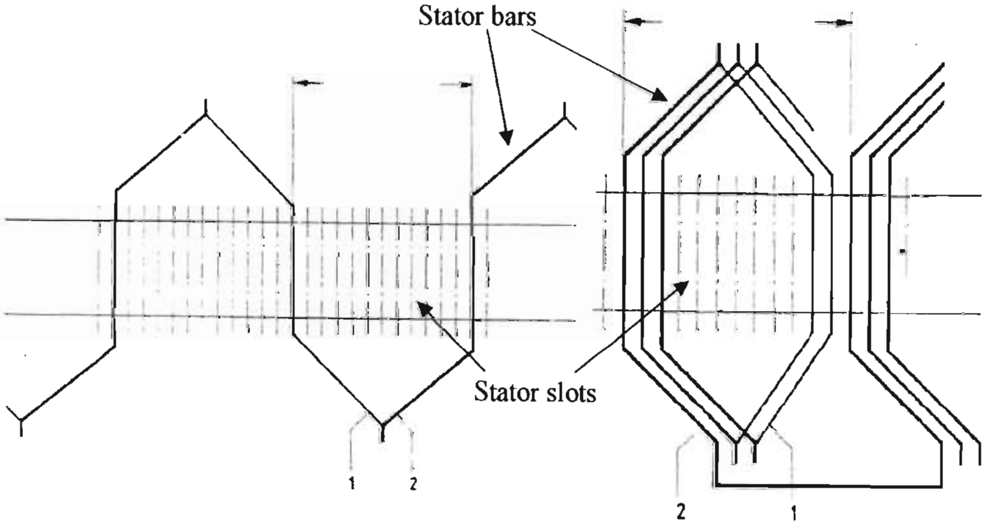


Figure 2-11: (a) Wave winding (b) Lap winding

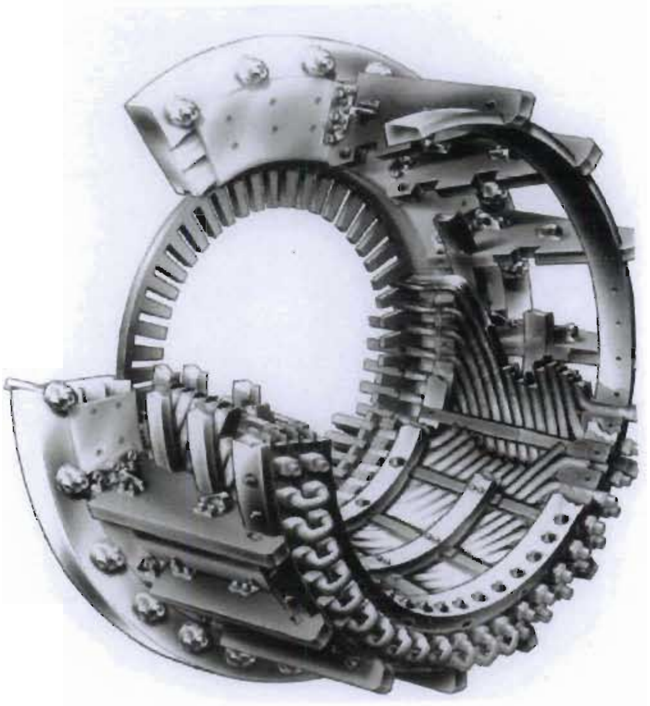


Figure 2-12: Overhang winding basket

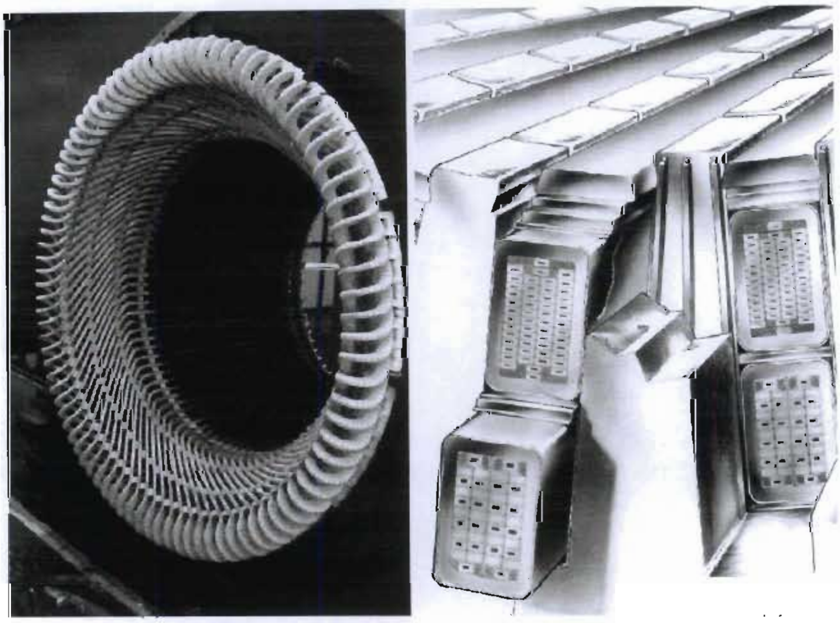


Figure 2-13: (a) Stator overhang and slot area (DTEC)

(b) Stator slot bar arrangement (Alstom)

The copper portion of the stator bars generates significant heat from I^2R losses in the winding. Since the copper in the bars is distributed in the slot in terms of depth also, there is a natural occurrence of Eddy currents in the copper due to the variation in the AC magnetic field from the top to the bottom of the slot. The losses are reduced by the conductors being made up of strands. Unfortunately, the strands are connected at the bar ends so that additional current can circulate from top to bottom strands in a single bar due to the variation in the flux distribution. This effect is minimized by transposing the strands. Transposition simply means that each strand occupies each position in the strand stack at least once over the full length of the bar. This is commonly known as Roebel transposition (refer to Figure 2-14).

In indirectly cooled machines, the strands are all solid and the heat generated in the conductors is removed by conduction through the ground wall insulation to the stator core. In a direct hydrogen cooled bar, the gas passes from end to end in rectangular ducts with low conductivity non-magnetic metal walls. Cooling is very effective. In a direct water cooled bar, the coolant passes through the hollow rectangular copper strands which are insulated and transposed. The hollow strands are evenly spread among solid stands. The solid strands are thinner which have lower Eddy current losses and contribute to the higher efficiency of the generator.

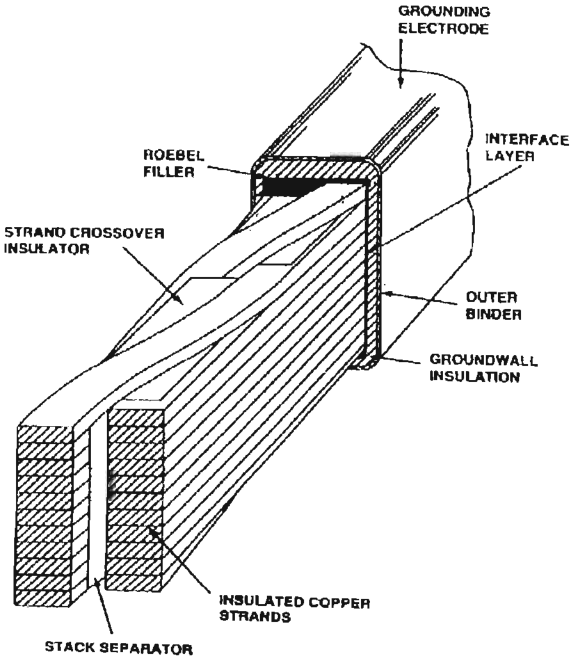
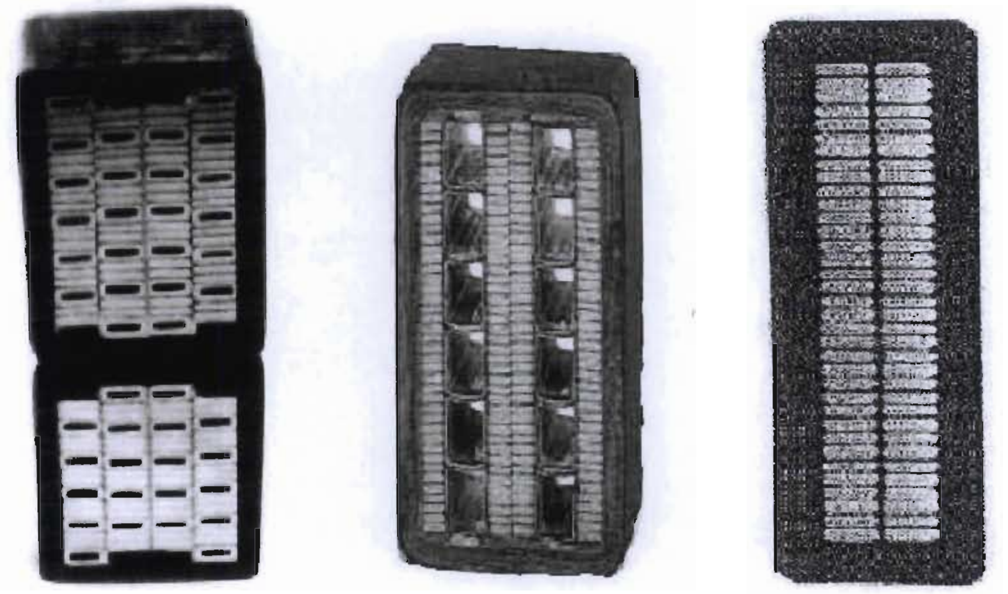


Figure 2-14: Roebel transposed stator bar (Siemens)



Direct water cooled Direct hydrogen cooled Indirectly cooled

Figure 2-15: Basic stator bar cross-section types (Maughan, 2005)

The slot section of a stator conductor bar endures significant and constant vibration forces. This relative motion of the bar is minimized by being tightly wedged in the slot to avoid damage due to bar bouncing. The stator winding can fail rapidly once it becomes loose in the slot. There are numerous types of wedging systems employed worldwide, but all have a common purpose not to allow any movement in the slot.

The electromagnetic forces on the end regions of the stator winding are significant as well, and complex in nature. The endwinding geometry is also complex, and does not lend itself to a simple support structure to restrain the endwinding under all modes of normal and abnormal operation. In addition, the strong electric fields in the end region require that non-conductive supports are used. Commonly support systems use blocks, tension devices and rings, which together with the bars themselves, form a rigid support structure.

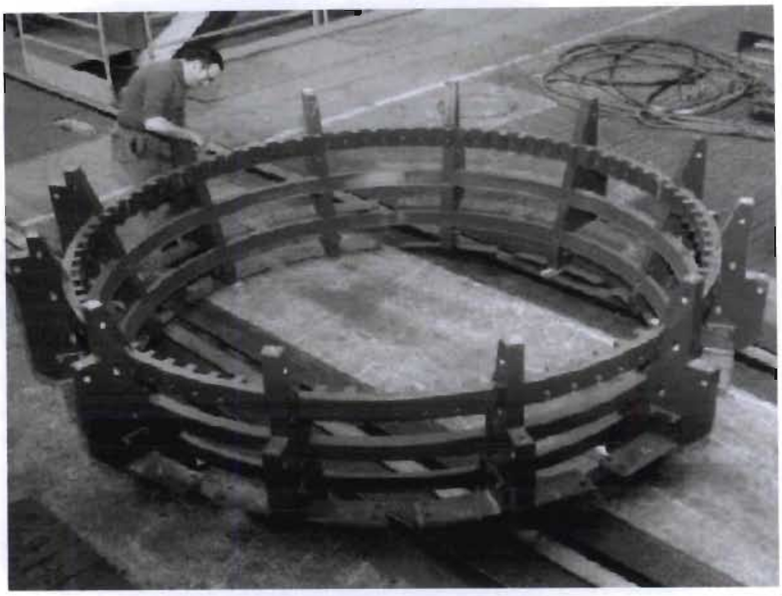


Figure 2-16: Endwinding support ring (Courtesy DTEC)

2.3.2. Rotor

A turbine generator rotor is commonly constructed from a single steel forging comprising of highly permeable magnetic steel. The forging acts as the main structure of the rotor and must possess excellent mechanical properties and magnetic characteristics. The rotor has smooth poles enabling it to withstand high centrifugal forces during operation. The main parts of the rotor are as follows: shaft body, rotor winding and excitation assembly.

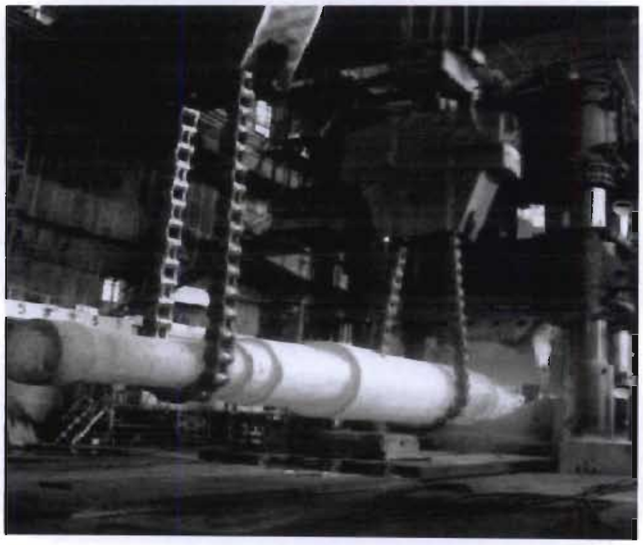


Figure 2-17: Forging of a rotor shaft (Alstom)

2.3.2.1. Shaft body

The shaft has two main functions, an electrical function of generating a rotating field and a mechanical function of transmitting torque. The shaft is the main structure of the rotor, made of a single forging whose ingot is made in an electric furnace and then vacuum cast. The forging consists of the main body, in which the winding slots are milled, pole face inertia slots are machined, the shaft, which rides on the bearings and supports the entire rotor, the turbine coupling, the hydrogen seal faces, and collector ring assembly. A bore hole is often machined at the centre of the forging through its full axial length. This is done mostly due to impurities and porosity in the forgings which tend to concentrate in the centre. The bore hole serves two purposes, firstly to remove material defects, and secondly to provide access for performing boresonic (ultra-sonic) inspections of the rotor bore.

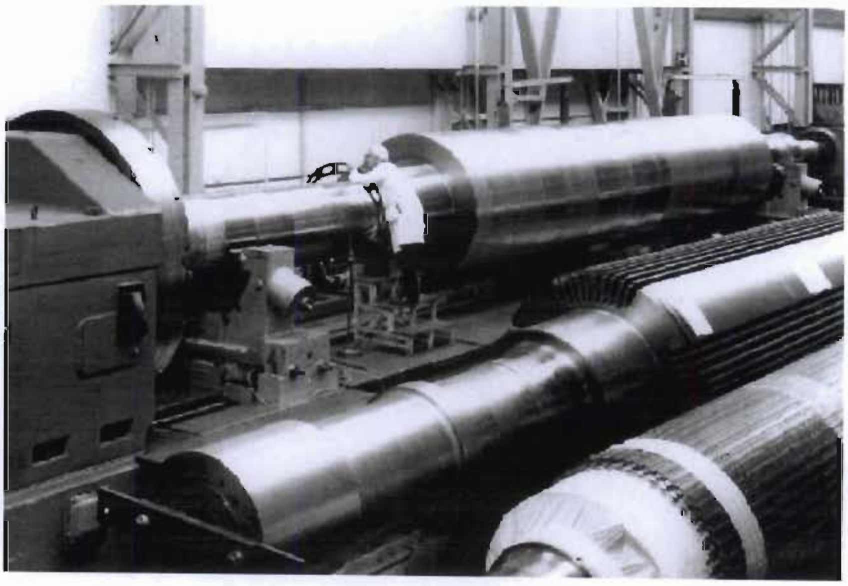


Figure 2-18: Machining of a rotor forging (Alstom)

The rotor teeth created by the milling of the shaft separate the winding slots and carry the centrifugal load of the copper coils. Wedges at the top of the slots transmit the radial load of the coils to the teeth. The wedges are of a complex design and are highly stressed. Adding to the complexity of the design, the wedges include radial ventilation holes for cooling gas to enter or escape the copper winding in the slot below.

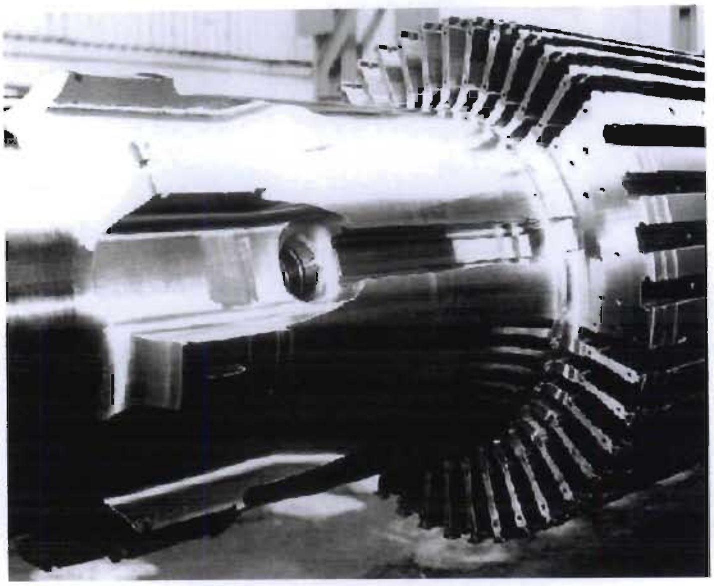


Figure 2-19: Final machined forging showing rotor teeth (Alstom)

The magnetic flux is carried by the rotor in the main body, and is DC in nature. There are two areas which carry the main flux, the solid forging under the winding slots, and the magnetic poles.

The shaft design of the rotor is critical in relation to its vibration characteristics. Shaft diameter and length greatly affect the critical speeds and balance of the rotor. Torsional vibrations are also a concern. Whenever a high current transient is experienced by the stator winding, a complex transient torque is experienced by the rotor. Fault conditions lead to high torsional stresses, and if these stresses exceed the torsional endurance limit of the forging, material failure can occur. This must be taken under consideration in the shaft design.

On the turbine end of the rotor, the shaft has a forged coupling plate which ensures the alignment of the rotors. The coupling has holes machined into it to accommodate coupling bolts as well as separating holes which facilitate plate separation during dismantling. The opposite end is coupled to an auxiliary machine. The auxiliary machine may be an exciter, oil pump or starting pony motor.

On each end of the rotor is an axial fan with individual blades mounted on a fan support ring. The fans create the necessary pressure to ensure hydrogen circulation through the rotor and stator circuits.

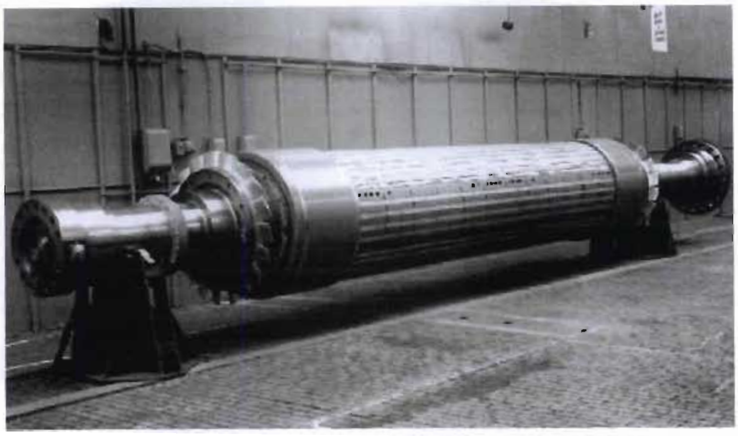


Figure 2-20: Fully assembled rotor with fans and couplings (Alstom)

2.3.2.2. Rotor winding

The rotor field winding is installed in the winding slots that are machined into the body. The winding is distributed around the rotor between the poles. The winding itself is made up of a series connected concentric coils. There are two main areas of the winding, the winding within the slot area, and the winding at the ends of the rotor, known as the overhang. The winding is insulated from the rotor body. In addition, the turns within each winding coil are separated with insulation. The insulation must be able to serve its intended purpose and be able to withstand the mechanical duty imposed by the rotational forces during operation.

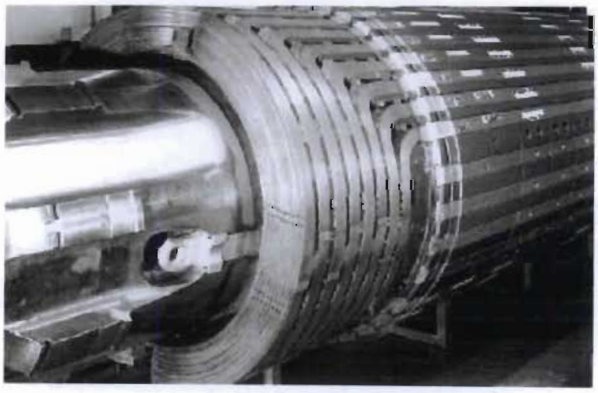
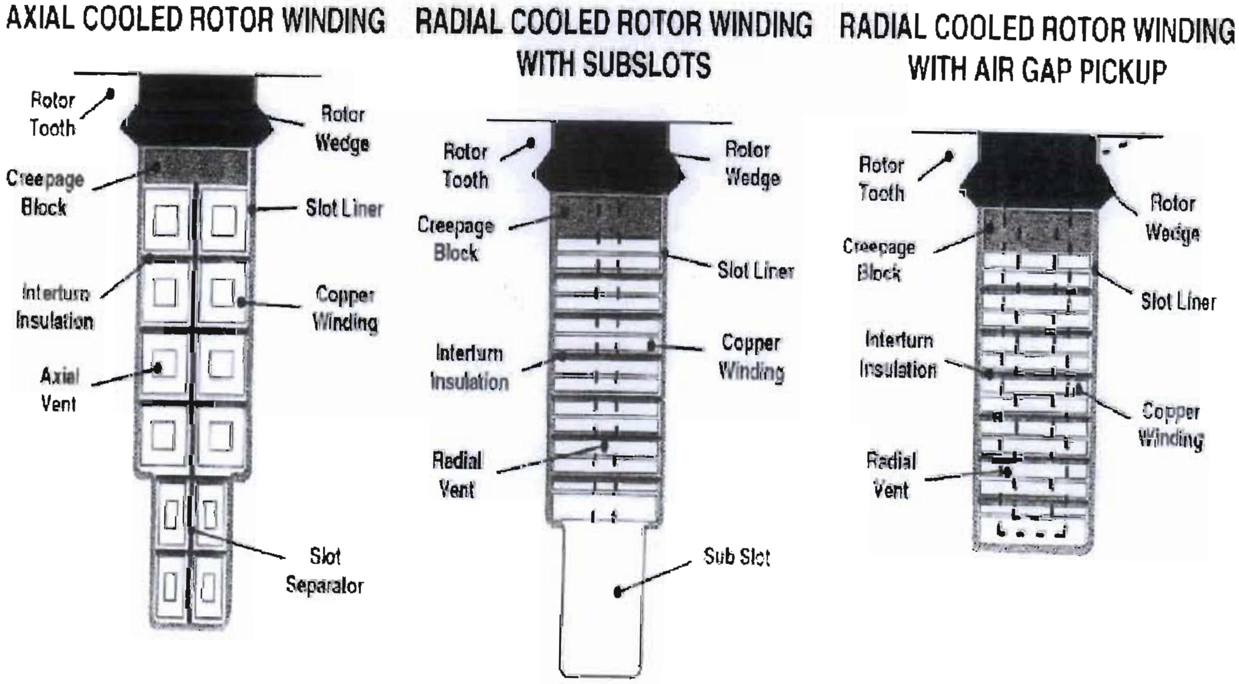


Figure 2-21: Rotor overhang and slot area (Alstom)

There are a number of copper winding designs employed to remove the heat produced in the field winding conductors during operation. The copper winding is cooled by direct contact with the hydrogen cooling gas. Cooling passages are provided for within the conductors to eliminate the temperature drop across the ground insulation and preserve the life of the insulation material. There are three main cooling designs: axial, radial and air gap pickup. In an axially cooled winding, the gas passes through axial passages in the conductors which are fed at both ends. The gas is then exhausted to the air gap at the axial centre of the rotor. In a radially cooled winding, radial passages in the stack of conductors are fed from sub-slots machined along the teeth of the rotor at the bottom of each slot. In the air gap pickup method, the cooling gas is picked up from the air gap and cooling is accomplished over a relatively short length of the rotor. The gas is then discharged back into the air gap.



AXIAL COOLED ROTOR WINDING

RADIAL COOLED ROTOR WINDING WITH SUBSLOTS

RADIAL COOLED ROTOR WINDING WITH AIR GAP PICKUP

Figure 2-22: Rotor winding slot contents designs (Alstom)

The rotor overhang windings are held in place against centrifugal force by Coil Retaining Rings (CRRs). The CRRs are composed of high strength non-magnetic steel. Non-magnetic CRRs is used so as to not overflux the stator core ends. The CRRs are generally the highest stressed component in the generator. The CRRs are shrunk fit onto a shoulder or landing on the rotor body. The CRRs experience complex stresses whether at standstill or in operation. A locking mechanism is employed to restrain the CRRs against axial movement that could be caused by very high axial forces due to the expansion of the field winding conductors.

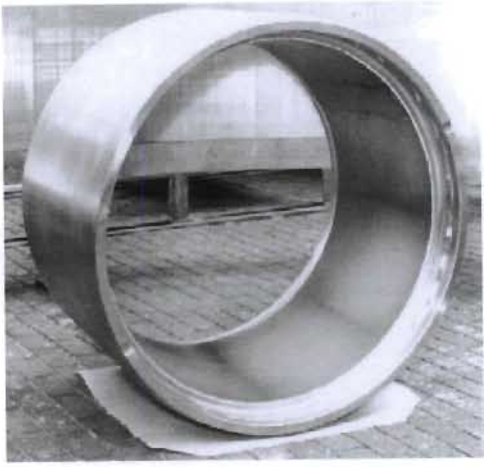


Figure 2-23: Coil retaining ring (Alstom)

2.3.2.3. Excitation assembly

DC current to the field winding is supplied by two methods. In the first, direct current is supplied by the exciter through a collector that has two rings on the rotor shaft. One ring for each polarity, and a sliding contact through graphite brushes. In the second, the exciter produces a poly-phase AC output from the winding on its rotating element. This output is rectified by the rotor mounted rectifiers. This produces a direct current which is delivered to the winding directly without the need for a collector. This is commonly referred to as a brushless excitation system.

2.4. Conclusion

An overview of generator design and operation was presented in this chapter. Now that basic generator principles have been explained, the effects of foreign material can be better understood. This study explores the effects of foreign object ingress in relation to generators and methods to minimise failure. To avoid failures, the management of this phenomenon is crucial. Thus foreign material management and industry practices need to be understood. The best solution to any problem is prevention: thus in the next section, foreign material management will be discussed.

Chapter 3

Foreign Material Management

3.1. Introduction

Foreign material management is a process where a system or equipment is protected by procedures and practices to prevent foreign material intrusion during commissioning, maintenance or inspections, in this instance in relation to turbogenerators. Foreign Material Exclusion (FME) is a term that originated in the nuclear industry, (Kerszenbaum, 1996; Klempner & Kerszenbaum, 2004). In this chapter the effects of foreign material, as well as foreign material exclusion, principles will be explored.

Foreign material (FM) can be described as any material that by quantity, nature or location was not accommodated in the intended design. A foreign object in the generator environment will lead to undesired operation and failure as described below.

3.2. Generator sensitivity to foreign material

The worst 'enemy' of a generator are foreign magnetic metallic objects, which would include tools, nails, bolts, nuts, wire, component fragments and other non-descript metallic objects (such as hand chains and ear rings). If left in the air gap or on the overhang, circulating currents will be induced within the object causing a rise in temperature. The temperature can reach well into the hundreds of degrees Celsius, destroying the insulation that it comes into contact with.

The strong magnetic field and windage could also cause the object to move violently around the air gap, impacting lamination plates or becoming lodged against laminations in the generator. This will result in the short circuiting of the lamination plates and a rapid increase in heat. Such a defect is almost impossible to detect, and over time the heat generated will melt the core and cause failure.

Further Eddy currents flowing within the core will produce a magnetic field in opposition to the main flux resulting in the foreign body being subjected to a 100Hz pulsating force. These objects known as "termites" or "worms," will hammer the core surface or drill through bar insulation causing failure. Typical objects that behave in this manner are iron shavings or cuttings (Kerszenbaum, 1996; Klempner & Kerszenbaum, 2004).

The thermal stability of the generator is dependant on adequate cooling and circulation of gas or water. The gas cooling path consists of hundreds of small passages in the core, rotor and the back of the core. Blockages of these paths can result in hot spots and failure. The stator conductor cooling system that comprises of hollow strands can be as narrow as two millimeters (mm). Blockages within these strands would be catastrophic.

Conductive debris can be picked up via the rotor cooling ducts. The debris can become lodged into small cavities within the winding causing turn to turn or turn to earth faults. Types of debris would include machine shavings, pieces of wire, nails, conductive dust, iron filings or split pins.

These failure mechanisms discussed, make it all that important for a utility to have excellent FME programs. Industry best-practices as well as FME programs will be explored in the next section.

3.3. Industry FME best-practices

Several FME programs exist and the intent in this section is not just to focus on one, but to get an overall analysis of industry trends. Original equipment manufacturers (OEM), research institutes and utilities have all implemented FME programs to some degree, some more rigorous than others.

There is no classic academic literature published on this subject currently, and information is not easily attained. Owing to the sensitive nature of information gathered from the two OEMs and the local utility company, they will not be mentioned by name. The guidelines from The Electric Power Research Institute (EPRI) and The Institute of Nuclear Power Operations (INPO) will be discussed openly.

3.3.1. EPRI FME guidelines

The EPRI FME Guidelines (TR-106756) is a document that sets out to provide a framework for utilities to create their own FME programs. The guideline outlines key practices that should be part of any successful FME program. The practices are as follows:

- Establishing boundaries

One should first create FME zones. These should be small and practical. Pre-task cleanliness of the FME zone and adjacent areas is essential, as well as the inspection of over-head gratings, walkways, railings, and other structures or components.

- Cleanliness of work area

To minimize the opportunity of foreign material intrusion, it is advisable to clean as one goes along, that is to remove tools and excess consumable materials, their containers and the cleaning materials used at the work site. This decreases the spread of FM to adjacent areas where they could possibly pose a potential FME concern.

- Unattended openings

All unattended openings into systems or components should be covered. Potential requirements for ventilation or ingress and/or egress when opening covers should be considered.

- Staging tools and materials

As far as possible, tools and materials should be staged outside the FME zone. Packaging and similar materials should not be introduced into the FME zone unless absolutely necessary. Exceptions can be made for components that are highly sensitive or small items that could easily be misplaced.

- Securing tools and materials

All tools, materials, and equipment prior to introducing them to the FME zone should be secured. They should be inspected to ensure that they do not contain loose or damaged parts that could become dislodged during use. The tools should also be cleaned so that dirt, debris, desiccants and excess lubricant are not introduced into the system.

- Ensure chemicals comply with the control program

All chemicals or chemical compounds introduced into the FME zone should comply with plant guidelines. The introduction of non-approved chemicals can become FM in a system.

- Control of trash

Refuse containers should not be kept within the FME zone. The removal of dirt and other refuse should be logged out as it accumulates according to the appropriate FME log.

- Securing of personal items

Personal items should be removed before entering the FME zone. Items such as clothing buttons and glove tops should be taped over to ensure that they do not become dislodged during work task performance. Safety equipment should also be securely fastened so that they are not dislodged while worn within the FME zone.

- Use of transparent materials

The use of transparent materials in an FME zone is not advisable since it is extremely difficult to detect and retrieve. Items that are used however, should be clearly marked to improve tracking and visibility.

- Awareness of introducing FM into other areas

Use of suitable precautions, such as covers or toe boards, when working on or above gratings to prevent introducing FM into other work areas.

- Protection of adjacent equipment

Precautions must be taken to avoid impacting other permanently installed material or equipment in, or near, the work area from possible FM intrusion by covering it, as necessary. Any openings that could compromise cleanliness during work activities should be protected. The FME device used should not impact the safe operation of adjacent equipment.

- Anticipate results of actions

When working within the FME zone, anticipate the results of planned action. Before initiating any task action, Stop and Think before Acting, then follow up with a Review (STAR). Expect the unexpected.

- Control of airborne FM

Special precautions need to be implemented to capture or control airborne FM when performing certain work tasks, example, spray painting, sand blasting, grinding, insulating or chemical cleaning. Vacuuming alone is not adequate to ensure material removal. Wipes, flushes and similar methods must be used to make certain that all grit and debris are removed to prevent intrusion.

- Wire wheels and brushes

Special consideration should be made prior to using wire wheels and wire brushes. The wire strands can separate from the wheels and brushes and might become a source of FM migrating into adjacent FME zones.

- Control of welding rods

The collection of unused welding rods and used rod stubs into an FME drawstring bag or any suitable container minimizes the risk of a stub being introduced into the system or component. Specialized clothing and supplies must be stored in an appropriate container in the FME zone when not in use.

- Control of waste material

Waste material and rubbish should be placed in proper containers and disposed of immediately as necessary.

- Cleanliness of electrical cabinets

All electrical enclosures should be free from FM at the end of each work task.

- Control of documents

All sheets of paper used in and around open systems and components should be secured. Items such as staples and paper clips have the potential to become FM.

- Accounting for materials and tools

Material and tool accounting within the work document or turnover process should be included. Where the use of an FME log is in effect, log tools and materials in and out in accordance with the plant's FME procedure.

- Loss of FME controls

In the event a loss of FME controls occur, work should stop immediately, and the first line supervisor, as well as the FME monitor, notified.

EPRI emphasises a "focus on prevention" attitude. This attitude requires that individuals plan through activities, performing them to prevent the introduction of FM.

3.3.2. INPO FME guidelines

INPO recognised that FME presented a continuing challenge to the industry and thus a work group was established to provide the industry with improved guidance in foreign material controls and standards. The guidelines are summarised as follows:

- Management support

Managers should encourage an attitude of prevention. Roles and responsibilities should be clear and ownership at every level must be encouraged.

- Ownership

The correct behaviour to promote excellence in FME is encouraged. Workers, supervisors and managers must continuously identify and correct program deficiencies which facilitates continuous improvement. Everyone is held responsible to rigorously implement FME practices.

- Housekeeping

Housekeeping and the condition of plant areas, equipment and systems must be maintained to high standards such that components are less likely to be subjected to foreign material incidents or events.

- FME procedure

The FME procedure provides guidance for FME controls through all phases of the work process. The procedure must clearly describe interfaces between the FME process and other plant processes such as housekeeping, work control and work planning. This provides workers with the information needed to plan, set up boundaries, implement controls and close out work areas to ensure the absence of foreign material in plant equipment, systems and components.

- Training

All personnel working in FME zones must be trained in regard to the FME procedure.

- Human performance

Work plans must be developed to prevent situations that could introduce foreign material during work activities. Foreign material hazards are discussed with workers during pre-job briefings. Foreign material conditions are assessed during supervisor observations at the job site. Deficiencies are identified, and controls established, to prevent the inadvertent introduction of foreign material.

- Work planning

Foreign material exclusion considerations are an integral part of the work planning process. FME plans include appropriate requirements for job site cleanliness, identification of critical points in the work where FME controls must be considered and reinforced when uncertain, workers should stop and obtain appropriate guidance prior to proceeding.

- Devices and tools

High quality devices and tools should be made readily available for implementing FME controls at the job site. Tools for the retrieval of FM should also be readily accessible.

- Observation of work

Plant observation programs specifically identify the need to observe FME practices during appropriate work activities.

- Tracking and trending of FME weaknesses

FME weaknesses identified during work observations, work performance, work planning or work control execution, self-assessments and training feedback processes should be captured in the corrective action program. Results from trends should be used to identify subtle performance problems and drive continuous improvement.

- Continuous improvement

Periodic self-assessments, corrective action program trends, worker feedback and job-site observations should be used effectively to identify gaps to excellent FME performance. Benchmarking is to be used to maintain an awareness of industry FME innovations and new techniques.

INPO stresses that the successful implementation of any FME program requires workers and supervisors to understand the program, accept their roles and responsibilities and recognise the behaviours necessary to implement the program effectively.

3.4. Benchmarking FME programs

The guidelines discussed above are an attempt to aid in producing an effective FME program. However both guidelines do complement each other and a synthesis of these guidelines will produce a very robust and tight FME program.

In this section, FME programs used by two OEM's and a local power utility will be discussed then benchmarked against the combined guidelines of EPRI and INPO.

- OEM One

The OEM whose FME procedure will be discussed in this section has the largest stake in the South African Power Market and is a key player in the industry.

The procedure makes provision for the creation of a clean condition area where the work is to be performed. The Supervisor is responsible for maintaining these clean conditions and all personnel must be vigilant and point out any actual or potential deficiencies.

There are two distinct cleanliness control levels, level one and level two, level two being the more stringent. In the level one control area, attention is given to house-keeping and maintaining the cleanliness. Anything being moved into this area (eg, tools, parts etc.) is inspected for any hazardous debris. Any activities that may cause the creation of harmful debris must be performed outside this area. Where this is not practicable, appropriate precautions must be taken to prevent the ingress of debris. This may involve any, or a combination of the following: vacuuming and cleaning; cocooning and covering components. It is not necessary to enclose this area within a barrier unless it is in the best interest of the work being carried-out, as deemed by supervision. Proper signage must be used to indicate that level 1 clean conditions apply.

The level two area possesses all the requirements of the level 1 area, with a few additions. This area is enclosed by a barrier and only authorized personnel are permitted to enter, and clean overshoes must be worn when accessing this area.

- OEM Two

This next OEM whose procedure will be analysed has the second largest stake in the South African Market and is heavily involved in the new build and return to service projects.

This procedure also makes provision for the creation of a clean condition area around the area where the work is to be performed. The area is fully barricaded and has a lockable entry. A tack mat is used at the entrance to capture any debris under foot. The area is controlled by a "Monitor" who is present at the entrance/exit at all times. The Monitor records all personnel and equipment in and out of the area in a log book. Only authorised personnel are allowed to enter. The Monitor must also inspect all the equipment entering the area for loose parts and debris. Essential equipment is only allowed into the area. The

Monitor further inspects all equipment leaving the area to make sure it is in the same condition as it entered.

Personnel are not allowed to carry any personal effects into the area and are required to wear clean condition coveralls and cloth overshoes at all times. Cleanliness and housekeeping in the area is enforced and maintained by the use of check-sheets to identify deficiencies. When work is suspended, all machine openings are covered by fire-retardant dust sheets. Any cutting, welding, drilling or filing that needs to be carried-out in the area must be authorised by the supervisor and precautions must be taken to eliminate any risk of contamination. If the component can be removed then the work must be carried out outside the area.

- Local power utility company (LPUC)

The LPUC echoes EPRI's "focus on prevention" philosophy. With a large fleet and the current energy crisis, FME has taken on a higher level of priority. This company has experienced failures due to foreign material and it is continuously striving to improve standards, (Tarrant, 2001).

The program has been heavily influenced by EPRI and INPO and implements their guidelines completely. The LPUC has even taken the guidelines a step further by introducing the following:

- Metal detectors when entering and leaving the clean condition area.
- Logging of everything entering and leaving the area.
- Physical barriers around all zones.
- Surveillance cameras in all zones.
- Peer review of clean condition planning.
- Peer review of implemented clean conditions.
- Appointment of a dedicated clean conditions officer responsible for all aspects of FME.

Table 3-1 is a summary of the benchmarking conducted against the guidelines set-out by EPRI and INPO. The guidelines are listed on the left-hand column. The three organisations are benchmarked against these guidelines with an "X" indicating conformity.

Guideline	Organisation Program		
	OEM 1	OEM 2	LPUC
Management support	X	X	X
Ownership	X		X
FME Procedure	X	X	X
Training			X
Human Performance			X
Work Planning			X
Establishing Boundaries	X	X	X
Cleanliness of work area and housekeeping	X	X	X
Unattended openings	X	X	X
Staging tools and materials	X	X	X
Securing tools and materials	X	X	X
Ensure chemicals comply to control program	X	X	X
Control of trash	X	X	X
Securing of personal items		X	X
Use of transparent materials			X
Awareness of introducing FM into other areas	X	X	X
Protection of adjacent equipment	X	X	X
Anticipate results and actions			X
Control of airborne FM			X
Wire wheels and brushes	X	X	X
Control of welding rods			X
Control of waste material	X	X	X
Cleanliness of electrical cabinets			X
Control of documents		X	X
Accounting for material and tools		X	X
High quality devices and tools			X
Observation of work	X	X	X
Tracking and trending of FME weakness			X

Guideline	Organisation Program		
	OEM 1	OEM 2	LPUC
Continuous improvement			X
Loss of FME controls			X

Table 3-1: FME guideline benchmarking

OEM One follows 15 out of the 30 guidelines, thus following 50% of the guidelines, and has a lot of catching-up to do in terms of strengthening their program. OEM Two follows 17 out of the 30 guidelines, thus following 57% of the guidelines, and even though better than OEM One, it still is not robust enough and will have to conform further to the guidelines. LPUC complies with the guidelines in totality and boasts the most robust program.

Experts agree that FME is a common problem and an FME program is vital. Klempner (Klempner, 2008) states that carelessness and complacency are usually the cause of poor FME. Stein (2008) of EPRI emphasizes the use of procedures and barriers to minimise FME risk. Kerzenbaum (Kerszenbaum, 2008) has dealt with this issue throughout his career and describes FM ingress as unfortunate. He discussed two incidents of FME failures, a washer left in a machine during an overhaul, and a major disaster where a wrench was left in a machine (this will be covered in a later chapter).

Kerzenbaum (2008) stresses the importance of training and does not put much confidence in OEM FME programs. Utilities must formulate their own programs and record keeping is a must. In his opinion, the most important thing is awareness. People working in these expensive machines must also understand the consequences of FM and have the right culture and take responsibility for their actions.

Tarrant (2001) states that the human component should not be ignored and FME practices should not only be seen as a practice, but a state of mind.

3.5. Conclusion

The hazards of foreign material ingress as well their negative effects were discussed in this chapter. This highlighted the importance and need for FME procedures and practices.

Standards can only be set by following industry best-practices. The chapter concluded with a benchmarking exercise to gain an overview of industry practices against the guidelines.

Foreign material management protects equipment by utilising procedures and practices to prevent FME. A foreign object is any material that by quantity, nature or location was not accommodated in the intended design.

Generators are sensitive to these foreign objects and this can lead to catastrophic failure.

The importance of FME procedures can not be overlooked. EPRI and INPO have produced guidelines for the industry, but many organisations fail to implement robust programs.

The aim of this study is to gain a better understanding of FM failure and attempt to minimise the risk by using condition monitoring techniques. The next chapter details the investigation into industrial FME failures.

Chapter 4

Industrial Experiences on FME Failure

4.1. Introduction

This chapter will investigate industrial incidents. This chapter will provide a better understanding of the magnitude of Foreign Material Ingress (FMI) incidents, as well as the response of condition monitoring equipment and protection systems when FM is present. It will also discuss the sources of FM and how the incident could have been avoided. Information on incidents is scarce and most utilities deem these incidents confidential and thus they rarely reach the public domain. All incidents covered are confidential and will be referred to under a pseudonym.

4.2. Background

In this section, the frequency of FMI events will be reviewed. All empirical data used involve nuclear powered utilities from the United States, (INPO, 2004). The incidents also include FMI on all components, not just the generator.

Figure 4-1 chronicles FME failures from the period of 1999 to 2003. One hundred and ten events were identified from January 2002 to April 2004. Sixty-nine FMI events were reported in 2003, compared to 33 in 2002. This represents a 109% increase in incidents as compared to the flat trend during the period of 1999 through to 2001. This rise is attributed to poor FME regimes.

The consequences of these events were unit trips, loss of generation and delays in the return to service of units. Forced power reductions took place impacting the power network and affecting customers.

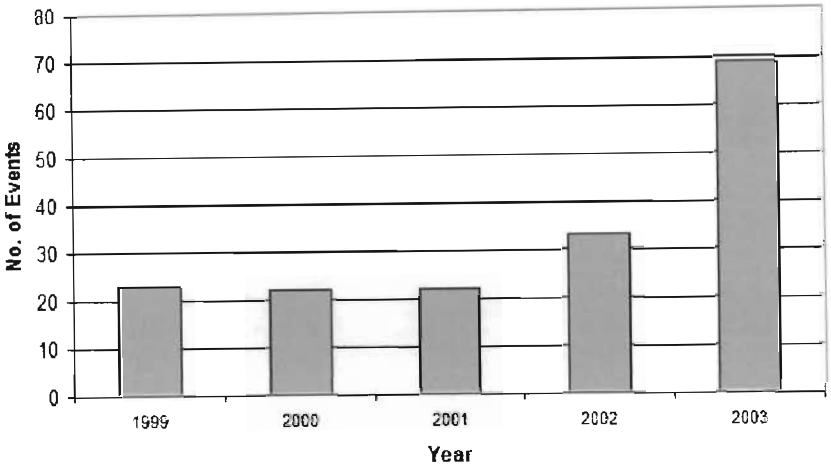


Figure 4-1: Graph of reported FMI incidents (INPO, 2004)

Internal findings found that weaknesses in FME programs were responsible for most of the incidents. The final result was lost revenue for utilities, high repair costs and disgruntled customers, which all could have been avoided.

This US experience shows that FMI is a common occurrence and that the industry is struggling to implement adequate FME programs and achieve the desired human behaviour.

4.3. Industrial Incidents

Eleven industrial incidents will be discussed below.

The incidents will be investigated in the following manner: type of power station; type and capacity of the generating unit; circumstances surrounding the incident; type and origin of FM; damage caused; response of the condition monitoring equipment and the resultant repair and cost. The details pertaining to some of the incidents are vague and not all the criteria mentioned above are known, therefore the incidents will be in the order of most information available, to the least.

4.3.1. Incident One

The following incident occurred at a large coal fired power station. The unit was a hydrogen/water cooled generator capable of generating in excess of 600MW. The unit had undergone routine maintenance. Repairs on the unit had been conducted by the OEM. After two weeks in operation the protection system of the unit tripped indicating a stator earth fault.

Upon further investigation of the fault condition, it was found that four pieces of high tensile bolt material were left in the generator. The metallic FM was thrown around violently in the air gap causing considerable damage. Lamination plates in the core were fused together as a result, allowing circulating currents to develop. This led to the core melting and damage to the stator bar insulation, causing an earth fault and the unit trip to occur.

The rotor surface was also damaged by the impacts of the FM. Approximately 4500 impact marks were found. The CRRs were spared from any major damage.

The condition monitoring equipment showed no abnormalities besides a front bearing vibration that fluctuated in and out of the alarm limits. This was not reason enough to indicate a major problem. During the numerous inspections that occurred prior to running the unit up, nothing out-of-the-ordinary was found.

The repairs ran into hundreds of millions of Rands in present value. The stator winding had to be unwound, core laminations had to be removed and new ones restacked, and new stator bars had to be wound. The repair took approximately one year to complete, and the abovementioned costs exclude the cost of lost generation.

The origin of the FM was never determined, but an internal report found the root cause was a failure in FME.

4.3.2. Incident two

This incident also occurred at a large coal fired power station. The unit was a hydrogen/water cooled generator capable of generating in excess of 600MW. After a full rewind of the rotor the unit was commissioned. After a short time in service the unit tripped on 'generator stator earth fault protection'.

An inspection of the generator revealed significant damage to the stator core. The damage was attributed to a balance weight that had unscrewed from the rotor body and fallen into the air gap during run up. The FM was moved through the gap violently and the magnetic field caused it to pound against the core surface. The FM damaged core laminations and the circulating currents that resulted, caused overheating and the core to melt, as shown in Figure 4-2. The molten core material damaged the adjacent stator bar insulation causing an earth fault.

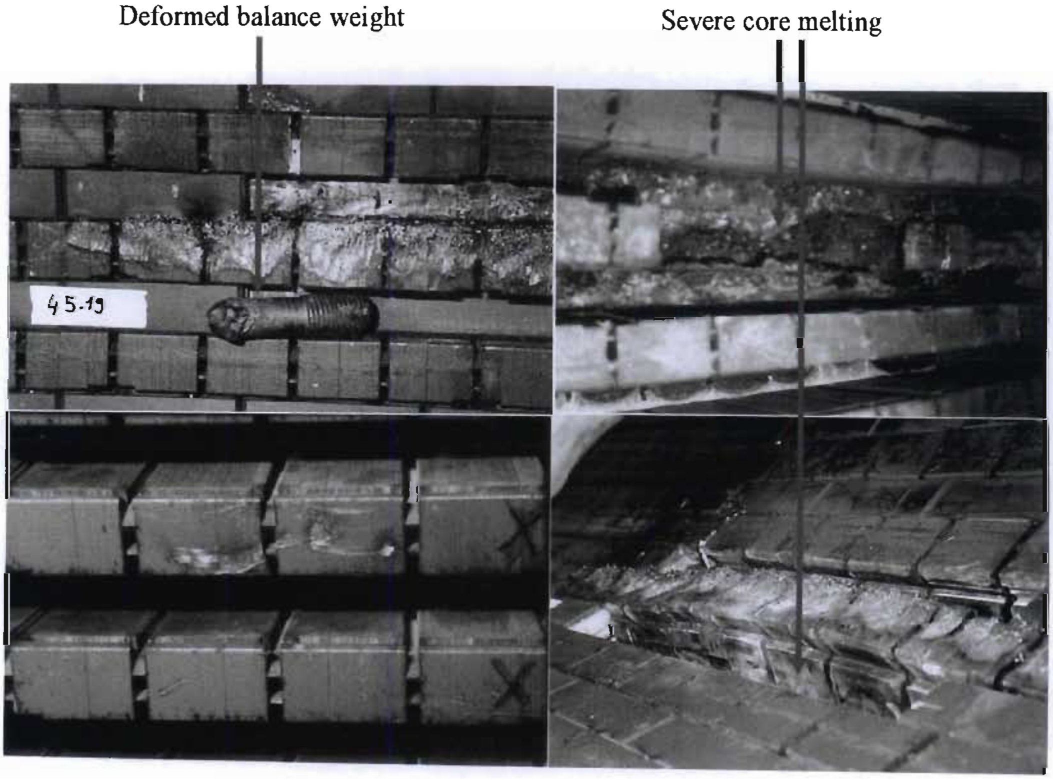


Figure 4-2: FM and core damage

Large impact marks were found on the surface of the rotor. The rotor windings also showed signs of overheating. The rotor and stator were contaminated by a sticky black substance.

The condition monitoring equipment showed a change in vibration levels which were not investigated as the vibrations were within operation limits.

The repair involved a complete rewind of the stator, along with a partial restacking of the core. It took in excess of three months. Costs are unknown.

An internal investigation found the root cause to be a failure in quality standards as the balance weight was inadequately locked in position.

4.3.3. Incident three

Incident three occurred at a medium-sized coal fired power station. During a general overhaul of a 350 MW two-pole, three phase, water cooled generator, it was decided that the unit be mothballed and returned to service at a later date. The unit was returned to service six years later. After a long period in operation the unit tripped on 'stator coolant flow low'.

The generator was stripped down and a leak in the stator coolant system was suspected. It was found that a phase line parallel connection inside the generator had overheated and failed. The insulation appeared to be discoloured. On further investigation it was established that rags had entered the stator water cooling system. The restricted coolant flow caused the bar, electrical connection and water box to overheat. This resulted in the solder of the electrical connection to run off, consequently creating an open circuit. A high current was then conducted along the copper tube of the water circuit causing it to overheat and rupture, resulting in the trip. Figure 4-3 shows the bar damage as well as the rag protruding from the water box.

The condition monitoring equipment was ineffective as the thermocouples that monitored the bar temperatures were defective. The Doppler Test used to identify restrictions in the pipe works was not sensitive enough to detect the problem, or was carried out prior to the rags moving from the area of the pumps into a position where they blocked the flow in the bars. See Appendix A for an overview of Doppler Testing.

The cost and magnitude of the repair is unknown, although it was relatively minor compared to the abovementioned incidents.

Figure 4-3: Overheated stator bar and FM within water box

Ironically the rags had entered the system during a cleaning operation where rags were used to plug coolant pipes to prevent FM ingress.

Several factors were subsequently found to have contributed to this failure: poor work planning, execution, and FME standards.

4.3.4. Incident four

Incident four occurred at a large coal fired power station. The unit in question was a two pole, three phase, water/hydrogen cooled generator capable of generating in excess of 600 MW. The unit was being returned to service after an extended outage. After three days in service the unit tripped on 'generator differential protection'.

Further enquiry into the shutdown revealed the presence of a metallic object. The object was lodged in the stator exciter side overhang winding between two adjacent bars. A closer inspection of the FM revealed that it was a specialised tool used by the OEM. The strong magnetic fields in the overhang created vibrational and frictional forces which caused the FM to bore through the bar insulation. This was aided by significant heating caused by circulating currents in the FM further degrading the insulation. Calculations estimate that the FM reached temperatures in excess of 750°C. This led to a phase to phase fault occurring and the unit tripping.

A large number of stator bars were damaged and minor damage was caused to the core. Carbon pollution was deposited throughout the generator including the rotor. The rotor was extensively polluted leading to an earth fault. The rotor had no signs of any physical impact damage.

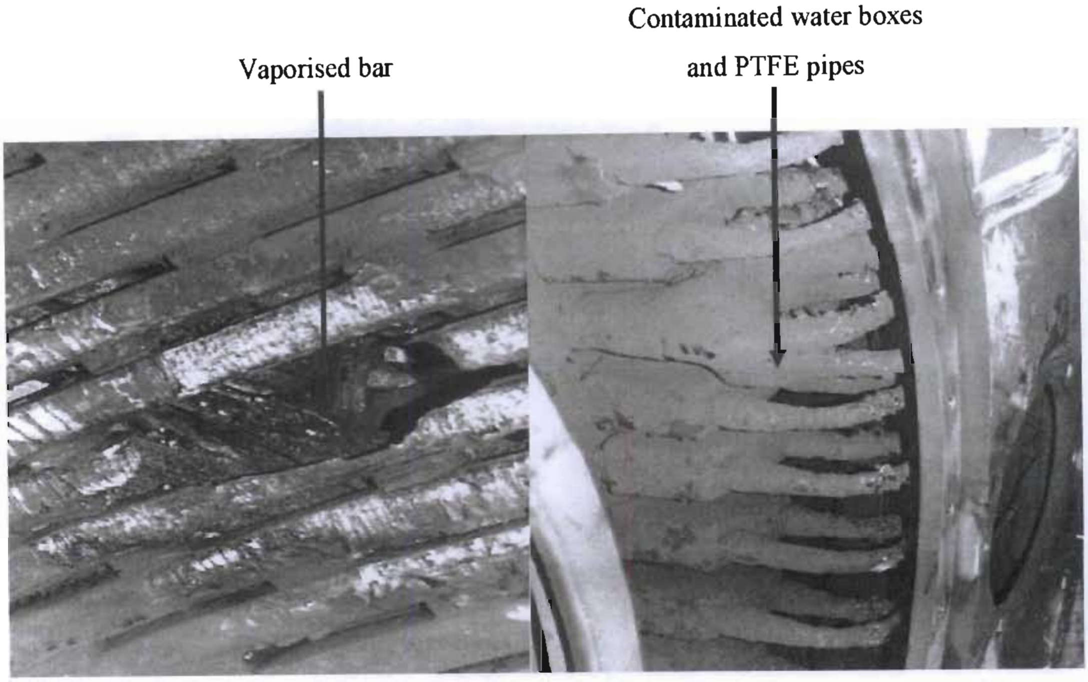


Figure 4-4: Destroyed overhang bars and extensive pollution

The condition monitoring equipment raised no alarms during this incident. The control room recorder showed that stator bar temperatures were increasing rapidly at the time of the trip, but had not yet reached alarm value. This has led to the introduction of temperature differential alarms in the temperature monitoring systems.

The repair involved a complete rewind of the generator. The cost is unknown at this moment.

It was observed by station personnel that the OEM had scant regard for FME procedures. During the outage there was an earlier incident of FM ingress where a tool broke and shrapnel fell into the stator windings. The incident was not reported by the OEM and the station personnel investigated the occurrence after they had observed that the tool was broken. A search took place and the tool piece was recovered. Station personnel were then concerned regarding the OEM's tardiness. Video camera surveillance as well as a twenty-four hour observation were instituted to monitor any shortcomings. Unfortunately these measures did not succeed in saving the machine.

Internal findings found that a shortcoming in FME practices and undesirable human behaviour caused the incident.

4.3.5. Incident five

The following incident occurred at a large coal fired power station. The unit was a two pole, three phase water/hydrogen cooled generator capable of generating in excess of 600 MW. The unit was in operation for approximately three days after a short outage. The unit tripped on 'stator earth fault protection'.

The damaged area on the exciter side of the generator was inspected and it was noticed that a section of a stator bar was totally vaporised. Surrounding stator bars were also damaged. The investigation revealed that the failure was the result of a phenomenon called 'plugging'. This is caused when the hollow copper conductor of a stator bar through which the cooling water flows gets corroded. The copper oxide particles created from this process are then deposited at constriction points in the hollows strands (for example where Roebel strands crossover or where the bar geometry changes). This subsequently leads to flow restrictions which inhibit cooling and lead to overheating and failure. This phenomenon is highly dependant on the stator cooling water chemistry. Please refer to Appendix B for more information of stator water chemistry.

The stator bar was starved of cooling water and the bar temperature began to rise rapidly. A section of the bar vaporised at the hot spot and the molten copper proceeded to damage adjacent stator bars causing the unit to trip (Figure 4-5). The melting point of copper is 1083°C (Bentor, 2008), and this intense heat was responsible for the damaged of the insulation of the adjacent stator bars.

The rotor CRR on the exciter side was subjected to high temperatures as well, causing its painted surface to blister and peel. A temperature over 400°C can damage the substructure of the CRR material and lead to cracking and failure. The stator and rotor were polluted by carbon deposits. The extent of the pollution is captured in Figure 4-6.

Figure 4-5: Area of extreme heating and bar damage

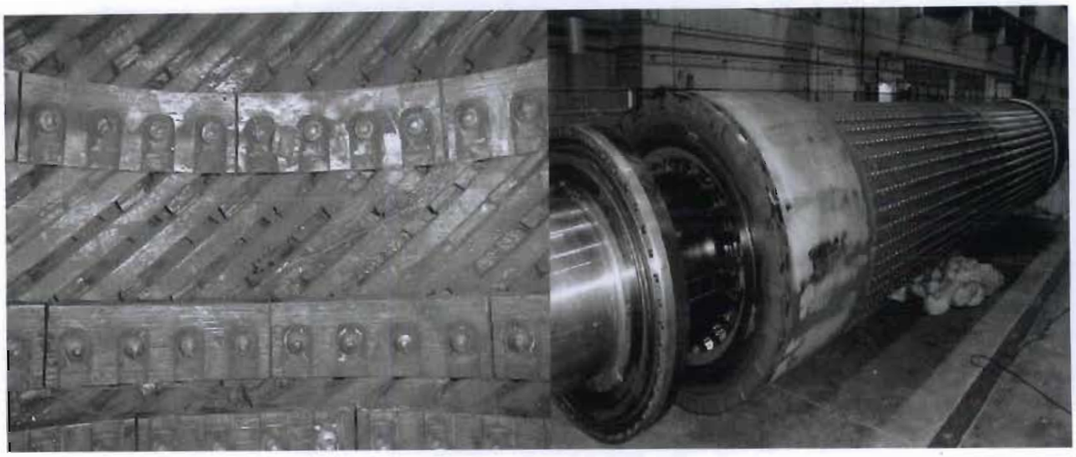


Figure 4-6: Global stator and rotor pollution

The condition monitoring equipment raised no alarms as the thermocouples were defective and bar temperatures could not be monitored.

The repair required a complete rewind of the stator and rotor, and the supply of new CRRs and took in excess of three months. The cost of the repair is unknown at this moment.

The root cause was found to be incorrect operational practices.

4.3.6. Incident six

This incident is similar to incident three and also occurred at a large coal fired power station. The unit was a hydrogen/water cooled generator capable of generating in excess of 600MW. After extensive stator repairs the unit was commissioned. After a month in service the unit tripped on 'generator stator earth fault protection'.

Significant damage to the stator core and rotor was observed. The damage was attributed to a balance weight that had unscrewed from the rotor body and fallen into the air gap during operation. The FM was moved through the gap violently and the magnetic field caused it to pound against the core surface. The FM damaged core laminations to the extent that deep holes were left in the core and the wedge dovetail area, as seen in Figure 4-7.

The rotor body and aluminium wedges were damaged severely (Figure 4-9). Due to the design of the rotor wedge, it was able to chip away at the FM and pollute the rest of the generator. The rotor damage is thought to have occurred during barring.

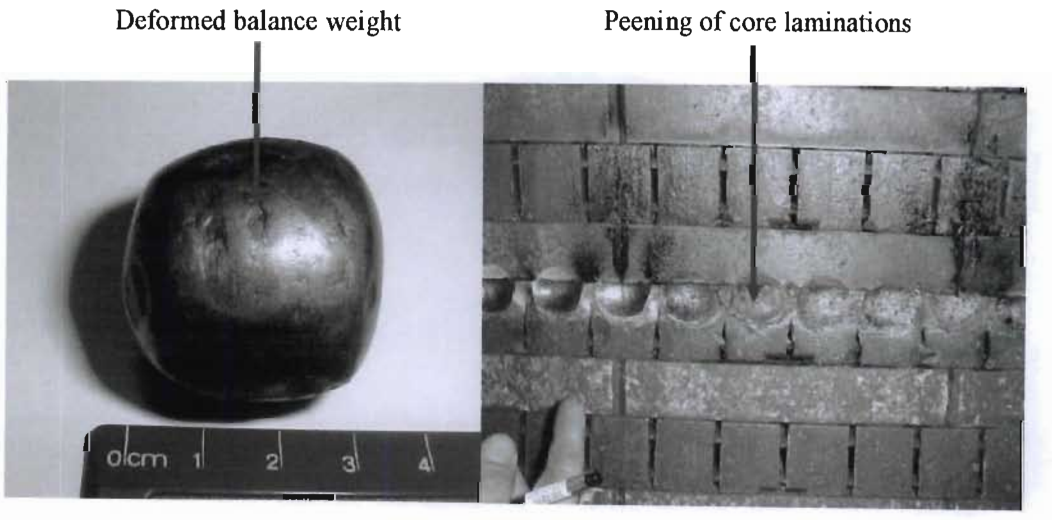


Figure 4-7: FM and core damage

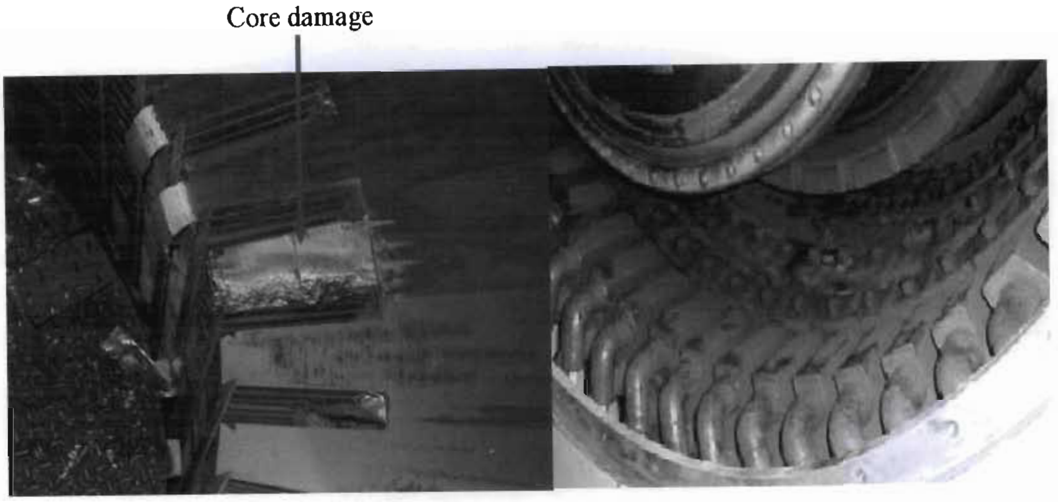


Figure 4-8: Core melting and global pollution of the rotor and stator

Figure 4-9: Empty balancing plug hole, damage to rotor body and wedges. Further plugs can be seen coming loose.

The condition monitoring equipment was unable to respond as the vibration monitors were offline, and no Generator Condition Monitor (GCM) was installed.

The repair costs ran into the hundreds of millions of Rands. The stator was rewound with new stator bars, the core was restacked and the rotor was rewound.

The root cause was found to be a failure in quality standards as the balance weight was never locked in position.

In the next incidents that will be discussed, information on the failure is scarce and therefore only what has been put into the public domain will be discussed.

4.3.7. Incident seven

The following incident occurred at a large nuclear power station. The unit was a hydrogen/water cooled generator capable of generating in excess of 900MW. After a refuelling outage the unit was re-commissioned. After five days in operation during loading of the generator the unit tripped as a result of 'generator stator earth fault protection'.

The investigation that followed confirmed an earth fault, and a bolt was retrieved from the generator as seen in Figure 4-10. The bolt was found in the turbine side overhang region. This, along with other unidentified magnetic material resulted in damage to a number of stator bars. There was also a high level of contamination (soot) throughout the generator. Copper deposits were also found on the rotor turbine end CRR.

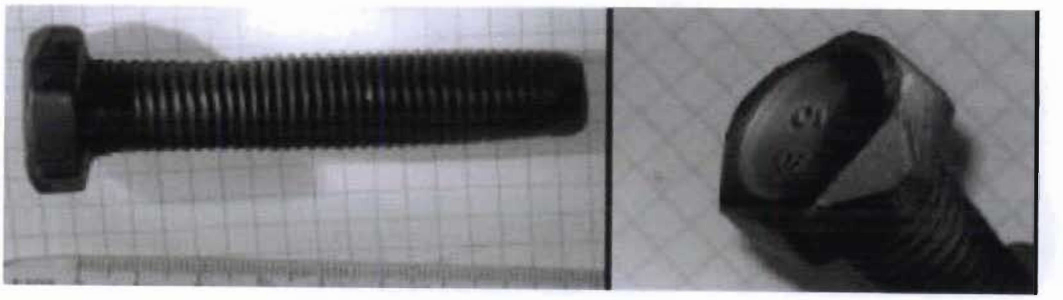


Figure 4-10: Foreign material

The bolt was tested and found to be similar to the type of bolt used on the stator end winding covers. Debris at the location of the fault was tested and magnetic material was identified. The FM at the failure location was heated up by circulating currents and caused a phase to phase fault.

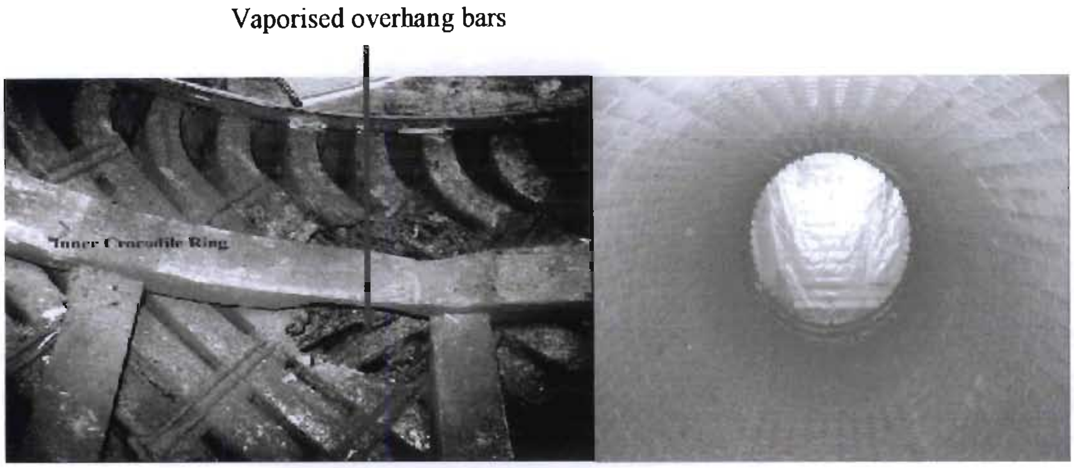


Figure 4-11: Damage to overhang and global pollution of stator.

The plant condition monitoring equipment was not capable of early detection of the fault. The Generator Condition Monitor (GCM) did log detection of overheating before and during the incident. However, it had not been set-up correctly and was in alarm as a result of low flow, so it did not activate a verified fault alarm. In addition, the monitoring system was not wired to the control room, and which was unaware of any problems with the equipment. Even if the alarm from the GCM had been received and verified, there were no response procedures in place, and the alarm would not have been sufficient on its own to cause the operator to shut the unit down.

The repair costs ran into the hundreds of millions of Rands, and severely impacted on the electricity supply situation. The rotor and stator were rewound.

After an investigation by the utility the root cause of the incident was a failure in FME implementation.

4.3.8. Incident eight

This incident occurred at a large nuclear power station. The unit was a hydrogen/water cooled generator capable of generating in excess of 900MW. Information on this incident is not very detailed.

A routine inspection of the generator air gap revealed a loose nut. The nut was located at the turbine end on the stator core. The rotor was removed and the core tested. Minor damage was found in the form of fused laminations and the core was repaired.

The nut was determined to be from outside the generator and was left in the generator during a previous outage. After an investigation the root cause was found to be a failure in FME procedures.

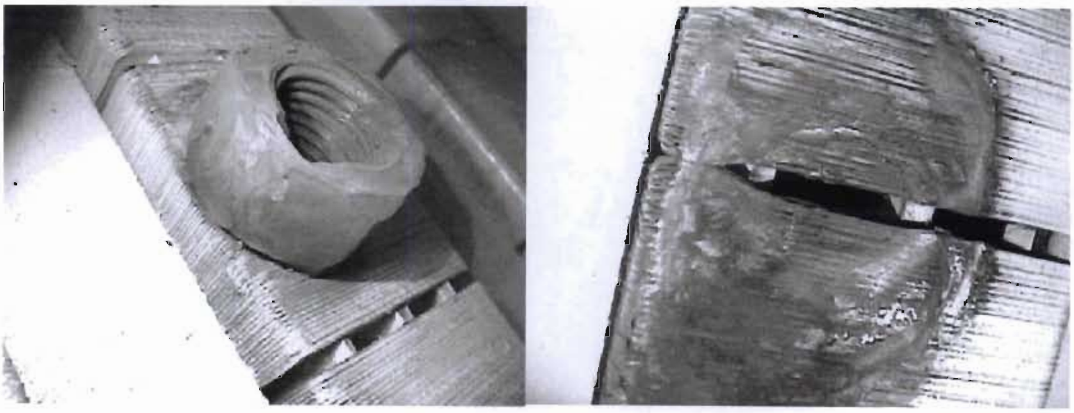


Figure 4-12: FM and core damage

4.3.9. Incident nine

This incident occurred at a large nuclear power station. The unit was a hydrogen/water cooled generator capable of generating in excess of 800MW. Information on this incident is not very detailed.

A routine inspection of the rotor air gap revealed the presence of several loose parts. Further inspection identified the material as a washer which was attached to the stator core. Circulating currents in the FM caused it to overheat and fuse to the core laminations. The rotor was removed and the damaged area was repaired.

The root cause was found to be a failure in FME procedures by a subsequent internal investigation.

4.3.10. Incident ten

The following incident occurred at a large nuclear power station. The unit was a hydrogen/water cooled generator capable of generating in excess of 900MW.

The only information known is that a spanner was left in the stator overhang area that resulted in a catastrophic failure. A series of pictures below chronicle the incident.

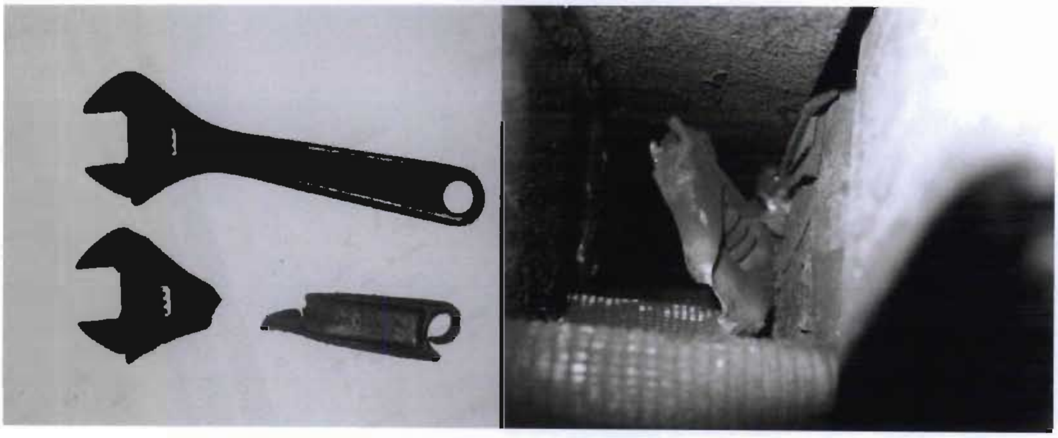


Figure 4-13: FM and FM in the stator overhang as found

Figure 4-14: Overhang bar damage and global pollution

Figure 4-15: Failed transformer

Figure 4-15 shows the far reaching consequences of FM in this case, which resulted in the failure of a transformer as well. This was probably as a result of the current surge on the system caused by the fault on the generator.

After an extensive investigation by the utility the root cause was found to be a failure in FME procedures.

4.3.11. Incident eleven

All that is known about this incident is that a washer was left in the overhang of a generator rotor.

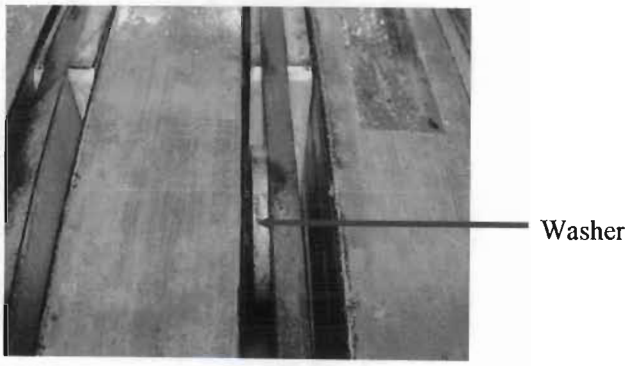


Figure 4-16: FM in rotor overhang

The extent of the damage caused, if any, is unknown.

In the next part of this chapter a summary and analysis of the incidents will be conducted.

4.4. Analysis

It can be seen that FM ingress has afflicted many different types of power plants and generating units. The consequences of FM ingress and the response of condition monitoring equipment to the FM are of particular importance to this study.

Table 4-1 is a summary of the major aspects that concern this study. The first column lists the incident followed by the approximate unit rating, type of FM, the area of ingress, the response of the condition monitoring equipment, what component was damaged and the critical failure factors that led to the incident.

The units that were affected were all large generators ranging from 350 MW, to in excess of 900 MW, coal fired and nuclear powered. The foreign material found illustrates the vulnerability of the generator. Apart from common metallic objects such as bolts, tools, washers and a nut, other not so typical FM was found. Rags entered the cooling water system in incident three. The unit of incident five fell victim to plugging, and in incidents two and six, rotor balance weights unscrewed and fell into the air gap.

FM can be deposited in numerous areas of a generator, the air gap being the most common followed by the stator overhang area. Both can be inspected, although in a number of cases the FM only entered the area after the machine was returned to service. FM entering the stator coolant system and flowing through the narrow hollow conductors of the bar is much more difficult to detect.

By and large it would seem that presently available condition monitoring equipment is either inherently incapable of detecting the symptoms of the majority of FM ingress, or is incorrectly utilised, rendering it ineffective. During the run-up of a unit at a large power station, there are many systems which have to be commissioned, and a large number of alarms which activate routinely. Unless someone is specifically watching the generator

Incident	Rating (MW)	Foreign material	Area of ingress	Monitoring response	Component damage	Critical failure factor(s)
One	600	Bolt	Air gap	Vibration	rotor, core, bars	Inspections, FME weakness
Two	600	Balance weight	Air gap	Vibration	rotor, core, bars	Quality standards
Three	350	Rags	Stator bar	None	bar	Monitoring equipment, FME weakness
Four	600	Tool	Stator overhang	None	overhang bars	Monitoring equipment, FME weakness
Five	600	Copper oxide	Stator bar	Off line	bars, CRR	Monitoring equipment , Operating standards
Six	600	Balance weight	Air gap	Off line	rotor , core	Monitoring equipment, Quality standards
Seven	900	Bolt	Stator overhang	GCM	rotor, core, bars, CRR	Monitoring equipment, FME weakness
Eight	900	Nut	Air gap	Unknown	core	FME weakness
Nine	800	Washer	Air gap	Unknown	core	FME weakness
Ten	900	Spanner	Stator Overhang	Unknown	overhang bars	FME weakness
Eleven	Unknown	Washer	Rotor overhang	Unknown	unknown	FME weakness

Table 4-1: Incident failure summary

monitoring, it appears to be unlikely that developing problems will be detected in time. There are usually a few signs that are exhibited, but little that can be quantified to indicate that FM is present in the generator. It could also be seen that some of the condition monitoring equipment was unable to validate any fault conditions. In incidents three, five and six, critical condition monitoring equipment was offline or defective when a fault occurred.

If these critical systems were online the results obtained from them would most likely have gone a long way towards furthering the understanding of a machine's response to FM. Incident seven shows that properly connected condition monitoring equipment is also vital to its successful operation. The only condition monitoring equipment that has shown some promise in the detection of FM is the GCM.

FM can cause damage to most of the major components when left in the generator. Of major concern would be the CRRs as mentioned in incidents five and seven. Failure to the CRRs could result in complete devastation to the machine as well as possible loss of life. The consequences of failure are far reaching and can affect other linked systems at a power station.

The major factor that led to the majority of these incidents was FME failure. Eight out of the eleven incidents were a direct result of weaknesses in FME programs. This amounts to 73% of the failures discussed. Incident one is a good example of taking all the right precautions but still not achieving the required human behaviour. These incidents could have been avoided with better FME procedures and standards or more skilled and knowledgeable personnel.

Poor quality standards and procedures have also resulted in major damage (incidents two and six). The inadequate locking of the balance weights should have been detected by quality control and inspection, and the locking procedure improved upon.

Operational regimes can also lead to FM ingress. Incident five is of particular significance as it illustrates that FM may not be as a result of personnel leaving something in the generator. It can be caused by operational deficiencies as well, and can be an inherent weakness built into the design of a generator. This incident could have been avoided if the condition monitoring equipment was operational and if the personnel followed effective operating procedures and standards.

The effects that FM has on a generator are complex. The avenues through which FM can enter a generator are countless, but every effort should be made to prevent FMI. No unit is immune to this problem, and it only takes one lapse in FME practices to cause a major failure.

4.5. Conclusion

A wide range of generating units was affected by FM ingress. The results are not limited to failure of and damage to the generator. The effects can be felt on a larger scale where a country's economy, that is dependent on a reliable supply of energy, is plunged into uncertainty when the power trips. Markets fall, businesses suffer and jobs are lost. A situation like this can spiral out of control very quickly.

The power crisis being experienced in South Africa at present was brought to the forefront during the Koeberg incident in 2005. It was estimated that this incident alone which led to power outages in the Western Cape cost businesses R500 million (The Star, 2006). The shortage of capacity led to most mines in the country shutting down for five days. South Africa being the largest producer of platinum in the world which, along with gold are the nations biggest export earners, could not cope with the loss of power (Lourens, 2009). This led to reduced output and high losses which eventually led to job losses. The mining industry was not the only industry affected. Steel and other smelting industries were forced to stop production (Faurie, 2008). All new construction projects in the country were halted. Town house complexes, petrol stations, factories and all other projects that required electricity provisions that had to be obtained from Eskom were delayed (Styan, 2008). Job creation was stifled and this made the unemployment situation in the country worse.

South Africa being the largest economy in Africa was hit by a severe economic downturn where many market analysts began to fear a recession due to the power crisis. Economists feared that the energy crisis will stunt growth in the country sufficiently enough to prevent government from attaining its goal of a 6% growth rate from 2010 onwards. In 2007 South Africa was ranked eighteenth in the Foreign Direct Investment Confidence Index. A prolonged energy crisis could cause a significant drop in investor confidence and a drop in ranking (Hill, 2008).

The social impact of job losses is yet to be realised and Eskoms' increase in energy tariffs will affect the entire country especially the poor, who are in desperate need of essential services. A holistic view of the consequences of such a crisis is hard to predict. Only time will reveal what effects the power crisis will have on the social and economic sectors in our country.

Thus the importance of good FME practices cannot be overstated. Working with good quality plans, well-trained personnel and operational guidelines can contribute to a healthy and FM-free Generator. Maintaining condition monitoring equipment and making sure systems are operational, as well as ensuring operators are trained in the correct response procedures, can mean the difference between total failure and minor damage.

Types of FM and methods of ingress were found to be various. Understanding of the effects of FM on a generator and the limitations of condition monitoring equipment in detecting these effects was gained in this chapter. Correct use of condition monitoring equipment can however, minimise the consequential damage to a generator, and this will be studied in more detail in the next chapter where the GCM will be evaluated for this purpose.

Chapter 5

Generator Condition/Core Monitor

5.1. Introduction

The Generator Condition Monitor (GCM) also known as the Core Monitor was identified in the previous chapter as a possible condition monitoring tool that could aid in detecting FM in a generator and minimising the consequential damage. In this chapter the GCM will be assessed for its suitability for this purpose.

5.2. Background

In the mid 1960s, an Ion Chamber Detector (ICD) was invented by General Electric (GE). Its purpose was to detect particulates produced by the thermal decomposition of organic materials. An application for the ICD was found when it was incorporated into the first Core Monitor (CM). This prototype was originally designed to respond to core overheating caused by circulating currents between laminations.

The Core Monitor proved itself early on during testing, when it flagged an alarm for overheating on the generator it was installed on. The operators chose to ignore the alarm as the CM was still a prototype. The generator failed in service a short while thereafter due to severe core overheating.

GE then offered the Core Monitor as part of their supervisory equipment for the condition monitoring of turbine generators. A licensing agreement was later signed with Environment One Corporation to manufacture and sell the equipment as well. The instrument is referred to as the Generator Condition Monitor (GCM) by Environment One Corporation and the same terminology will be followed throughout this chapter (Maughan, 2007).

Figure 5-1: The GCM by Environment One Corporation

5.3. Operation

The main components of the GCM are an Ion Chamber Detector, electrometer alarm circuit, recorder, differential pressure gauge and a filter. All of these are contained in an explosion-proof housing. Figure 5-2 shows a schematic of the GCM's construction.

The ionisation chamber possesses a weak alpha radiation source arranged to generate an ion current flow across a stream of hydrogen. The hydrogen flow is facilitated by the main generator fan differential pressure.

As the sample hydrogen enters the mixing chamber, it is bombarded by alpha particles from thorium-232 contained in a mantle, which lines the outside of the mixing chamber. The bombardment produces ion pairs of hydrogen, some of which recombine, and some of which enter the electrode chamber, where the negative ions are attracted to the outer electrode. An ion collector measures the current produced by the ions attracted to the outer electrode. The measured current is amplified by the electrometer and indicated by the recorder, (Skala, 1966).

When submicron particles of the type produced by the thermal decomposition of organic material are present in the gas stream, they pick up ions upon colliding with them and carry them past the outer electrode. The current flow is reduced at a rate proportional to the

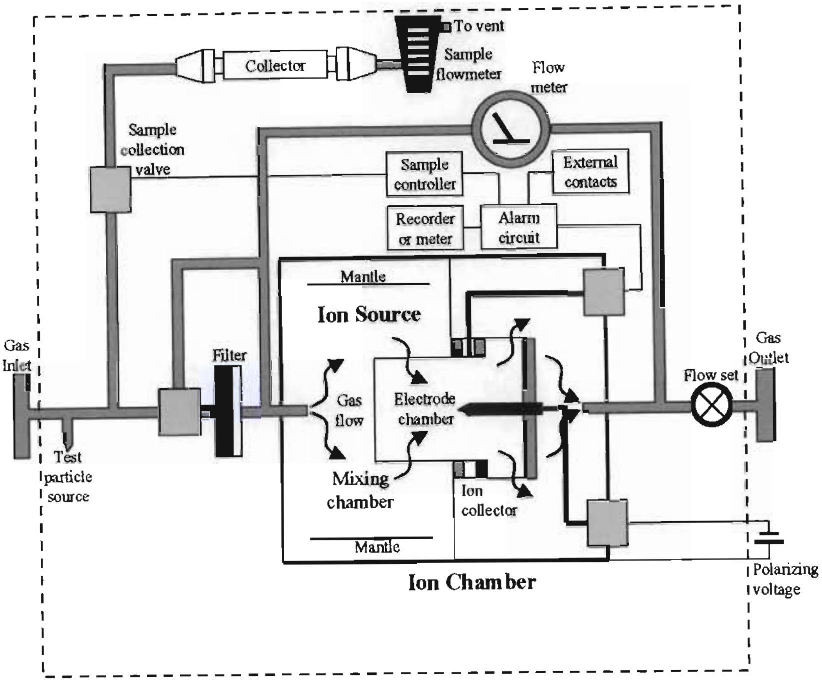


Figure 5-2: Schematic diagram of GCM (Kawahata, Kilmartin, & Skala, 1991)

concentration of the submicron particles. The reduction in current is a measure of the extent of the overheating. This output current is continually recorded and actuates an alarm system when it drops below a specified value, (Barton, Carson, & Echeverria, 1975; Barton, Carson, Gill, Ligan, & Webb, 1981).

GCMs automatically take samples of the hydrogen on receipt of a confirmed overheating alarm. Once the current measured by the ion collector decreases below a certain pre-set point, the sample collection valve opens, gas is diverted through the sampler and a sample is collected. The sampled pyrolysis products are then removed to allow sample analysis in a laboratory. The sample is analyzed using a gas chromatograph/mass spectrometer to determine the source of overheating.

The alarm can be verified by an automatic alarm verification circuit. When activated, all the hydrogen passes through the filter/solenoid valve assembly. The filter removes all the submicron particles within the hydrogen. If the alarm is valid and thermally produced particles are still present, the ion chamber detector current will return to its normal level. The gas then bypasses the filter, and if the output current drops to below alarm level a second

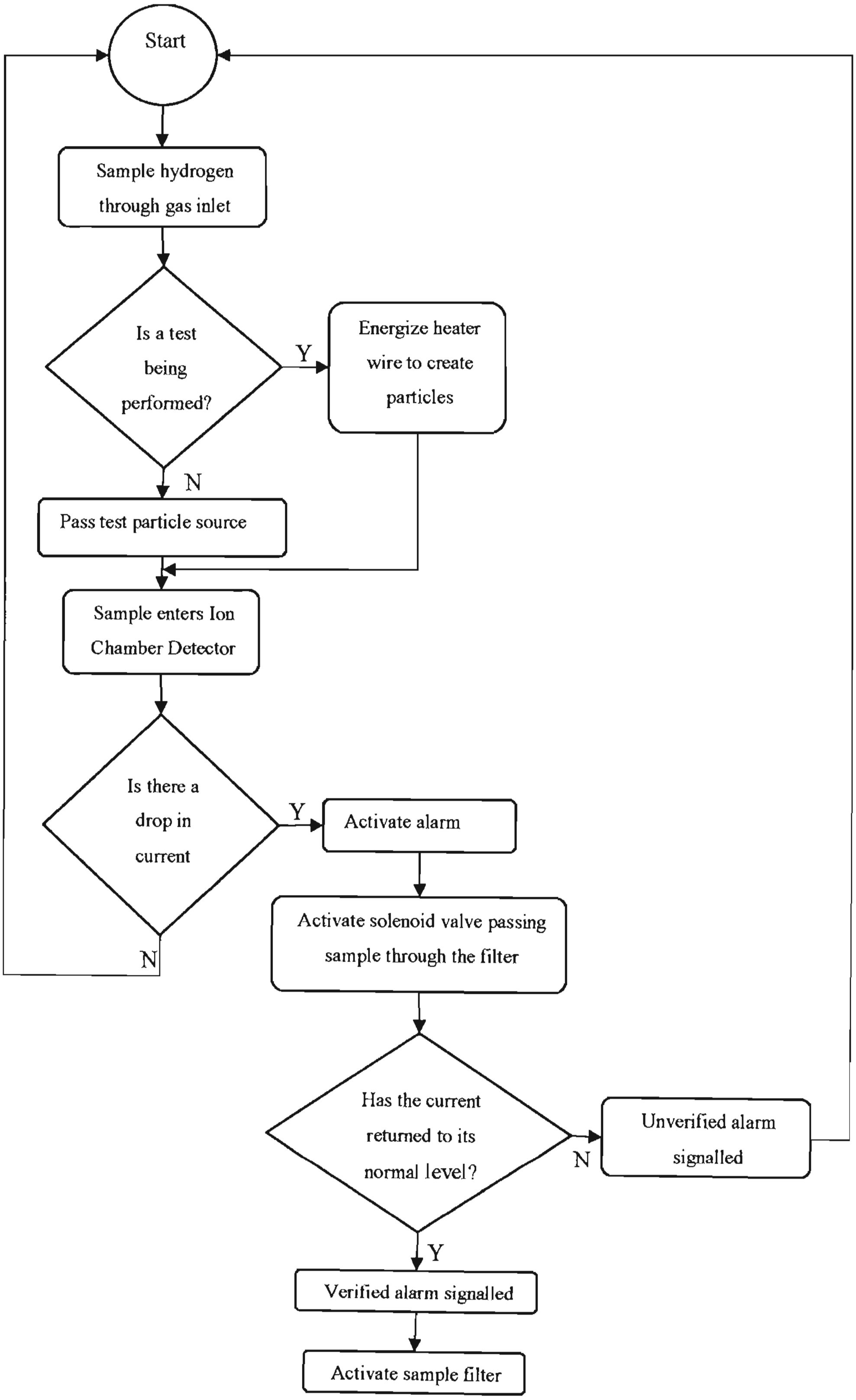


Figure 5-3: Flow chart of GCM operation

time, the presence of pyrolytic particles and the existence of overheating in the generator is confirmed, and a verified alarm flag is raised, (Skala, 1986). Refer to Figure 5-3 for a flow chart representation of the logic operation of the GCM.

5.4. Use of the GCM to detect FM

Insulation materials begin to break down chemically when they have reached their thermal particulation point (TPP). This gives rise to an increase in concentration of small particles within the generator. When FM is present in the generator, it almost always creates overheating, whether within itself, or as a result of damage inflicted to generator components. The ability of the GCM to quickly detect overheating will aid in minimising the consequential damage caused by FM.

Insulation systems used in modern turbo generators consist of either organic polymers or synthetic epoxy resins. Mechanical strength or improved electrical properties are achieved by the use of glass fibre or mica. Laboratory testing (Wallis & Kilmartin, 2003) has shown that different materials in the generator begin to particulate at different temperatures (refer to Table 5-1). The testing done during simulated operation conditions and materials used, were cut into 2cm square test pieces.

Sample	Sample Material	TPP Temperature (°C)
1	Core Plate	195
2	End ring insulation	218
3	Nomex	205
4	Epoxy glass	211
5	Coated epoxy glass	274
6	Mica insulation tape	215
7	Formed epoxy glass	195
8	Epoxy coated resistor	242
9	SAE 10 oil	190

Table 5-1: Thermal particulation point of generator materials (Wallis & Kilmartin, 2003)

The temperatures for the onset of particulation for different materials ranged from 190°C to 274°C. In practical testing, the GCM was found to be sensitive enough to detect particulation of an area as small as $10cm^2$ within a minute, (Kawahata et al, 1991).

From Chapter Four it was seen that FM can cause temperature rises within the generator up to hundreds of degrees Celsius. FM was also seen to affect numerous parts of the generator (Table 4-1) that are composed of different materials as listed in Table 4-1. In all the known incidents, common occurrence was that either the core or stator bars, (or both), were damaged as a result of overheating. If the GCM is unable to detect the overheating of the FM itself (depending on its composition) it will however still be able to detect the consequential effects of the FM.

Now that it has been established that the GCM can be an effective tool to quickly detect overheating, one problem still remains. If a GCM alarm is flagged and the generator is shut down, how does one find the area of damage and execute an appropriate repair if necessary? If action was taken swiftly enough, the damage will not be as graphic or widespread as the incidents described in Chapter Three. This could become a challenging process as there are literally kilometres of winding inside the machine, and many areas which are difficult to access without significant disassembly of the generator, (Barton et al., 1981).

The manufacturers have provided a solution, in the form of a sacrificial tagging compound known as 'Gen Tags'. The function of the compound is to produce pyrolysate particulates in a chemically and thermally stable manner, each of which is uniquely identifiable by gas chromatography. Six unique tagging compounds exist, which allow six critical areas inside the generator to be individually tagged (please refer to Table 4-2). The Gen Tag is designed to release particles at a temperature that is higher than expected during normal operation but lower than one that would cause damage to the machine. This also makes the compound suitable to aid in the early detection of overheating.

Gen Tag Compound	Colour	Applied Area
N-Dodecyl Imide	Sudan Yellow	Exciter end overhang
Cyclo-Dodecyl Imide	Sudan Orange	Turbine end overhang
Cyclo-Octyl Imide	Sudan Irisol	Core internal diameter
Dihexyl Amic Acid	Iron Blue	Rotor body surface
Adamantyl Imide	Green	Bushings and lower leads
Cyclo-Heptyl Imide	Sudan Blue	Transformers and reactors

Table 5-2: Gen Tags and applied area (Kawahata et al, 1991)

As the area painted with Gen Tags increases in temperature, particulates are released into the gas stream. These particulates are 'sensed' by the GCM which raises an alarm and takes a sample. Chemical analysis of the sample will uniquely identify the Gen Tag and identify the area of overheating.

5.5. Inherent limitations of the GCM

The GCM does have some limitations that can affect its performance. Knowledge of these limitations and the possible mitigation thereof will aid in diagnosing alarms and taking the appropriate action.

Decompositions may not always be detectable by the GCM. There are two reasons for this occurrence. The first is that heat build up can be so slow that an appreciable number of particulates may not be emitted, and that particulates that are generated, settle within the generator and do not reach critical concentration in the gas stream, thus being undetectable. There is no practical solution to this phenomenon. Secondly, due to the properties of certain insulation systems used in the generator, decomposition may not occur at typical temperatures, even under the worst conditions. While insulation systems with better integrity are desired, it does reduce the ability of the GCM to detect heat build up. This can be easily mitigated by the use of Gen Tags that decompose at lower temperatures.

It has been found that oil mist within the cooling gas can cause a decrease in the current flow in the ionisation chamber and hence an erroneous overheating signal, resulting in a false alarm. However, this event will not result in a verified alarm being produced as a result of the functionality of the verification procedure. Certain manufactures have overcome this problem by the introduction of oil vapour traps and heating of the ionisation chamber, (Carson, Barton, & Gill, 1978). This method has been found to decrease the sensitivity of the instrument slightly, (Braun & Brown, 1990).

The ability to conduct an analysis of the sampling done by the GCM is not possessed in South Africa at present. This does limit the effectiveness of the GCM locally, although it will still generate a verified alarm if operated correctly. Thus the generator can still be shut down sufficiently early; it is just that the analysis of where the overheating occurred may be delayed.

Care should be taken when commissioning the GCM, as it does rely on a constant gas flow rate. If the flow is decreased because of a blockage, clogging or incorrect installation, this will result in false alarms.

5.6. Reaction philosophy

Any overheating within the generator must be seen as a concern that could prove to be dangerous and should be acted upon. Greater than 80% current output from the GCM's ICD is seen as a normal or ideal operating condition. In order to avoid false alarms, no action should be taken until the GCM output falls below 50% and a verification alarm is confirmed, (Wallis & Kilmartin, 2003).

Once the alarm is confirmed, action should be taken to reduce the overheating and consequential damage. The area of overheating will not be known, so corrective action must encompass all possibilities. A developed fault can accelerate towards failure at an alarming rate. Environment One Corporation recommends tripping the generator if the GCM output is below 20%.

A reduction in load is generally the safest course of action for most events. The load reduction should be done in steps until the GCM recovers fully. This will lead to a reduction in stator current, core flux and rotor current and voltage. This will slow down any developing fault, to a pace where analysis may be carried out. If the GCM is still in an alarm condition at no load, the generator must be tripped immediately.

Concurrently, all other condition monitoring equipment must be monitored such as thermocouples and vibration sensors, and measurements such as, stator and rotor parameters for any anomalies. This information taken in conjunction with the GCM output can assist in the decision to trip the generator or not. It may also assist in localising the source of the overheating. Please refer to Appendix C for details on generator monitoring.

5.7. FME overview

FME is not just dependent on one factor to eliminate the risks associated with FMI. A robust FME procedure in conjunction with effective condition monitoring techniques can mitigate this risk. Table 5-3 is a summary of all aspects that will create a solid foundation for FME. The table lists all the factors that are pertinent to FME, and classifies them into procedural and condition based factors, which is denoted by an "X" in the appropriate column.

The majority of the factors listed are procedural, and this highlights the importance of having a good FME procedure. If the procedure does fail, the condition based FME factors will aid in detecting and minimising the consequent damage.

FME Factor	Procedural	Condition Based
Management support	X	
Ownership	X	
Training	X	
Human Performance	X	
Work Planning	X	
Establishing Boundaries	X	
Cleanliness of work area and housekeeping	X	
Unattended openings	X	
Staging tools and materials	X	
Securing tools and materials	X	
Ensure chemicals comply to control program	X	
Control of trash	X	
Securing of personal items	X	
Use of transparent materials	X	

FME Factor	Procedural	Condition Based
Awareness of introducing FM into other areas	X	
Protection of adjacent equipment	X	
Anticipate results and actions	X	
Control of airborne FM	X	
Wire wheels and brushes	X	
Control of welding rods	X	
Control of waste material	X	
Cleanliness of electrical cabinets	X	
Control of documents	X	
Accounting for material and tools	X	
Devices and tools	X	
Observation of work	X	
Tracking and trending of FME weakness	X	
Continuous improvement	X	
Loss of FME controls	X	
The GCM		X
Thermocouples		X
Vibration monitoring		X
Generator Parameters		X

Table 5-3: FME overview matrix

However instituting all these measures requires immense resources and time. Once the procedure has been drafted and accepted by all the role players, numerous other associated procedures being utilised will have to be revisited. Procedures that do not comply will have to be revised, resulting in another lengthy exercise. The infrastructure required for implementing the procedure will then have to be created. Personnel will have to be trained in accordance to the new procedures and be expected to change the manner in which they perform their duties. This sudden change could have an adverse effect on their performance. The new working structure may decrease worker morale. Contract personnel will have to be specially trained before they can be allowed on site.

All the new procedures will add more lead time to outages where the processes being followed will be more rigorous and time consuming than previously experienced. What would have taken one working shift to complete, may become a two-shift operation. This will escalate the generation losses experienced. This may be a difficult pill to swallow for utilities that rely on quick outages, minimum downtime and minimum losses.

Management support is critical in implementing the above structure. The procedural changes being introduced, although detailed and complex, should be conveyed in a positive and progressive manner. This will ensure that the new skills being taught will be received openly and executed appropriately.

The basis of a good FME program is robust procedures. Even though these procedures may require immense resources and time, they are essential for the protection of the generator. While the utility may lose revenue due to artificially extended outages, it pales in comparison to the loss of a generator worth hundreds of millions due to an FMI incident.

The condition-based solutions to FME can be quite expensive to install and maintain. Many utilities may not be in a position to install all these different types of monitoring equipment on every generating unit and may opt for the bare necessities to save costs.

The expertise required to analyse and interpret the condition monitoring outputs takes experience and time. The GCM may be a reliable tool but only to a person who is familiar with its operation and use. The same would apply to other condition-based equipment. The cost saving aspect of the GCM, is that a utility can purchase just one unit and use it on a rotational basis whenever a generator is being commissioned.

Once a utility has realised the benefits of a good FME program, the desired human behaviour can be achieved more easily.

5.8. Conclusion

The GCM has come a long way in its evolution and capabilities from the 1960s. Initially seen as an unreliable instrument that was riddled with false alarms, the modern GCM is an exceptionally sensitive device that has reached a high state of reliability.

Its ability to detect thermal decomposition promptly, coupled with the added advantage of using Gen Tags, makes the GCM ideally suited for the detection of FM, FM effects, and minimising subsequent damage. It may have limitations, but proves to be a better suited device for the proposed purpose of detecting FM (or minimising its consequences) than other monitoring techniques.

If set-up and used correctly, the GCM can mean the difference between a short outage to address minor repairs, and a major outage taking several months and costing millions.

It was also noted that a combination of good FME practices/procedures and condition-based monitoring can be effective in reducing FMI and consequent damage.

Chapter 6

Conclusion

6.1. Introduction

In this study, a variety of subjects related to FME on hydrogen/water cooled large turbogenerators were investigated. The study succeeded in investigating the influence of FM on large turbo generators and providing a solution to the problem. It was clearly shown that the effects of FM are catastrophic. The failures associated with FMI are often unspoken in the industry, and it is a sensitive area. This coupled with a lack of classic literature on the subject, made investigating the phenomena difficult.

The theoretical overview of the generator in Chapter 2 showed that by design it is susceptible to FM ingress. The electrical and mechanical effects of FM were discussed. FME best-practices by EPRI and INPO were evaluated, and in a benchmarking exercise it was found that major role players in the industry do not follow adequate FME practices. All the experts interviewed highlighted the importance of good FME practices.

The focus then shifted to industrial FME incidents, where it was seen that the effects of FMI are widespread and no generator is immune to such failures. Table 3-1 summarised all the major aspects of the incidents investigated. The factors that led to these failures varied. The effects of FMI on the condition monitoring equipment were also evaluated.

The GCM, together with other condition monitoring equipment when applied correctly, can minimise the effects of FMI. The reaction philosophy to the condition monitoring equipment was also discussed.

6.2. Solving the FME problem

The FME problem can be solved by applying the correct practices and utilising condition-based equipment effectively. All role players in the industry should align themselves to industrial best-practices, as highlighted by INPO and EPRI. This should culminate in the development of a robust FME procedure that will be enforced at all times. Implementing such a procedure throughout an organisation is challenging, and the resources required are vast. Every effort should be made to streamline these procedures and create efficiency as they will lead to further time losses during outages when implemented.

From a certain perspective, the FME problem is a human one. If the personnel involved with the maintenance and commissioning of these large generators are not adequately trained, or do not possess the proper human behaviour, a failure is bound to occur. Personnel should be made aware of the risks associated with FMI, as they can acquire a greater understanding and better relate to the problem. Skill levels in the industry are also of a major concern. An unskilled worker may bypass many FME practices as a result of ignorance of the consequences.

Making sure that condition monitoring equipment is commissioned correctly and is in a good working condition is also crucial. The personnel monitoring this equipment must have the expertise to interpret and react appropriately to a fault condition. Furthermore, they must be confident that the equipment is working correctly and that the data being logged is trustworthy. In many of the incidents that were discussed, the condition monitoring equipment was faulty or offline.

The effects of an FMI incident are far-reaching, and do not just impact the utility. The Koeberg incident in South Africa highlighted the economic and social consequences of such a failure. By utilising all the factors in Table 4-3 effectively, the FME problem can be solved, or at least the consequences minimised.

6.3. Future work

The investigation into FME must be seen as the beginning of further research in the field. One of the major outcomes of the study was that certain condition-monitoring equipment (when offline, or if improperly connected, or dysfunctional) was that it was therefore unable to be proved, as it was not operational, or the operators were not sure of how to react. Further monitoring and testing should be done on vibration sensors, temperature sensors and generator parameters.

The use of other condition-based tools should also be investigated. Electro Magnetic Interference (EMI) signatures could be yet another possible way of more precisely detecting foreign objects. The use of radio frequency noise measurements provides a large spectrum of coverage on the generator. FM within the generator can generate partial discharge (PD). This PD can be seen at the resonant frequency of the area surrounding the object. EMI is a frequency domain analysis of discharges, and as such the frequency where the PD can be seen, indicates the location of the PD event. This technique has been widely used by Doble Industries a lead player in the industry and can be adapted for use to minimise FMI. There have already been a few reports of how EMI was successfully used by Doble Industries to detect FM in a generator.

The human factor of skills within the workforce and how they contribute to FMI is also an area to be investigated. In South Africa and worldwide, the lack of skilled people working on generators is alarming, and the situation is getting worse as more and more skilled people reach retirement age and are lost to the industry.

Appendix A

Doppler Testing

The Doppler Test is designed to detect restrictions in the stator water cooling system. It is carried out on each of the Polytetrafluoroethylene (PTFE) hoses connecting the cooling water manifold to the stator winding, preferably on the outlet side of the bar.

The test works on the Doppler principle. Two probes are used, one an ultrasound transmitter, and one a receiver. The probes are placed on either side of the PTFE hose, with a transmitting gel to improve the contact. An ultrasonic beam is generated at a specific frequency, and passes through the PTFE hose and the water. Depending on the speed of the water flow, it is Doppler shifted, and that frequency is detected by the receiver. The electronics compares the transmitted and received signals, and calculates the speed of the water. As the inside diameter of the pipe is known, the flow rate of the water can then be calculated.

There are no set acceptance criteria, only comparative data. Once the test is complete, the mean is calculated, and ±10% is then considered acceptable for an individual PTFE pipe. Comparison to previous test results is also useful.

Appendix B

Stator Water Chemistry

One of the most important functions of the Stator Cooling Water System is to maintain the electrical conductivity of the stator cooling water within a specific range. A de-ionising system is used to keep the conductivity low. A high conductivity can result in electrical tracking to ground. Two major components affect water chemistry, oxygen content and pH.

The optimum target value of pH to achieve low conductivity is 8.5. Low oxygen systems can lead to the formation of cuprous oxide. A build up of cuprous oxide will lead to plugging of the stator hollow conductors. On the other hand, a high oxygen system promotes the formation of cupric oxide which forms a protective layer around the hollow conductor surface, which is favoured.

Depending on the OEM of the generator, two major operating regimes can be followed: low oxygen/elevated pH or high oxygen/elevated pH system. A low corrosion and low conductive system is guaranteed if the regimes are operated within the OEM specified parameters (Gonzalez, 1995; Klempner & Kerszenbaum, 2004).

Appendix C

Generator Monitoring

Temperature Monitoring:

This is the most common technique of on-line monitoring; the extent of temperature monitoring varies according to OEM and machine design. Usually at least 6 bars will be monitored (with Resistance Temperature Detectors (RTDs) between bars in the slot), and 6 areas of the core. On water-cooled windings, each PTFE pipe carrying water from the bars will be monitored so that each bar temperature is known. Note that any variation in a bar's temperature is of concern, not just when it reaches alarm value. Inlet and outlet air/gas/water temperatures are also often monitored.

Endwinding Vibration Monitoring:

Fiber-optic accelerometers can be mounted directly on the winding to give an accurate measurement of vibrations experienced during operation.

Partial Discharge Monitoring:

Either capacitive couplers, or slot couplers can be fitted to the generator. These are essentially local antennae to directly detect PD activity on a bar. The capacitive couplers are designed to block the power frequency, usually 50Hz, and to pass the high frequency signals resulting from partial discharge activity in a winding. Specialised software counts the number of pulses received and their magnitude, to give an idea of the severity of the discharge activity within the winding. Increasing trends can indicate that a machine is about to fail, and so plans can be made to prepare for a rewind. Also, a stator earth fault can cause severe damage to the core, requiring a restack. This is extremely expensive and time consuming.

Shaft Current Monitor:

Shaft currents occur as a result of various magnetic imbalances within the generator. FME can cause these imbalances.

Stray Flux Probe:

The stray flux test is a simple and effective test to pick up any discontinuities in the rotor winding. It does however have the disadvantages that it can only be performed with the winding excited and the rotor spinning, and that analysis is required to determine the presence of any discontinuities.

In a round rotor, the coils are distributed in slots around the circumference of the rotor in such a way that they contribute to an effectively sinusoidal main flux wave cutting the stator coils. However, each coil, which can be seen as a 'wire' carrying current, will have its own flux pattern around it. This is called the stray or leakage flux of each coil. As corresponding coils in the A and B poles in a two-pole rotor have the same number of turns and the same current flowing through them, their ampere-turns should be the same, and hence the stray flux induced by the ampere-turns should be the same. If there are any shorted turns in a coil, the effective number of turns the current passes through is reduced, and hence the effective ampere-turns is reduced. This will induce a corresponding decrease in the stray flux level around that coil indicating a fault.

Rotor Telemetry System:

The contemporary method of determining rotor winding temperatures is to derive it from excitation current and voltage. This only gives a rough indication of the average temperature, and is unlikely to detect localized overheating. With a rotor telemetry system, RTDs can be located in every rotor slot, and the information can then be transmitted to the stationary receiver via a rotating antenna. The telemetry is digital, with a very high sampling rate, making it extremely accurate.

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