

GENERATOR PLANT CONDITION ASSESSMENT AT DUVHA POWER STATION

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Declaration

I, Kamal Khandoo Dayah Makan declare that this research report is my own, unaided work. It is submitted in partial fulfilment of the requirements for the degree of Master of Science in Engineering, at the University of the Witwatersrand. It has not been submitted before for any degrees or examinations in this or any other university.



Kamal Khandoo Dayah Makan
29 August 2010

Confidentiality

Due to the sensitivity and nature of the information content included in this report and the use of ALSTOM's proprietary plant assessment tool, this report may not be made available to the public for a period of at least 5 (five) years.

Abstract

An overall plant condition assessment that included a plant integrity assessment and maintenance review has been conducted on Duvha Power Station Units 1 to 6 Generators. Plant process parameters revealed instrumentation errors and discrepancies between plant gauges and the operator's mimic across all units. Various parameters were also found not to be correctly set to design specifications. The plant integrity assessment supported by input streams from monitored, inspection and feature findings are then combined to develop an assessment of the unit's sub-components condition which are then summed to obtain an overall assessed condition score. A criticality review then develops the sub component analysis and assessed condition score to achieve a ranked sub component score. Unit 4 was found to have the highest overall condition and criticality assessed score. Units 1, 3, 4 and 5 outage plans are in line with the assessment recommendations. Recommendations, classified in terms of immediate, short and long term actions, are then made based on the findings.

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1. Introduction

Due to the present shortage of power that South Africa is experiencing, it was decided that an assessment of Duvha Power Station's generators be performed, to ensure safe, reliable and continuous operation of their units.

The author's contribution to the plant assessment was to conduct a plant walk down to obtain an understanding of the individual units present operational conditions when compared to their design specifications. Subsequently the author was responsible to conduct an analysis of the required input streams for process indicator, inspection condition and features for an analytical assessment tool. This tool was used to facilitate the analysis process of the author's findings in a manner that would easily allow interpretation and presentation of the results.

The output from the tool for the individual units overall assessed conditions was then developed further, by the author, by including operational risk in order to obtain a ranked criticality order for the sub-components across all six Duvha generators. Thereafter a review of Duvha Power Station's maintenance regime was conducted by the author and compared to the findings from the assessment.

This report provides the findings from the assessment of the main generator units at Duvha Power Station and has been compiled based on the following assumptions:

- The operating regime will not change and will remain as a base-load station.
- The output capacity of the main generators will not be increased.

2. Literature Review

2.1. Statistics on Generator Failures

According to a study published by VGB PowerTech in November 2005, the main failure areas on generators are stator (45%, see figure 1 for details) and rotor (45%, see figure 2 for details) [1].

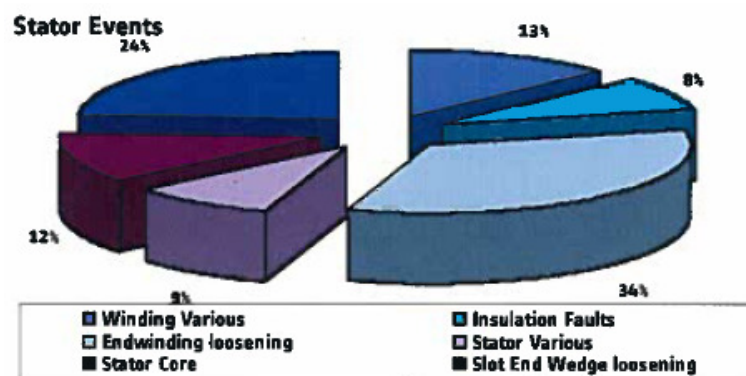


Figure 1. Generator Stator Events [1]

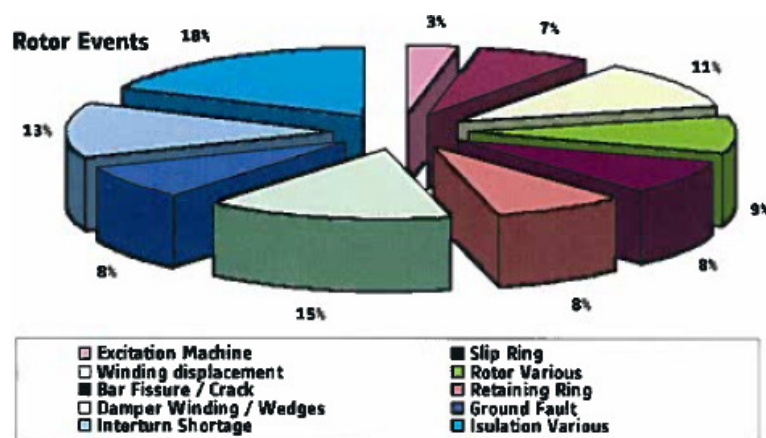


Figure 2. Generator Rotor Events [1]

Majority of the stator failures are due to deficiencies within the winding or the insulation system. One third of the rotor events are due to failures in relation to the rotor winding.

It is important to note that most of these effects can be detected by a diagnostic or monitoring system. An example of one method would be to carry out a Failure Mode Effect Criticality Analysis (FMECA), which identifies main known failure modes and evaluates probability and impact [1]. One Original Equipment Manufacturer (OEM), ALSTOM, has carried out a detailed FMECA for its generator fleet. The data from such an analysis has been used in assessing Duvha Power Station's generators; refer to section 6, Plant Integrity Assessment.

2.2. Generator Maintenance Strategies

Eskom Power Stations conduct their turbine generator maintenance on a time-based strategy. After a certain number of operating hours an inspection is scheduled. This is the traditional approach to generator maintenance. Most power stations in Europe and the United States of America have adopted a new approach to maintaining their generators. This new approach is entitled Condition Based Maintenance (CBM).

Eskom, thus far, has not been forced to adapt to such a maintenance regime, due to the fact that it is not competing against any other power producing competitors. However the increasing cost pressure in a de-regulated global energy market is forcing power stations, in such markets, to reduce their production costs for electrical energy [2]. This also increases the pressure on the power stations to reduce their maintenance and spares holding related costs. This resulted, in the past 15 years, showing significant changes in the maintenance regimes of the power stations in almost all countries [1]. All power stations would like to increase their power output and efficiency. This is not only a wish but also a vital requirement if the power stations are to increase their plant's competitive position in the market.

Three main parameters exist for power stations [1]:

- Reliability – Run the plant on highest efficiency with minimised risk of unforeseen incidents.
- Availability – Deliver contracted supply of power at all times.
- Maintainability – Conduct outages and shut downs at lowest possible cost.

The three parameters will inherently conflict with each other. One way to overcome this and to make the station competitive is to maximise knowledge about the station's past and current operational condition, as will be seen in the conclusion chapter of this report, for Duvha Power Station. Another way would be to change the station's maintenance approach, i.e. changing from Time Based Maintenance (TBM) to Condition Based Maintenance (CBM).

It is important to mention that power stations apply different maintenance methodologies depending on the type of power station and the specific operational requirements for their generators. For example, a nuclear power station with requirements of fixed outage schedules with the critical path of the outage linked to refuelling will have different maintenance requirements compared to an industrial power producer or coal-fired power station.

Reduced maintenance costs can be achieved by reducing the outage duration and/or extending the outage intervals. To fulfil these requirements without losing a high availability rate, a combination of preventive and predictive maintenance strategies is needed.

2.2.1. Preventive and Predictive Maintenance Strategy

There are two main types of periodic inspections:

- **Minor Inspection – Rotor stays in place (rotor-in-situ)**

For a minor inspection, the end covers are removed and bearings dismantled but the rotor stays in place. The inspection is limited to the accessible parts, such as brush gear, slip-rings or rotating exciter and stator end winding.

- **Major Inspection – Rotor removed**

For a major inspection the main requirement is to remove the rotor. Thereafter, end covers, bearings, brush gear and coolers are removed or dismantled to allow a comprehensive inspection to be performed.

Maintenance Strategies		Preventive		Predictive
Inspection Services		Off-line Inspections		On-line Inspections
		Minor	Major	Monitoring
1	On-line measurement before shutdown			
2	Disassembly Inspections			
3	Generator Diagnostics & Electrical Tests			
4	Reassembly inspections			
5	On-line final test			

Figure 3. Maintenance main tasks and generator status condition for Preventative and Predictive Strategy [1]

It is recommended by [1], that the 5 steps from figure 3 be covered by detailed work scopes which include:

1. On-line measurement before shutdown

Operational data checks, shaft-voltage (AC and DC), inter-turn shortage, auxiliaries system check (seal oil, gas, water, etc.).

2. Disassembly inspections

Recording of quality measurements like machine settings, shaft alignment, mechanical inspections of specified critical parts.

3. Generator diagnostic and electrical tests

Slot wedge tightness, bump test, insulation resistance, loss factor measurement, contact coefficient measurement, video endoscopic inspection, protection systems test, etc.

4. Reassembly inspections

Tightness tests, DC-high voltage tests, shaft alignment, mechanical tests.

5. On-line final tests

Check of rotor earth fault protection, auxiliaries' logic sequence, AVR test, gas consumption, etc.

2.2.2. Time-Based Maintenance vs. Condition-Based Maintenance

Time-Based Maintenance (TBM) is presently the manner in which Eskom conduct maintenance on its generators and is normally the approach described in the station's operation and maintenance manuals. Pure TBM strategy has the advantages of:

- Predictability of the actions
- Standardised packages
- Controlled scope of work

Disadvantages of TBM are situations where unforeseen incidents, findings or results appear. TBM only applies during standstill of the generator, thus no indication can be given while in operation. Even if desired, TBM inspections can not give information on-line about the current condition of the generator.

Figure 4 from [1] illustrates the differences between TBM and CBM. It makes mention of an on-line diagnostic product called AMODIS[®], which will be discussed later.

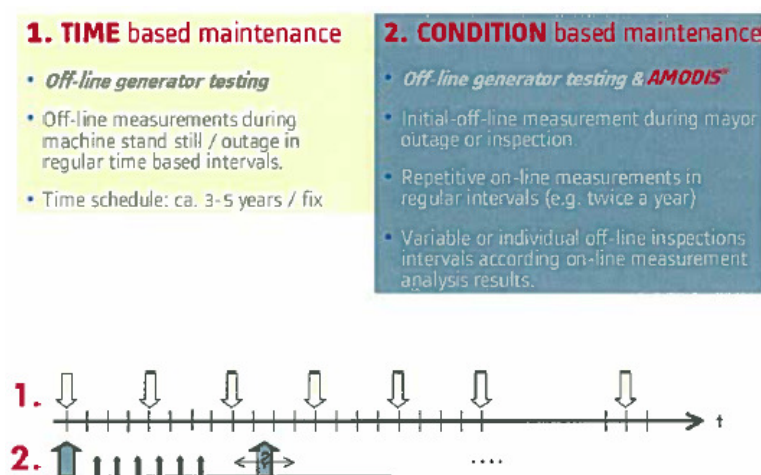


Figure 4. TBM vs. CBM [1]

Increased competition between power producers operating in a competitive market has forced them to optimise these maintenance methodologies. Presently, Eskom Power Stations do not compete with one another but this may change once independent power producers enter the market or if Eskom Power Stations are forced to compete against each other.

To benefit from the full cost saving potential of an overall plant maintenance strategy, [1] states that long-term trending together with on-line monitoring techniques should be used. In addition, use of the “three pillar concept”, see figure 5, extended outage intervals and shorter outage durations, should be implemented.

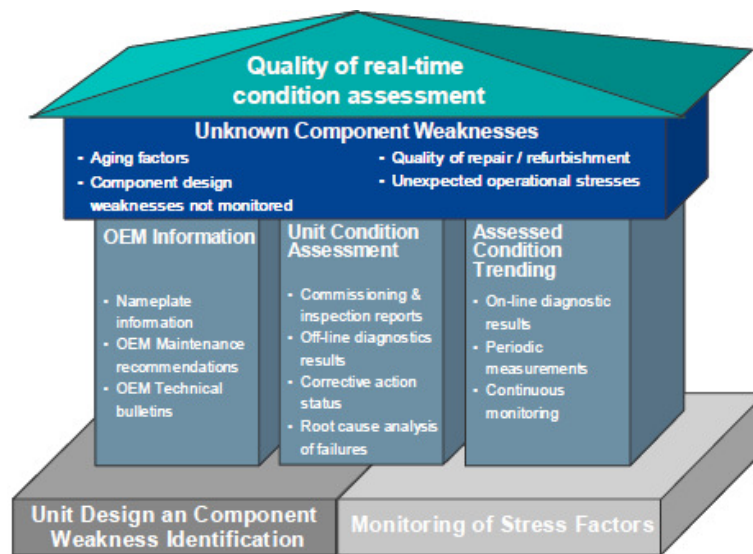


Figure 5. Quality of Real-Time Condition Assessment [1]

The application of CBM requires various basic elements according to figure 6 [3], for a reliable diagnostic decision to be made. Figure 6, gives emphasis to the knowledge infrastructure needed and to the general process of diagnostic decision making.

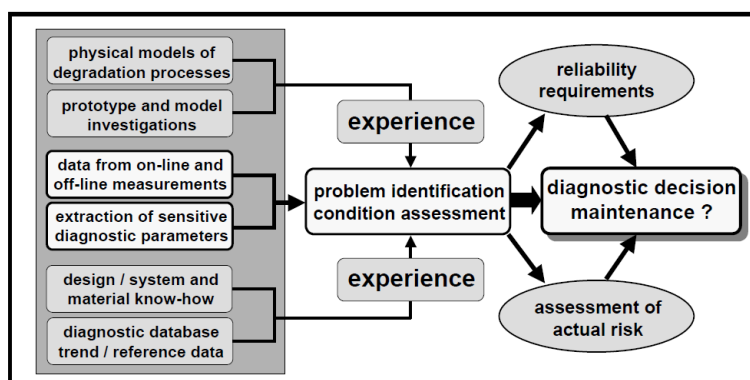


Figure 6. Knowledge infrastructure needed for a diagnostic decision making process within CBM strategies [3]

The following key elements are considered essential for a CBM process to be achieved [1]:

1. On-Line Measurement

Data retrieved from continuous monitoring providing information of the equipment condition during service.

2. Diagnostic Parameters

A set of appropriate parameters, derived from the original measured data.

3. Catalogue of Typical Failure Modes

A catalogue / database containing detailed information about specific generator failures and effects in context to it.

4. Know-How

Design, system and material knowledge for generator assessment.

5. Diagnostic Database

A large expert knowledge base reflecting decision-making processes and unit history information.

6. Decision Rules

Clear criteria's that provide an unambiguous assessment of equipment condition, based on the information available.

7. Unit Signature

The established condition of the unit for baseline so that comparison from that established condition and trending can be accomplished.

Consolidation and subsequent reviewing of data of the 7 points above, makes it clear that the application of CBM is a demanding task. The key however, is to proceed efficiently and to effectively process the huge amount of information, virtually in real time, within advanced CBM strategies.

Figure 5, illustrates a basic methodology for the quality of real-time condition assessment. It explains that known and unknown weaknesses of the generator's major components needs to be identified and the stress factors, i.e. Temperature, Electrical, Ambient conditions and Mechanical stresses, referred to as TEAM, are to be monitored.

2.3. Monitoring Systems

2.3.1. An approach by ABB to Predictive Maintenance Strategy

In a paper by T. Bertheau, M. Hoof, and T. Laird [4], common methods used by ABB for conducting partial discharge measurements, as a key tool in predictive maintenance strategies are discussed. Special attention is given to on-line monitoring and the generation of alarms. Bertheau, Hoof, et al, explains that for many years, all maintenance was done using a time-based maintenance strategy and defines time-based maintenance as after pre-defined periods of time, that are based on hours of operation and number of start/stop cycles, that an off-line inspection be performed.

The paper by Bertheau, Hoof, et al states that power stations are now employing the more cost-effective approach, that being condition-based maintenance. The paper focuses on permanent on-line partial discharge measurements as an important additional tool to enable condition-based maintenance strategies to be applied. This, according to ABB, can be achieved by efficient trending of the partial discharge behaviour. ABB developed a data storage method that provides both, an efficient Long Time Storage (LTS), without storing too much data and a Short Time Storage (STS) without compromising data quality and accuracy.

The ABB Trend-Analysis Program (within the PD monitoring system) generates a Level Alarm, when certain pre-defined warning or alarm levels are exceeded, based on the data from the STS. A Trend Alarm is generated by the PD monitoring system when a dangerous change of PD activity is detected, based on the LTS data.

If an alarm is generated, the machine does not have to be shut down immediately [4]. Usually there is enough time for a manual PD data analysis to be performed.

2.3.2. ALSTOM's Tool for Improving Generator Availability

Maintenance, according to pre-defined time intervals, is being replaced by condition based maintenance [5]. However, [5] explains that for key components like the generator, that it is not only necessary to obtain a reliable assessment of the actual state of the machine from diagnostic investigations, but also to estimate the remaining life and failure probability of the machine. Refer to the following sections:

2.3.2.1. Fundamental Concept of Lifetime Assessment

A process concept by ALSTOM, called Lifetime Assessment, which is based on experience, design and system knowledge, is described in [5]. The fundamental concept of the Lifetime Assessment is that, as a machine becomes older, the various degradation processes, and above all, their interactions, play a decisive part for the reliability and thus for the remaining life of the individual components. The idea, therefore, behind the Lifetime Assessment is to find these endangered components and to introduce specific countermeasures.

In the past, investigations and test methods were developed in the diagnostics field to determine the condition of machine components and assess their state of ageing [5]. The rapid advances made in computer and information technologies since then, now allows computer systems to utilise extensive "Data Mining" fields [5], to perform extensive diagnostic and statistical analyses.

The Lifetime Assessment combines different ageing models for the individual stress factors in order to produce the best possible model of the generator with reference to the expected remaining life. Figure 7, shows an overview of the components involved in the Lifetime Assessment concept.

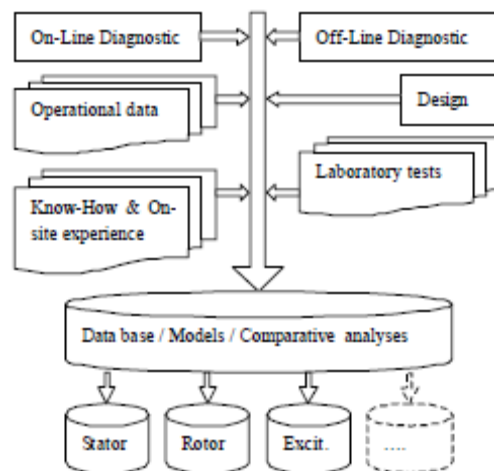


Figure 7. Schematic diagram for the Lifetime Assessment concept [5]

The aim of the Lifetime Assessment is to determine, as reliably as possible, the point when, as a result of advanced ageing, the failure probability, see figure 8, increases super-proportionally as compared to that for normal operation.

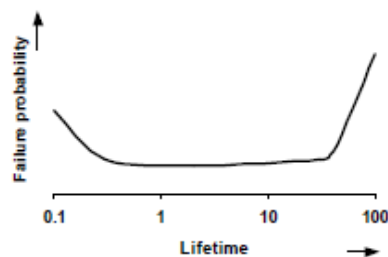


Figure 8. Development of failure probability as a function of time [5]

2.3.2.2. Examples of Lifetime Assessment

The Lifetime Assessment paper [5] includes three examples where the Lifetime Assessment on air-cooled turbo-generators was performed. The three examples are summarised next.

Example 1:

Turbo-generator: air cooled / 85MVA / 13.8kV / 60 Hz / built 1980.

An off-line inspection within the scope of the planned outage was performed and the results evaluated using the Lifetime Assessment method. Taking all boundary conditions into consideration, which needs to be entered into the Lifetime Assessment for evaluation, the stator in question was shown to have a high failure risk. It was decided to take corrective measures immediately. Figure 9, shows the compilation of the evaluation principle and a “failure curve” that is assigned to each evaluation criterion.

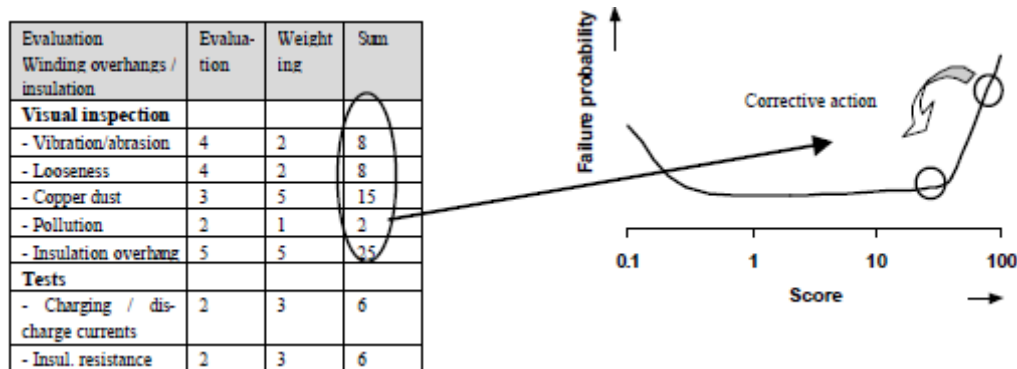


Figure 9. Example of an evaluation of the insulation condition [5]

After completing the corrective measures, the vibration level had decreased, which in-turn decreased the short-term expected failure risk [5].

Example 2:

Turbo-generator: air-cooled / 40.5MVA / 13.8kV / 60Hz / Built 1976.

The initial inspection of the machine did not reveal anything unusual but in fact, indicated that the unit was in a good and reliable condition. Even the standard visual inspection of the individual components did not reveal any deficiencies [5].

Additional Lifetime Assessment endoscopic inspections were carried out, not included in the normal diagnostic program, which detected degradation of the corona protection system. The Lifetime overall Assessment for this machine then gave the failure probability as being higher than 1%, refer to figure 10 [5].

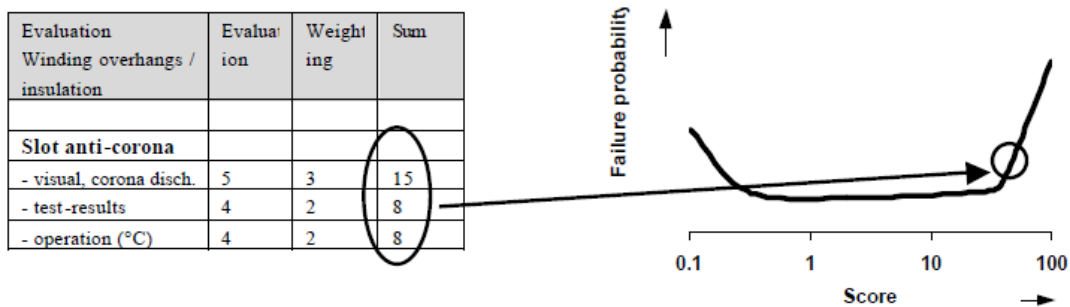


Figure 10. Example of evaluation of the slot corona protection [5]

The user was advised to have the fault, causing the high failure probability, rectified. The stator was rewound immediately and operated in a reliable condition within six months of replacing the winding.

A third example is also presented in [5]. The generator appeared to be in a healthy condition until the use of the Lifetime Assessment tool. The Lifetime Assessment tool indicated the urgent need for corrective measures because the rotor winding insulation was in a very poor condition. Immediate corrective measures were then taken by the user.

The real life examples from [5] show that the execution of a Lifetime Assessment not only can avoid unplanned operational outages of an electrical machine, but also high efficiency for further operation can be ensured by specific reinvestment. The paper [5], states that an exact time of failure determination is not yet possible, but at least there is a real possibility of estimating the reliability for further operation, especially for older power stations [5].

2.3.3. ALSTOM's WIDIPRO® & ACTS

In order to obtain a reliable assessment of the actual condition of a machine, one needs to conduct diagnostic investigations, trend the status of the machine as well as estimate the failure probability of the machine. This implies that a combination of off-line and on-line diagnostic methods is necessary for a reliable assessment of the generator condition. On-line and off-line diagnostic methods, used by ALSTOM and the process involved are discussed in [6] and summarised below:

2.3.3.1. WIDIPRO®

For off-line inspections, ALSTOM uses the WIDIPRO® (Winding Diagnostic Inspection PROgram). These are a series of non-destructive measurements, each yielding partial information on the condition of the system.

All collected data are stored in the WIDIPRO® database, including physical characteristics of the machine and unit operational data, where thousands of measurements over the last 30 years are available. This then allows the engineer today to recall similar cases from the past and to compare with. The time involved for this process is reduced to a fraction, by the application of a data mining algorithm, which avoids having to do a cost intensive manual assessment [6].

2.3.3.2. ACTS

As mentioned before, only the combination of off-line and on-line diagnosis and monitoring methods will allow the implementation of condition-based maintenance. The ALSTOM ACTS (Assessed Condition Trending System) includes all available information, which allows the engineer to assess the machine condition [6]. ACTS uses all visual inspection information, measurements taken at standstill of the machine (WIDIPRO® inspection) and on-line diagnostic from all inspected machines [6]. Figure 11 [6], shows the principle used.

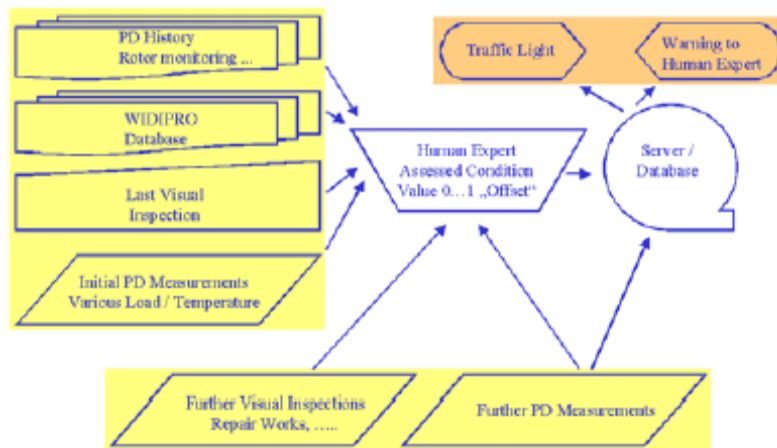


Figure 11. Concept of Assessed Condition Trending System (ACTS) [6]

The engineer is supported by a database containing all available information from off-line diagnosis and on-line measurements. The algorithms allow automatic sorting of the data and finding similar cases for aiding the engineer.

2.3.4. ALSTOM's AMODIS®

An important way to gain diagnostic information is through continuous monitoring of the machine during operation. For this reason ALSTOM developed AMODIS®, (ALSTOM Monitoring and Diagnostic System). This is a PC-based plant monitoring and diagnostic system. It consists of a wide range of modules that cover all major parts of the power station such as boiler, gas turbine, steam turbine generator and transformer, see figure 12 [7].

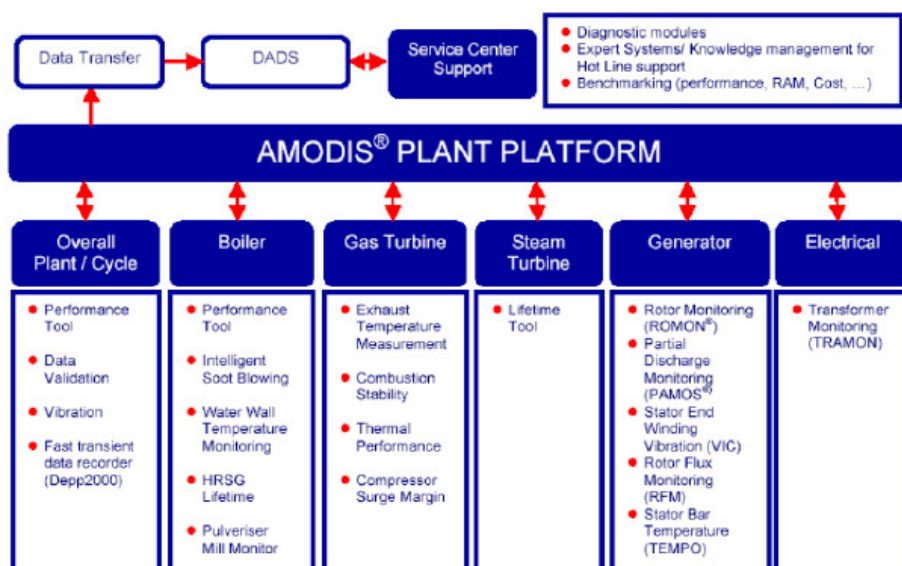


Figure 12. AMODIS® Plant Monitoring System [7]

Each module can be installed independently or in combination with any of the other modules. The modules are interconnected by an Ethernet Network and send their data to a platform computer where a software package is installed for long-time trending and display purposes [7].

The following cases explain the use of AMODIS® to identify and prevent failures [7]:

2.3.4.1. AMODIS®: Rotor Condition Monitoring

In 2004, a turbo-generator in East Asia experienced intermittent sudden steps in the measured vibration values at the generator bearings. An AMODIS® system with a ROMON-II module was connected to observe and trend the shaft voltage. On analysis of the data it was seen that the 6th harmonic drops from 3V to very low values, 200mV and jumps back after 3 days to 3V and the cycle repeats itself. The OEM experts identified this to be caused by a short circuit in the rotor windings. An inspection of the rotor windings with a boroscope showed debris and dirt in the end winding. This dirt and debris was carefully cleaned away. The machine was re-started and the high level of the 6th harmonic did not appear.

2.3.4.2. AMODIS®: Stator Condition Monitoring

A on-line partial discharge (PD) measurement using AMODIS® and module PAMOS showed unusually high PD readings, approximately 10 times higher than previous measurements taken by the customer [1]. According to the OEM expert analysis of the AMODIS® PD data, the origin of the PD was some kind of sparking in the end-winding caused by moisture or surface contamination. Analysis of the cooling gas was performed and a visual inspection of the end winding during an outage was done. The gas analysis showed high moisture content within the cooling gas caused by a defective dryer. The dryer was replaced and the machine restarted. A subsequent on-line PD measurement showed normal behaviour.

2.3.5. GE's Root-Cause Diagnostics

A paper by an ex-General Electric generator specialist, now president of Maughan Engineering Consultants [8], discusses the importance of having state of the art monitoring equipment in good operating condition and list 5 examples where the root cause of failure was mis-diagnosed resulting in major expenditures for incorrect or insufficient repairs. The paper summarises the condition monitoring challenge for the generator owners as follows:

- 1) Be certain that the generator monitoring equipment is state-of-the art and kept in good operating condition.
- 2) Record and retain monitoring equipment information.
- 3) Use ones' own good judgment to assure that the diagnostics information from on-site appears plausible.
- 4) Bring in additional support *early* in the event the diagnostic information is suspicious.

Mis-diagnosis of the root cause of generator failures can be exceptionally costly. The five diagnostic errors observed are listed below. The direct repair cost associated with these listed incidents ranged from a few hundred thousand to many millions of dollars [8]:

- 1) Ring of fire stator winding failure on a 900MW water-cooled winding was incorrectly blamed to the piping arrangement. Had the correct error not been identified by further consultation, then a repeat of the massive stator winding failure would have been inevitable.
- 2) Stator winding failure on a 200MW stator incorrectly attributed to "lightning". Corrective action was based on the mis-diagnostics. The unit failed again several months later at the same location for the same cause – partial discharge.
- 3) On a 250MW generator, contamination of a core end packing was judged to be from minor stator bar vibration and no corrective action was taken. The root problem was core looseness and the winding failed to ground a few weeks thereafter.

- 4) Core discolouration over-looked at location of stator winding failure. The 80MW stator was rewound without correcting the core-iron condition. New replacement winding failed in service shortly after return to service.
- 5) Asphalt stator winding incorrectly diagnosed as having rapid migration of the ground-wall. Recommendation was to perform an immediate stator rewind on the 200 MW machine to avoid catastrophic service failure. In fact migration had long-since ceased and the stator was completely serviceable without any repair required.

2.3.6. GE's Generator Maintenance/Assessment Approach

A paper by Maughan entitled, 'Inspection/Test Impact on Maintenance of Generators' [9], re-emphasises that during the last 20 years, there has been increasing pressure within the power generation industry to extend operating periods between inspection/maintenance outages. The paper also acknowledges that an important approach to outage extension has been that of Predictive Maintenance.

To accomplish Predictive Maintenance, beyond review of operating and maintenance records, Maughan states that there are three primary tools: monitoring devices, inspection and test. The paper [9], addresses aspects of each of these three assessment tools. Each of these three assessment tools has important weaknesses, which are explained in [10], though.

If all three tools are used wisely, [10], states that it is possible to decrease but not eliminate exposure to forced outages. If the tools are used well, planning and execution of needed maintenance can be considerably improved in content and quality.

The paper [10], addresses aspects of each of the three topics:

- a) The strengths and weaknesses of standard and optional monitoring equipment.
- b) Inspection equipment and procedures that will help assure an accurate visual assessment of the generator components.
- c) Limitations and strengths of off-line test procedures and equipment.

Some common generator deterioration mechanisms assessed by the three tools are addressed in [10].

In the conclusion of his paper [10], Maughan states that accurately predicting the timing and scope of all needed maintenance on an operating generator is not possible with the present state of the art of generator monitoring, inspection and test tools. Maughan states that the present five year periods between inspections may not be appropriate but that on the other hand, an arbitrary and long period between inspections may result in neither reliable life nor low maintenance cost.

2.4. Comparison between condition monitoring equipment: RFM

There are many generator condition monitoring devices that can be used to monitor various components of the generator. In the following section, a comparison of Rotor Flux Monitoring (RFM) equipment will be compared.

A flux probe is a small coil of fine wire mounted on a rod which supports it in the generator air gap. There exist two basic types, a permanent and a temporary. The permanent probe is a flexible rod which can bend to permit the rotor to be removed or inserted. The temporary probe is a long rigid rod which is inserted through a seal during generator operation, passing through a radial ventilation duct in the stator lamination to the air gap.

The signal from the flux probe is then channelled through a waveform analyser and a computer software analysis program. When completed and depending on the OEM monitoring equipment, the analysis will provide the following, as minimum, outputs [11]:

- Integration of the probe signal to construct the air gap flux density waveform.
- Voltage spike amplitude measurements.
- Amplitude averaging.
- Pole-to-pole coil ratios.
- Tabular and graphical presentation of the analysis.

The theory and principles of rotor flux monitoring are well explained in [12, 13].

The use of air gap flux probes is an effective method to detect generator rotor winding shorted turns as a means of preventative maintenance. This is because air gap flux probe data can pinpoint the number and location (pole and coil) of shorted turns without having to take the generator off-line [12], depending on the type of Rotor Flux Monitoring (RFM) equipment installed, as will be seen in the example that follows:

Example on RFM:

A 1200MW unit installed in 1980 in USA operated reliably until April 2003. In April 2003 and again in October 2003, the unit experienced a step increase in shaft vibration [13]. The vibration level of the machine as compared to ISO 10816-2:1996 indicated that the unit was operating in zone C/D, which is unacceptable for long term service.

On both occasions, the step changes were associated with severe grid disturbances and large negative sequence currents from the switchyard recording data. A thermal sensitivity test combined with the customer's initial flux probe test revealed four inter-turn short circuits within the winding. The sensitivity test showed that the vibrations were sensitive to excitation current, hence thermally induced, thus caused by the inter-turn short circuits.

The inter-turn faults deteriorating further resulting in either the generator having to be shut down or worse developing into an earth fault, was un-acceptable to the customer, who needed the unit to operate until March 2008, when the next major outage was possible. An Emergency Response Plan (ERP) [13] was developed to ensure that the effect of the unit being forced from service was minimised.

A vital part of the ERP was the identification and location of the inter-turn faults using rotor flux monitoring of the air gap search coils. This identification approach is discussed in full detail in [13].

Initial readings on full load indicated the presence of 3 or 4 inter-turn faults see figure 13.

A detailed study was conducted using the OEM's Rotor Flux Monitoring (RFM) equipment, which identified 8 inter-turn faults and their location: pole and coil. This meant that if the customer's data had only been used, then at best the work program for the repair would have to have been doubled and at worst not all faults would have been identified and repaired.

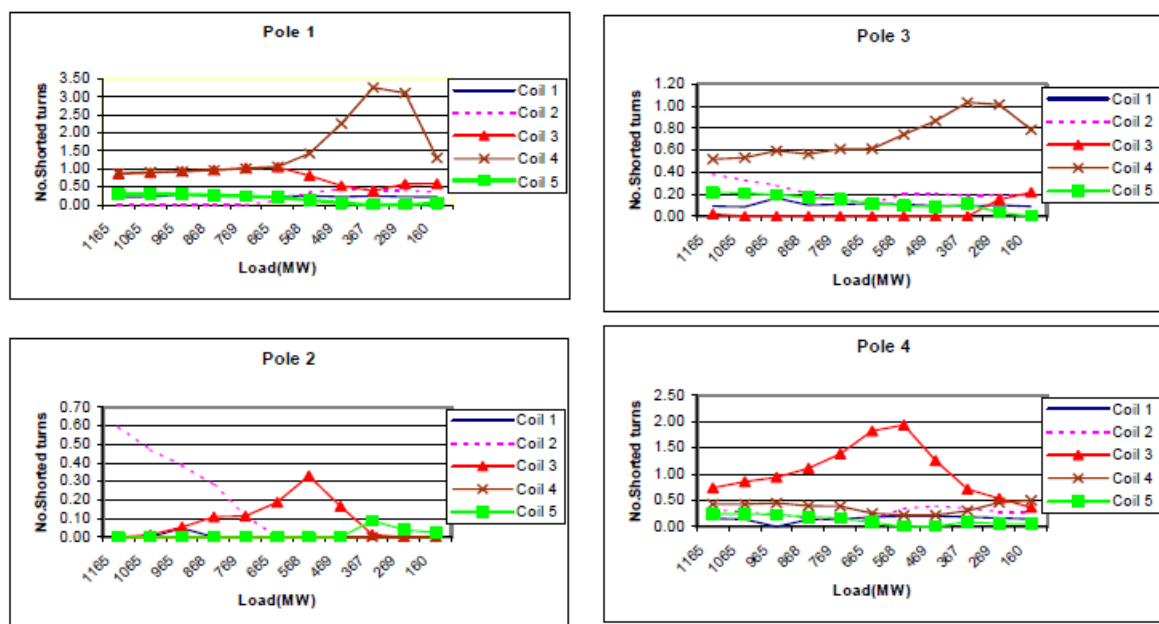


Figure 13. Original RFM identification of 4 inter-turn faults [13]

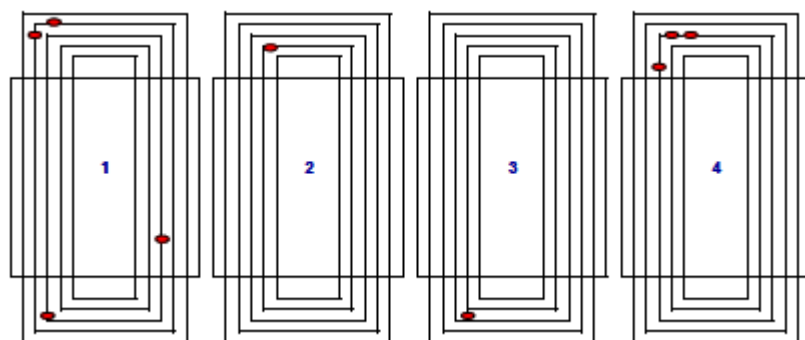


Figure 14. Location & Position of 8 inter-turn faults identified by OEM RFM [13]

Figure 14, shows the fault position in each of the poles. In total 8 faults in 5 coils were identified.

3. Objective

The objective of the project was to identify areas of greatest risks within the 600MW generators, to develop a sound understanding of the integrity of the equipment, to conduct a review of the maintenance regime and to generate short, medium and long term recommendations, so that the generators can continue to operate in a safe and reliable manner.

4. Equipment covered

Duvha units 1 to 6: 600MW Generator, specifically:

- 1) Generator rotor,
- 2) Generator stator,
- 3) Excitation System:
 - Main exciter:
 - Exciter stator,
 - Rotating exciter assembly,
 - Rotating rectifier unit,
 - Permanent magnet generator,
 - Instrument brush gear.
- 4) Bearings and pedestals:
 - No. 9 bearing: generator front end,
 - No. 10 bearing: generator rear end,
 - No. 11 bearing: exciter rear end,
 - No. 12 bearing: PMG front end,
 - No. 13 bearing: PMG rear end.
- 5) Generator auxiliary systems i.e. seal oil system, stator water system, hydrogen system and barring gear.

5. Plant Process Parameters

A snapshot of the plant process parameters for Duvha Power Station during the plant visit was collected using the station's installed instrumentation. The station's units screen extracts and collected plant walk-down data are enclosed in Appendix A1, figures 19 - 24. The process parameters enclosed by a red box in the screen dump extracts are viewed to be questionable by the author. This is because the parameter value is not what it should be, based on the load condition. Refer to the design, specification, alarm or recommended values as listed in the plant walk-down data for unit 1, in Appendix A1: Plant Walk-Down captured Table.

5.1. Plant Walk-Down Analysis Unit 1

At the time of the snapshot data capture, Duvha unit 1 was on load at 503MW, 239MVAR, 14.4kA, 22.2kV, with its output data included in Appendix A1: Figure 19 and Table of Plant Walk-Down data. The generator was running within the designed parameters as defined in the operation and maintenance manuals.

However, the author noted discrepancies between the plant gauges and the operator's mimic, for example, a comparison of plant gauge and mimic data showed the stator water system inlet temperature on the mimic as 23°C and on the plant it read 51°C. Clarification on what is taken as the reference reading or if a master gauge is used for commissioning was unable to be established by the author. The author is therefore concerned about the instrumentation accuracy.

It is important to calibrate and match plant and mimic data to ensure that the plant is being operated by accurate data. Differences in indicated values can lead to operational uncertainty and the true condition of the plant not being fully understood.

→ Urgent calibration and matching between the plant and mimic data is required.^a

^a "→" denotes corrective actions to be actioned in conjunction with Criticality Review Table. See Conclusion.

For the stator water system the stator inlet and outlet pressures were not set to the recommended design specification, the inlet and outlet pressures should be 365kPa and 110kPa, respectively. Refer to Appendix A1: Figure 19, Table of Plant Walk-Down data.

The stator water inlet temperature, according to the plant gauge, was at 51 °C (alarm point is 43°C) resulting in a standing alarm, which means no protection for the plant if the alarm temperature increases further. The stator water flow rate was under the minimum recommended level of 21l/sec. The outlet temperature of 68°C was close to alarm value, (alarm point is 72°C) however the temperature differential of 17°C is acceptable.

The excessively high inlet temperature is due to a deficiency within the auxiliary cooling water (ACW) or primary cooling water system.

The excitation system and instrumentation brush gear were operating within permissible parameters with no standing alarms on the operator's desk when reviewed during the plant visit. However, the calculated rotor winding resistance from the measured rotor voltage and current, yielded unrealistic values and are indicative of errors in the base parameter measurements. Refer to Appendix A1: Figure 19, Generator extract, red information box.

The bearing vibrations and temperature were all within the permissible parameters when reviewed during the plant visit.

The seal oil/gas differential pressures were not correct as the turbine end was 120kPa and exciter end was 145kPa with the permissible minimum recommended pressure being 140kPa. The low differential pressure at the turbine end being the one of concern. Refer to Appendix A1: Figure 19: Table of Plant Walk-Down data.

5.2. Plant Walk-Down Analysis Unit 2

At the time of the snapshot data capture, Duvha unit 2 was on load at 595MW, 250MVAR, 16.7kA, 22.2kV, with its output parameters included in Appendix A1: Figure 20 and Table of Plant Walk-Down data. These values indicate that the generator was running within the designed parameters. There is however a concern again with the instrumentation accuracy.

There was a discrepancy between the plant gauges and the operator's mimic, for example, the neutral terminal outlet temperature. From the snapshot of process parameters taken, the plant mimic read 54°C, whilst on the plant the parameter read 38°C. Again, clarification on what is taken as the reference reading or if a master gauge is used for commissioning was unable to be established.

→ Urgent calibration of the plant and mimic data input should be conducted.

The stator water system according to the plant gauges were within permissible parameters with the inlet pressure a little high at 370kPa and the flow under the design recommended flow of 21l/sec. The stator water generator inlet temperature was at 43°C, which is at the alarm value i.e. 43°C. Refer to Appendix A1: Figure 20 and Table of Plant Walk-Down data.

The stator winding and core temperatures according to the operator's mimic were within permissible parameters. It is however a concern that 12 of the thermocouples are not reading meaning that there might be hot spots that can be overlooked.

→ Hence it is important to restore instrumentation functionality to a sufficient level that will allow for monitoring functionality and for condition based assessments to be effective.

The excitation system and instrumentation brush gear were operating within permissible parameters with no standing alarms on the operator's desk when reviewed during the plant visit by the author.

The bearing vibrations and temperatures were all within the permissible parameters with bearing no. 9, the highest.

Analysis of hydrogen cooler hot gas and cold gas temperatures, based on the temperature differential, indicated a cooler load imbalance with the left hand side, (looking from turbine end to exciter end), front/turbine end cooler indicated to be carrying away minimal losses.

5.3. Plant Walk-Down Analysis Unit 3

At the time of the snap shot data capture, Duvha unit 3 was on load at 549MW, 5MVA_r, 14.2kA and 22.3kV, with its output parameters included in Appendix A1: Figure 21 and Table of Plant Walk-Down data. These values indicate that the generator was running within the designed parameters. There is again the concern that the instrumentation accuracy is a problem, with many discrepancies between the plant gauges and the operator's mimic.

→ Urgent calibration of the plant and mimic data should be conducted.

The stator water system according to the plant gauges were not within permissible parameters with the inlet pressure at 365kPa, the outlet pressure at 90kPa and with the flow rate at 22l/sec. Refer to Appendix 1, Figure 21: Table of Plant Walk-Down Data.

The generator stator water inlet temperature was at 46°C, which is over the alarm value of 43°C, resulting in a standing alarm, with no protection if the alarm temperature increases further, which is not considered best practice.

The stator winding and core temperatures according to the operator's mimic were within permissible parameters; however there were a high number of stator temperature thermocouples that were not functioning. This is of concern to the author as it limits the effectiveness of condition based monitoring and also increases the operational risk on the unit, as no prior early warning indication of a potential fault occurring can be detected.

The temperatures of the exciter end hydrogen seal could not be obtained, as the thermocouples were not functioning. This coupled to the fact that the vibration of bearing no. 10 was the highest in the turbine-generator train at 106µm, results in the author's conclusion that the unit is in an unhealthy running condition.

→ An investigation of the exciter end of the machine should be conducted to identify any hidden defects/root cause for the bearing 10 high relative vibration reading.

The excitation system and instrumentation brush gear were operating within permissible parameters with no standing alarms on the operator's desk.

Hydrogen gas purity value is normally expected to be around 99%, with alarm action at 95%. The unit 3 hydrogen purity, according to station instrumentation, was found to be the lowest of the units during the visit at 96.5%. A purity decrease of 1% results in an increase in friction and windage losses of 10%; furthermore a purity change of 3% can have a 15% effect on the coolant's specific heat capacity and subsequently affect the ability to effectively cool the machine.

→ The reason for the low hydrogen gas purity should be investigated and action taken to restore it to normal operating values.

5.4. Plant Walk-Down Analysis Unit 4

At the time of the snap shot data capture, Duvha unit 4 was on load at 602MW, 208MVAR, 16.5kA, 22.3kV with its output parameters included in Appendix A1, Figure 22 and Table of Plant Walk-Down data. The process parameters indicate that the generator was running within the designed parameters. There is the concern again that the instrumentation accuracy is a problem. There were discrepancies between the plant gauges and the operator's mimic, for example, for the stator water system.

The generator stator temperature (AKZ code SP01T042) was reading 2047°C, which clearly indicates an instrumentation error. Any instrumentation channel defects results in a reduction in the plant data available to the operators and increases the operational risk to the unit.

→ Hence all instrumentation faults should be identified and rectified.

The generator inlet temperature of 41 °C was close to the alarm value of 43 °C, with the high unit load probably being the reason for this.

The stator winding and core temperatures according to the operator's mimic were within permissible parameters.

There were no exciter voltage and current readings on this unit. On investigation it was found that the supply to the field cubicle was switched off. On enquiry it was advised that the reason that it was switched off was due to one brush wetting power supply being faulty. This is a very unhealthy running condition as there is no rotor earth fault alarm with this supply switched off.

ALSTOM Operational Philosophy Statement OPS008, "Action in the Event of a Rotor Earth Fault", [14], instructs that in the event of a rotor earth fault that the unit should be de-loaded and de-excited as soon as is practicable and the reason for the earth fault investigated and corrected before returning on load.

With no rotor earth fault alarm coverage there is an operational risk that a single point breakdown of the rotor winding insulation will remain undetected. In the event of a second earth fault, at any point in the system, the passage of the resulting large fault currents will cause severe and irreparable arcing damage to the rotor body, rotor end winding retaining rings or to the excitation system.

The ALSTOM report S180/05/040/a, dated July 2005 [15] details the investigation into a possible inter-turn fault on unit 4 rotor S/N S2079/05. A summary extract is included in Appendix A2a. The report was unable to fully conclude the possibility of the presence of an inter-turn fault and further testing/investigation was recommended.

The ALSTOM report S180/06/029/a, dated August 2006 [16], reported on the additional testing, resulting in the final conclusion that no current carrying inter-turn faults existed in the rotor S2079/05. A summary extract is included in Appendix A2b.

The bearing vibrations and temperatures were all within the permissible parameters with bearing no. 10 having the highest vibration.

The ALSTOM OPS006 [14], recommends that the hydrogen gas pressure dew point be maintained in the range of -25 °C to +10 °C. The plant instrumentation indicated a gas drier outlet dew point of 20 °C.

→ True moisture levels for unit 4 to be established and the hydrogen gas condition returned to within recommended moisture levels.

The stator water system pH during the plant walk down was at 9.92, outside the recommended range of between 8 and 8.5.

→ The true stator water chemistry conditions needs to be verified for compliance with the adopted chemistry regime.

5.5. Plant Walk-Down Analysis Unit 5

At the time of the snap shot data capture, Duvha unit 5 was on load at 526MW, 228 MVar, 14.8kA and 22.3kV with the following parameters captured in Appendix A1, Figure 23 and Table of Plant Walk-Down data. The generator was running within the designed parameters; however the re-occurring issue of the instrumentation accuracy is of concern again.

There was a discrepancy between the plant gauges and the operator's mimic for the stator water system. The stator water system parameters according to the plant gauges are not within permissible values, with the inlet pressure too low at 350kPa. For the indicated outlet pressure of a low 95kPa, it is expected that the flow should be higher than the recorded 21l/sec. Due to the high stator water differential pressure, possible flow restrictions in the stator bars (copper hollow strands) may exist.

→ The unit 5 process parameters should be reviewed to ascertain the true condition of the stator water cooling system, focusing on the stator winding cooling channels.

The bearing vibrations and temperatures were all within the permissible parameters with bearing no. 10 noted as the highest during the plant visit.

The plant snapshot data showed the inlet dew point at 25°C. This implies that either the instrumentation is faulty or that the hydrogen coolant moisture levels are excessively high. The condition of the hydrogen coolant is critical to the long-term efficiency and reliability of the unit.

→ The hydrogen coolant system should be investigated to establish the actual condition of it and any root cause issues are to be corrected.

5.6. Plant Walk-Down Analysis Unit 6

At the time of the snap shot data capture, Duvha unit 6 was on load at 549MW, 13.8MVA_r, 14.2kA and 22.34kV, with the process parameters captured in Appendix A1, Figure 24 and Table of Plant Walk-Down data.

The stator winding and core temperatures according to the operator's mimic were within permissible parameters, with 2 thermocouples not reading. Any instrumentation channel defects results in a reduction in the plant data available to the operators and increases the operational risk to the unit. For this reason instrumentation faults should be prosecuted and rectified.

The plant data capture indicated a problem with the hydrogen coolant system. The generator hydrogen gas casing pressure was recorded at a low value of 390kPa. The hydrogen gas dryer has a standing alarm with an inlet dew point of -3 and outlet of +3°C. Whilst these levels are within the recommended range, the fact that the dryer outlet dew point is actually higher than the inlet is indicative of dysfunctional gas dryer.

→ The hydrogen gas dryer functionality and instrumentation should be investigated to establish its true condition and any root cause issues corrected, as operating with standing alarms results in no protection for the plant if the alarm temperature increases further.

The excitation system and instrumentation for the brush gear were operating within permissible parameters with no standing alarms on the operator's desk.

The bearing vibrations and temperatures were all within the permissible parameters with bearing 10 having the highest vibrations.

5.7. Discussion of the Plant Process Parameters from Plant Walk-down

A high number of data channels connected to instrumentation were found not to be operational across all 6 units. These results in ineffective condition based monitoring and increase the operational risk due to the early detection of faults not being possible.

Numerous discrepancies between the plant gauges and the operator's mimic diagrams were found across all 6 units. It is important to have correctly calibrated and matching plant and mimic data in order to ensure that the station is controlled by valid and accurate data.

All units except for unit 3 have no stator water conductivity measurement and unit 3's value of 20ug/l appears to be incorrect. Recommended design value is 2μS/cm.

The hydrogen cooling gas outlet dew point was found not to be consistent across all units. Units 1, 2, 3, and 5 all having very low dew point readings. Unit 2 and 4 readings indicative of dysfunctional driers.

All units' except for unit 1, seal oil/gas differential pressure were not set to the design recommended value of 140kPa. Stator water, seal oil and hydrogen gas pressure interrelationship is critical to the operational and long term health of the generator. If the correct differential pressures are not maintained then any minor defect or leak increases significantly. Water into gas leaks due to incorrect pressures results in long term issues of insulation degradation.

Information received with regards to Eskom Generation fleet Unit Capability Loss Factor (UCLF), show a 17.7% year to date, of which the seal oil systems and seals are the biggest contributor at 8.4%.

6. Plant Integrity Assessment

The report up to now has discussed the assessed condition of the units based on the captured plant walk-down data. The condition of the plant will now be assessed and discussed using ALSTOM's Plant Integrity Assessment tool, which is an analytical process used to provide an understanding of the condition of the plant. An explanation of the ALSTOM Plant Integrity Assessment process is included in Appendix A3. Words beginning with a capital letter are key words for terminology used in the assessment and required input parameters for the analytical tool.

What follows in this report explains how the inputs into the analytical tool have been decided for Process Indicator, Inspection Condition and Feature inputs (refer to section 6.1), and how the Final Assessed Condition scores for the sub-components of the generator were obtained for the Plant Condition Assessment.

The outputs of the tool are then compared for consistency by the author with what the sub-component's condition should reflect based on the author's past experiences and knowledge of Duvha Power Station.

6.1. Duvha Process Parameter Assessment

Due to the plant walk-down data having discrepancies between plant gauges and operator's mimic, it was decided that the Process Parameter data be taken from the station VA system. Data from the period May 2007 to February 2008 was obtained. The following section explain the input methodology for unit 1 Process Parameter findings/scores as indicated in Appendix A4, under column "Process Indicator", with the data analysis for the Process Parameters as conducted by the author for unit 1 included as Appendix A5. The inputs into the analytical tool for Process Parameters for the other units have undergone this same analysis process.

6.1.1. Duvha Unit 1 Process Parameters

Generator Load Factor

The generator load data is included in Appendix A5, as figure 27. The author compared this data to the generator capability chart and found the data to be within the boundaries of the design parameters. The author did note load conditions above the maximum rated 600MW which have been entered into the analytical tool to be taken into account.

Stator Winding Temperatures

Analysis of the Stator Winding Temperatures, figure 28, Appendix A5, indicates that the temperatures are within design specifications. Highest temperature was 70.12°C, with highest average temperature of 55.4°C. The generator stator bars are insulated with class F insulation (maximum temperature 155°C). However the author has noted rapid load changes which do result in a degree of thermal cycling and accordingly entered into the tool. Long term effects of thermal cycling are detrimental to the insulation.

Core Body & Tooth Temperatures

The Core Body and Tooth Temperatures were noted to be high, with the highest temperature of 119.2°C (maximum 130°C, core plate insulation class F) and 106.37°C, respectively. Refer to figure 29, Appendix A5. On analysis of the high temperatures, a correlation was noted between the low generator casing pressure and low hydrogen purity as the causes.

Stator Water Outlet Temperatures

The highest Stator Water Outlet Temperature was 79.16°C (above the alarm setting of 72°C. Refer to figure 30 in Appendix A5. The author attributes this to the high Cold Condenser cooling water Inlet Temperature as the higher this temperature the higher the stator water inlet temperature, hence the higher outlet temperature. Two temperature signals, 01A_SP01T088 and 01A_SP01T089 are of concern as they both indicated values higher than the alarm setting and were 10°C higher than the rest of the other Outlet Temperatures.

Hydrogen Gas Temperatures

The average cooled gas temperatures have been found to be close to the average alarm value of 41 °C, at 39.73 °C. The reason for this is again due to the high Cold Condenser cooling water Inlet Temperature. The highest Hot Gas temperature was 79.93 °C; the alarm setting is at 75 °C and trip value set at 90 °C. But the reason for this is most likely due to the high Cooled Gas temperature.

However what is concerning to the author is the variance in temperatures above alarm value and within 10 °C of the trip value, as can be seen in figure 31 in Appendix A5, which are not linked to load changes. Experience has shown that such behaviour is related to deteriorating gas coolers.

Hydrogen Cooler Performance – Delta ΔT

An analysis of the Hydrogen Cooler performance revealed poor cooling performance, see figure 15.

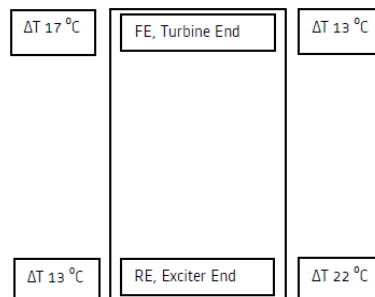


Figure 15. hydrogen Cooler ΔT Analysis

The left hand (LH) Turbine End (TE) cooler average ΔT was 16.56 °C and the Exciter End (EE) average ΔT was 13.24 °C. The Right Hand (RH) Exciter End cooler average ΔT was 22.19 °C and the TE average ΔT was 12.9 °C. The design ΔT value across the coolers should be 20 - 29 °C. Only one cooler on unit 1 is performing within specification.

Hydrogen Seal Temperatures

The highest Hydrogen Seal Temperature was 447.5°C (RH turbine end of the generator), refer to figure 32, Appendix A5. This is regarded as an instrument error by the author, because the LH turbine end of the generator thermocouple did not read the same temperature. The rest of the seals temperatures were noted to be running much colder than expected, with the alarm value set at a high value of 130°C, which is also regarded as an instrumentation error.

Generator Hydrogen Stator Water Pressure Differential

The Gas to Water differential was found to be at the incorrect relationship, by the author, with the Stator Water pressure being greater than the Hydrogen gas frame pressure. Refer to figure 33, Appendix A5. The differential pressure should be 35kPa between the Hydrogen at 400kPa and Stator Water at 365kPa.

The low hydrogen pressure on unit 1 will result in wetting of the insulation, if a leak occurs. This will result in the electrical strength of the insulation decreasing. In addition the leakage water can de-laminate the insulation, which leads to partial discharge.

Bearing and Pedestals

The analysis of the data captured indicated no significant maximum or minimum concerns, but an analysis of the trend within the data reveals a significant upward trend (36% change) for bearing 11 exciter front end. Refer to figure 34, Appendix A5.

6.2. Duvha Inspection Assessment

Following on from the Process Parameter assessment, all available outage reports and reference material was reviewed by the author, in order to have an understanding of and to develop the As Found and As Left condition for the Duvha unit components from an Inspection Assessment point of view. The following sections provide the details for the individual unit Inspection findings scores, as indicated in Appendix A4, under column "Inspection Condition".

6.2.1. Duvha Unit 1 Inspection

The Rotek report [18] that reported on the 1991 major outage, contains details of a planned slot wedge modification to address the issue of end of core wedge looseness. The report contains the recommendation that the stator coolant system must be closely monitored for temperature increases and flow rate fluctuations due to copper oxide deposits that were noted during the outage. This supports the observed high values in a number of Process Parameter temperatures and is a significant finding according to the author for the analytical tool. The report also noted damage to the unit's hydrogen seal carrier.

The Rotek report [19] noted that during the November 2001 turbine outage, during the planned generator inspection work scope, that both FE and RE hydrogen seals were scrapped. Records suggest that prior to this outage; the unit has been operational for 18 years from commissioning with only one generator inspection outage evident, which is difficult for the author to believe and may more likely be that some outage reports are missing.

The ALSTOM outage visit report [20] gave Duvha support during the January 2002 minor outage when a number of stator winding leaks were identified. Due to the method of conducting leak detection and repair activities, the report recommended that all winding overhang support bolts be torque tightened after 12 months of running, due date February 2003, due to overhang supports being disturbed. An inspection in December 2002 is noted but with no records of the torque tightening being performed. And again a major outage in 2005 indicated no records of this activity being done. During the Inspection analysis it has not been possible to confirm that this action has been completed and it thus considered as a significant finding by the author for input into the analytical tool.

Summary findings from the captured partial discharge results [21], reported that the red phase displays signs of slight de-lamination at the line end. Blue and white phases display slot discharges and de-lamination towards the neutral end. The report also advises on possible loose bracing in the overhang at the turbine end and recommended that capacitive couplers be fitted to the generator.

Partial discharge couplers are installed to Duvha unit 1 with on-line monitoring, however no data from the system could be obtained to support the assessment.

6.2.2. Duvha Unit 2 Inspection

For Duvha unit 2 after the 2003 incident recovery (where the generator was destroyed by a hydrogen explosion), the amount of information obtained has not been able to fully support the Inspection analysis.

However, from the information collected, the principle driver from the unit inspection records has been the journal bearings and associated subcomponents, due to the following Inspection findings by the author:

In February 2004, in response to a high unit vibration signature, a bearing inspection was conducted which resulted in a number of findings. The interim inspection report [22] summary findings stated: No. 9 bearing top keep clearance excessive (0.25mm), No. 9 bearing half joint open 0.127mm, generator coupling periphery found low by 0.15mm, radial rubs No. 9 bearing rear LHS and pedestal 5 rear LHS oil wipers, evidence of running lightly on bearing 9 and toward the top of the clearance.

In March 2004, in response to a rapid increase in metal temperature of bearing 11 (exciter rear), a forced outage shutdown and unit strip down was conducted [23]. A full investigation of the generator and exciter PMG was conducted to determine the loading present on bearing 11. Bearing 11 was found to be wiped, bearing 12 was low. Actions were taken to address the misalignment and the unit returned to service. These finding are considered significant by the author and accordingly taken into account for the assessment.

On installation of the ex-Isle of Grain stator (S/N S3126/01/820) coolant flows in the mains terminal hoses were reported as high and a modification advised by OEM, but the terminal manifold was returned to original condition [24].

6.2.3. Duvha Unit 3 Inspection

The 2002 outage, classified by Duvha as a mini GO but classified by the author as a major outage based on the rotor removal/exchange, did not involve the OEM. The following findings were found in the OEM report [25]:

The stator terminal insulation was not in accordance with OEM specification, which results in reduced integrity.

Stator winding pressure and vacuum tests were not conducted in accordance with OEM specifications.

During the return to service a leak was discovered on the stator water manifold equalising pipe; alignment of main manifold after full O-ring replacement could have been the possible root cause.

Several PTFE hoses were refitted with deep cuts and abrasions due to non-availability of spare hoses and the long lead time of 14 weeks did not support the outage.

Inner to outer frame seals were found on inspection to have deteriorated and no remedial actions were conducted during the 2002 outage. The report recommended replacing the seals at the next opportunity.

These Inspection findings have all been taken into account in the Inspection Condition input of the assessment, refer to Appendix A4, under column Inspection Condition.

6.2.4. Duvha Unit 4 Inspection

The scope of work of the Duvha unit 4 general outage in 2003 for the main generator included the main rotor removal and stator inspection. The results of the inspection found evidence of stator fretting at the rear end in three areas: 6 o'clock outboard circumferential, 7 o'clock inboard circumferential and at 10 o'clock bracket [26]. This is mostly likely due to the stator earth fault that occurred on this unit.

The rotor shaft revalidation which was conducted as part of the rewind in 2003, showed a number of areas where the rotor forging required machining and hand dressing to reduce the return to service risk to a minimum.

The rotor journals were found to have machined grooves and plunger groove crack indications which were removed by machining and hand dressing. Some rotor slot teeth ears were found cracked and left in that condition.

The author believes that the rotor forging condition as is does not contribute to a significant in service risk; with the as Left findings still being taken into account into the assessment, refer to Appendix A4, under column Inspection Condition.

6.2.5. Duvha Unit 5 Inspection

During the interim outage, conducted in 2001, 5 litres of oil was found in the generator casing [27]. The route cause of the finding was not established; most likely due to poor stator frame/casing sealing.

All other visual and inspection activities conducted in 2001, showed the stator core and winding to be in a good condition with no substantial findings, aside from the thermal aging process on the stator winding and insulation.

Three repairs to stator winding coolant system leaks were achieved in 2004; one on the stator water manifold, exciter end top bar 2 and exciter end top bar 12. All leak sites were repaired using locktite sealer, which is a temporary repair method.

The general outage inspection in 2004 also included a wedge tightness test, which indicated deterioration of wedge tightness. A re-wedge was not possible with the condition left in the As Found state.

6.2.6. Duvha Unit 6 Inspection

The rotor exchange conducted in 2007 (S2068/02 out, S2079/06 in), which was driven by inter turn faults on the in-situ rotor resulted in the main stator consequential damage after the rotor “dropping” incident. The ALSTOM inspection report [28], reported cracks on the stator inboard winding support brackets and stator cooling water leaks were identified during the 2007 outage whilst re-commissioning the unit.

6.3. Feature Risk Assessment

The Feature risk table for Duvha Power Station is included as Table 1, with the key identified Features for the components: main rotor, main stator and exciter, analysed and confirmed by the author for their present, as fitted, design known modifications. The key features have been included in Appendix A6 with their Feature scores included in Table 1.

Table 1: Duvha Power Station Plant Feature Risk Table [17]

Berth	Rotor Serial No.	Rotor Feature Score (a)	Stator Serial No.	Stator Feature Score (b)	Exciter Serial No.	Exciter Feature Score (c)	Overall Unit Feature Score (a+b+c)
Duvha 1	S2068/03	30	S2068/01	66	S2068/01	0	96
Duvha 2	DAX3233/0003	50	S3126/01	62	S2068/02	0	112
Duvha 3	S2125/03	69	S2068/03	54	S2068/03	6	129
Duvha 4	S2079/05	61	S2068/04	62	S2079/04	0	123
Duvha 5	S2068/01	95	S2068/05	62	S2079/05	0	157
Duvha 6	S2079/06	53	S2068/06	44	S2079/06	0	97
Spare Rotor	S2068/02	56					

6.3.1. Duvha Unit 1 Feature

For Duvha unit 1 (rotor S2068/03) the Feature score is low based on the rotor being a rewind unit benefiting from consolidated coils, 3-land seating arrangement and 18Cr/18Mn coil retaining rings.

The stator Feature score differentiator is driven by the back of core bar feature, i.e. insulated or un-insulated. Duvha unit 1 has un-insulated back of core bars.

6.3.2. Duvha Unit 2 Feature

The rotor DAX3233/0003 low Feature score is due to the revalidation rewind conducted in 2003. It's score is not as low as unit 1, due to it being an imported rotor with no known past operational data.

The stator key differentiator Feature compared to Duvha unit 1 and 3 is its insulated core. The only other Feature differentiator for the stator design is the end of core pack ventilation arrangement that allows Duvha unit 6 to have larger margins of operation at leading power factors.

6.3.3. Duvha Unit 3 Feature

Rotor S2125/03 installed in Duvha unit 3 has the second highest Feature score of the Duvha installed rotors. This is due to its manufacturing period of 1981 and no recorded full refurbishment rewind work scope having been conducted. The rotor was held as a spare during 2002 with no refurbishment recorded.

The key drivers of the Feature score are unconsolidated coils and associated top packer material, 18Mn/4Cr coil retaining rings and associated sub components such as end winding retaining ring liner material.

Duvha unit 3 stator Features are common to unit 1 with un-insulated back of core bars. The other significant core Feature is the core end packet arrangement, common for units 1-5, different on unit 6.

6.3.4. Duvha Unit 4 Feature

Rotor S2079/05 has been rewound and the significant rotor Feature drivers of 18Mn/18Cr EWRR and consolidated coils having been implemented. The relative high score for the rewound rotor being driven by not implementing the rotor forging modifications/features, 3-land seating arrangement and auxiliary rotor component modifications during the 2003 rewind scope of work.

6.3.5. Duvha Unit 5 Feature

Rotor S2068/01 has the highest Feature score of the rotors in service at Duvha. This rotor has had a non OEM, rewind done in 1997. OEM records still show the principle drivers for the rotor Feature score as being present on the rotor. The non OEM rewind only removed the EWRR stress corrosion cracking risk with the fitting of 18Mn/18Cr EWRR, according to the author.

The stator Feature score is comparable with Duvha units 1-4, with the main driver being attributed to the unknown in service modifications.

Duvha unit 5 overall Feature score is the highest when compared to the other units. This is a combination of rotor, stator and exciter Feature drivers. The rotor Feature would have been lower if OEM modifications were implemented during the non-OEM rewind.

6.3.6. Duvha Unit 6 Feature

Duvha unit 6 rotor S2079/06 is a rewound rotor with consolidated coils, 3-land seating, 18Mn/18Cr EWRR, which should result in a low Feature score. But a number of features could not be verified during the analysis, by the author, which is the reason behind this rotor score being higher than unit 1 and unit 2 rotors, due to worst case scenarios being assumed.

Duvha unit 6 stator Features represent the latest core design from all Duvha stators. The core end packet arrangement with better ventilation, (common for units 1-5, different on unit 6), results in larger margins for normal operation and for operation at leading power factors compared to the other Duvha stators. The overall result is the lowest stator Feature score of the Duvha units.

6.4. Plant Condition Assessment Scoring

The plant condition assessment scoring is summing up of the Process Parameter, Inspection and Feature scores, from Appendix A4, with the aid of weighting coefficients to develop the Assessed Condition Score. At the simplest level it is a 0, 1, 2, 3, input, but this is modified depending on the parameter being assessed by a set of rules that have been developed and fine-tuned over a number of years, which defines the method of interpretation of the input data by the analytical tool.

The findings from the analysis as conducted by the author, for Process Indicator (section 6.1), Inspection Condition (section 6.2) and Features (section 6.3) are used as the basis for input into the analytical tool. The key then is to use the tool to focus the analysis of the findings and the drivers/reasons behind the results, to obtain a ranked order for corrective actions, based on the Condition Assessed Score.

It is important to note that the final scores are not as significant as their order relative to each other for the different units; provided that the input data has been entered in a consistent manner relative to the findings for the sub-components for each unit.

The scoring output, at this stage, is not a direct link to operational risk as impact (Consequence of Failure, CoF), is not yet considered. This is done during the Criticality Review, section 7.

However this still allows comparisons between units to be made to target highest priority corrective actions based on Assessed Condition Scores and later with the inclusion of Consequence of Failure, Criticality Scores.

The analytical tool is then used to display the results graphically which allows the worst unit to be identified easily.

The plant condition assessment scoring summary is presented as figures 16 and 17, with the Assessed Condition Score details for individual units, included in Appendix A4.

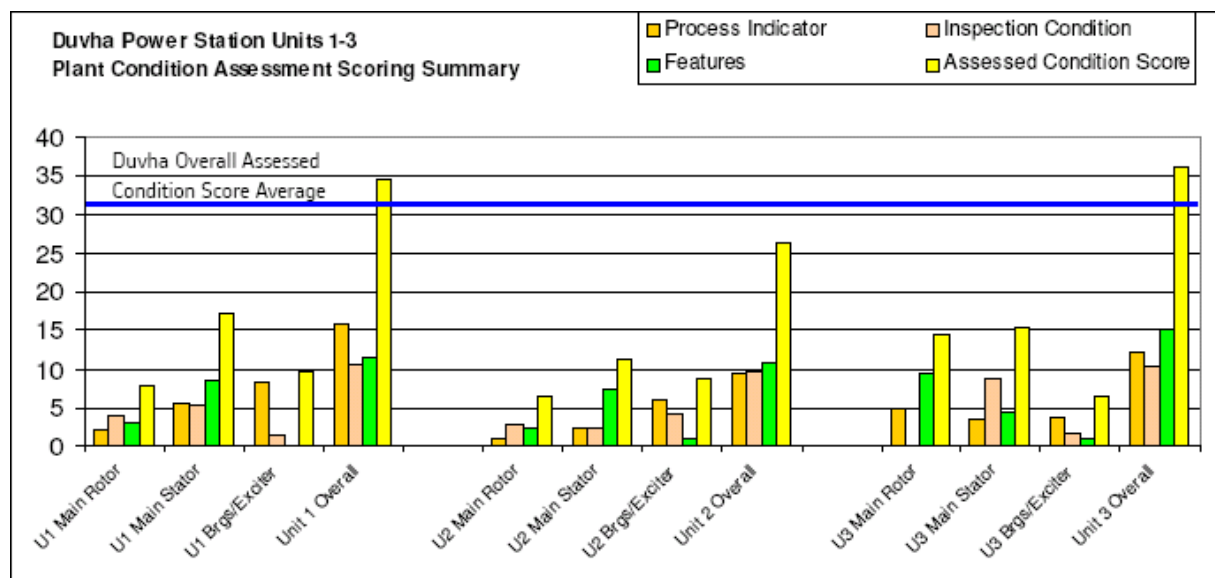


Figure 16. Duvha Power Station Units 1-3 Plant Condition Assessment Scoring [17]

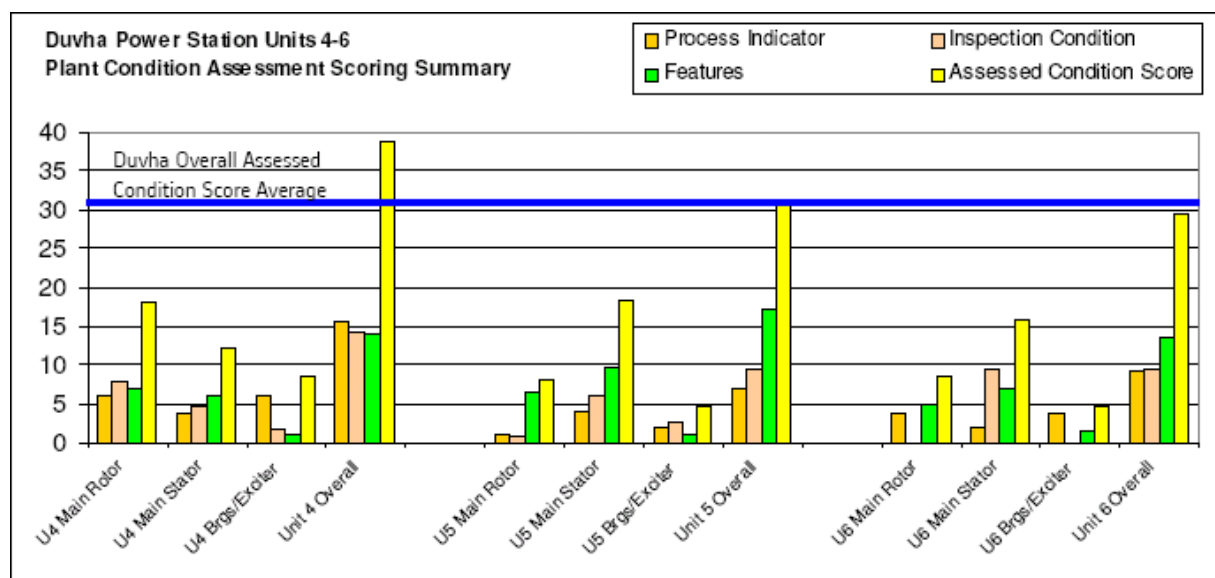


Figure 17. Duvha Power Station Units 4-6 Plant Condition Assessment Scoring [17]

Figures 16 and 17 illustrate the subcomponent scores having been grouped into the key component areas of main rotor, main stator and bearing & exciter, with the summation of the unit overall score for each unit. A discussion of figure 16 and 17 is presented below for the individual units:

6.4.1. Duvha Unit 1 Assessed Condition Status

From figure 16, it can be seen that the highest component score is the main stator, with its contributing scores indicating no significant difference between the Process and Inspection findings with the driver being the main stator's Feature findings.

The highest component process parameter score is Bearings/Exciter, which is driven by the findings of the vibration trend on bearing 11, main exciter.

Looking at the overall component scores, the Process Indicator score is the highest and thus identified as the key driver. The process score is being driven by the current operational practices, poor unit cooling and the discrepancies found during the analysis of the process parameter data.

6.4.2. Duvha Unit 2 Assessed Condition Status

Duvha unit 2, main stator has the highest component score, figure 16, which is due to the condition and operational issues, following the rebuild in 2003 and cooling issues with the hydrogen cooler differential temperatures.

The main contributor to the Bearings/Exciter score is due to the issues with bearings and shaft alignment, from the Inspection Condition Findings.

6.4.3. Duvha Unit 3 Assessed Condition Status

There is no significant difference between the unit 3 component scores for the main rotor and main stator. For the main rotor score it is important to note that no Inspection data was collated to support the analysis. Unit 3 Bearing/Exciter Feature score is driven by the presence of 18Mn/4Cr exciter coil retaining rings and the operational risk of stress corrosion cracking.

6.4.4. Duvha Unit 4 Assessed Condition Status

Duvha unit 4 overall unit score is being driven by the main rotor, refer to figure 17. The main rotor overall score is higher than expected for a rewind rotor. This is because the rotor Inspection score contributors are principally from the As Left condition following the 2003 rewind, where a number of rotor forging defects were left as found and not addressed. The corresponding Feature score also being driven by the present Features of the rotor remaining as original build, with the 2003 rewind being based on a “reuse of component” policy, therefore not upgrading/modifying the rotor Features to latest technology and current best engineering practice.

6.4.5. Duvha Unit 5 Assessed Condition Status

Looking at figure 17: unit 5, the Overall Assessed Condition score is driven by the main stator with its Feature score being the main contributor. This is due to the unknown in service modifications. The second highest contributing factor being the main rotor Feature which is as a result of the non-OEM rewind and all OEM modifications not being implemented.

6.4.6. Duvha Unit 6 Assessed Condition Score

The Overall Condition Accessed score for unit 6 is also driven by the main stator, with the main stator score been driven by its Inspection Condition findings. This is due to the rotor ‘dropping’ incident, which reported cracks on the stator inboard winding support brackets and no record of repairs being done.

6.5. Duvha Plant Condition Assessment Scoring Discussion

Comparison of the Overall Assessed Condition scores for the individual units against the average reveals that the Duvha units all fall within a similar scoring pattern, station average ± 30 . The notable exceptions being unit 2, with the lowest score due to the 2003 rebuild and unit 4, which has the highest Overall Assessed Condition score.

The unit 4, with the highest Overall Assessed Condition score indicates that there are underlying issues with the unit condition, which is in-line with the author's analysis findings. It will be shown, that the unit 4 criticality review results in the second highest criticality score which is driven by the Process Indicator findings for example hydrogen seal temperatures.

The unit 2, main rotor with four years service represents the best practice from the other Duvha units with the lowest assessed score with no significant deviations between the contributing fields of Process Indicators, Inspection conditions and Feature scores.

The bench mark for the bearings/exciter component group is being set by units 5 and 6. Unit 3 bearings/exciter assessed condition score whilst low contains the Feature driver of 18Mn/4Cr coil retaining rings that presents an in service risk of stress corrosion cracking.

7. Duvha Criticality Review

The criticality review develops the component analysis and Assessed Condition Scores to achieve a ranked component score that incorporates unit operational risk.

Sub-components Assessed Condition Scores greater than 1, from Appendix A4, are pulled through to develop the Criticality Review. This is to ensure the capture of all sub-components falling just below the set criticality review threshold score of 1.5, refer to Appendix A3, after a Consequence of Failure (CoF) is carried out, as the criticality scores would then be elevated (above set threshold) and included in the criticality ranked listing.

The Consequence of Failure analysis is developed from 3 aspects, abbreviated S, W and D:

- S – Whether the failure would cause the unit to be Shutdown. 1 implies no shutdown through to 10 which implies instant unit Shutdown.
- W – The amount of Work needed to rectify the problem. 1, no work required through to 10, major Work required, i.e. greater than 2 months.
- D – Damage to other parts of the machine. 1, no Damage to other component through to 10, catastrophic failure to generator.

The average of S, W and D results in the CoF score, with the Criticality Score = Assessed Condition Score x CoF.

The criticality review table for Duvha units is presented in Table 2. The table displays the identified issues in a ranked order of criticality for all 6 units:

Table 2: Duvha Power Station Criticality Review Table

Unit	Station Criticality Ranked Order	Sub Component	Assessed Condition Scores	Originally Ranked Order	Key Driver Description	Impact Assessment				Criticality Score
						S	D	W	CoF	
Duvha 1	1	Bearing Liners	3.50	1	Vibration	10	5	5	6.67	23.33
Duvha 1	2	Inlet & Outlet Manifold Temperatures	2.52	2	Recorded temps & Cu deposits	10	5	5	6.67	16.80
Duvha 3	3	Manifold Temperatures	2.50	2	Values frequently in alarm	10	5	5	6.67	16.67
Duvha 4	4	Manifold Temperatures	2.00	5	Values frequently in alarm	10	5	5	6.67	13.33
Duvha 4	5	Bearing Liners	2.00	6	Vibration	10	5	5	6.67	13.33
Duvha 5	6	Manifold Temperatures	2.00	2	Values frequently in alarm	10	5	5	6.67	13.33
Duvha 1	7	Manifolds	2.06	4	Hydrogen Pressure	8	6	5	6.33	13.05
Duvha 1	8	Shaft ends general	2.15	3	Vibration	2	8	6	5.33	11.47
Duvha 4	9	Shaft ends general	2.15	1	Minor damage unit vibration signature	2	8	6	5.33	11.47
Duvha 2	10	Exciter Bearings	2.24	1	Vibration & Temperature	4	4	5	4.33	9.71
Duvha 3	11	FE Seal Journal	2.00	3	Lack of monitoring, spurious values, lack of reliable monitoring	2	5	6	4.33	8.67
Duvha 3	12	RE Seal Journal	2.00	4	Lack of monitoring, spurious values, lack of reliable monitoring	2	5	6	4.33	8.67
Duvha 4	13	FE Hydrogen Seal	2.00	3	Process Parameters: Temperatures unknown in service condition	2	5	6	4.33	8.67
Duvha 4	14	RE Hydrogen Seal	2.00	4	Process Parameters: Temperatures unknown in service condition	2	5	6	4.33	8.67
Duvha 3	15	LNB Coil Slot Portion	1.29	8	Low stator water flow, Doppler results-foreign matter blockages	10	9	1	6.67	8.60
Duvha 3	16	Rotor Pole Slot Dampers	2.00	5	Feature	1	8	2	3.67	7.33
Duvha 6	17	Rotor Pole Slot Dampers	2.00	2	Feature	1	8	2	3.67	7.33
Duvha 1	18	LFB Coil Slot Portion	1.29	6	High Temps	1	10	5	5.33	6.88
Duvha 5	19	Hydrogen Coolers	2.06	1	Cold Gas temp in alarm instrumentation faults	2	3	5	3.33	6.87
Duvha 2	20	Hydrogen Coolers	2.00	2	Hot gas temperatures & delta T values	2	3	5	3.33	6.67
Duvha 6	21	Stator End Winding Support System	1.33	4	Residual damage after rotor drop incident	1	8	6	5.00	6.65
Duvha 2	22	Jacking Oil Hoses & Pipes	1.96	6	High operating pressure & inspection findings	1	4	5	3.33	6.53
Duvha 2	23	Manifolds	1.25	3	2003 rebuild alignment fit & Feature driven mod state	5	5	5	5.00	6.25
Duvha 6	24	Hydrogen Coolers	1.74	3	Cold gas temp in alarm instrumentation faults	2	3	5	3.33	5.80
Duvha 6	25	Manifold Connection Pipes	1.25	6	In Service Leaks	7	5	1	4.33	5.42
Duvha 5	26	Stator Coils (Grouped)	1.02	3	Doppler Blue Phase PI & Locktite coil repair	6	8	1	5.00	5.10
Duvha 6	27	Manifolds	1.12	7	In Service Leaks	7	5	1	4.33	4.85
Duvha 2	28	Main Generator Bearing Liner	1.00	4	RTS Vibration Issues	4	5	5	4.67	4.67

The Criticality Review findings, Table 2, for each unit, are summarised below with the operational risks, based on the assessment findings by the author and OEM opinion, also listed for each unit.

7.1. Duvha Unit 1 Criticality Review

- Bearing 11, exciter front end vibration trend should be confirmed and monitored.
- Stator water and gas differential pressure excursions place Duvha unit 1 at risk of further stator water leaks.

- The hydrogen cooler imbalance ΔT , is considered a significant issue, which should be rectified at the earliest opportunity.
- Stator water outlet temperatures should be closely monitored.
- Winding overhang support bolt security should be confirmed by confirmation of re-torque activity or as planned activity for the next outage.

7.2. Operational Risks Identified for Duvha Unit 1

- Generator hydrogen gas, stator water differentials.
- Bearing 11 vibrations.
- Hydrogen cooler imbalanced ΔT .

7.3. Duvha Unit 2 Criticality Review

- Increased monitoring and strategic spares support should be considered for Duvha unit 2 exciter bearings.
- The hydrogen cooler imbalance ΔT is considered a significant issue that should be rectified at the earliest opportunity.
- The jacking oil pressure should be adjusted and pipes monitored for fractures at earliest opportunity, see last bullet.
- The manifolds should be adjusted for correct fit and alignment and monitored for cracks propagating due to vibration, at earliest opportunity, see last bullet.
- Duvha unit 2 minor outage inspection frequency should be in accordance with ALSTOM OPS 015 [14] (every 2 years until the unit vibration signature and bearing wear rates after the 2003 rebuild can be established, e.g. Up to planned general outage in 2013).

7.4. Operational Risks Identified for Duvha Unit 2

- Hydrogen coolers poor performance.

7.5. Duvha Unit 3 Criticality Review

- Stator water inlet pressure should be adjusted to 365kPa and Hydrogen cooler instrumentation and performance should be investigated, which will have a positive affect on the manifold temperatures.
- Hydrogen seal thermocouples should be investigated and restored at next opportunity.
- Hydrogen seal inspection should be targeted for next planned outage.
- Replace 18Mn/4Cr exciter rotor coil retaining rings with 18Mn/18Cr to reduce stress corrosion cracking risk.
- Regular periodic stator inspection should be conducted as recommended in ALSTOM OPS 015 [14], with targeted inspection (TVA probe) and review of general findings for indications on top bar 42 defects.

7.6. Operational Risks Identified for Duvha Unit 3

- Generator hydrogen gas, stator water differentials.
- Exciter end hydrogen seal poor condition and unknown operating temperatures.
- Turbine end hydrogen seal poor condition or instrumentation fault.
- Stator top bar 42 poor condition.
- Exciter rotor coil retaining ring material (18Mn/4Cr risk).

7.7. Duvha Unit 4

- Stator water inlet pressure should be adjusted to 365kPa and Hydrogen cooler instrumentation and performance should be investigated, which will have a positive affect on the manifold temperatures.
- Increased monitoring and strategic spares support should be considered for Duvha unit 4 bearings.
- Rotor shaft ends to be monitored for crack propagation.
- Hydrogen seal temperature instrumentation requires investigation and restoration at earliest opportunity.

- At next outage opportunity a sample of the PTFE hoses (at least 3 hoses) should be removed and analysed for overheating affects.

7.8. Operational Risks Identified for Duvha Unit 4

- Generator hydrogen gas, stator water differentials.
- Hydrogen seal temperatures parameters indicate either instrumentation errors or poor likely condition of the hydrogen seals at the exciter end.

7.9. Duvha Unit 5 Criticality Review

- Instrumentation issues on the manifold and hydrogen cooler temperatures to be investigated and rectified.

7.10. Operational Risks Identified for Duvha Unit 5

- No significant issues.

7.11. Duvha Unit 6 Criticality Review

- Routine monitoring should target bearing 10 to detect any in service deterioration.
- Inspection of the stator end winding support system should be included in the work scope for the next inspection, whilst risk mitigation actions to be identified to address consequential damage, resulting from the rotor dropping incident.
- In service leaks on the manifolds to be closely monitored until repairs can be executed.
- Instrumentation issues on the hydrogen cooler temperatures to be investigated and rectified.

7.12. Operational Risks Identified for Duvha Unit 6

- No significant issues.

7.13. Duvha Criticality Score Comparison Discussion

Figure 18, shows the highest unit criticality being unit 1 with its key drivers being the Process Parameters findings. The adverse vibration trend on bearing 11 is also a significant identified operational risk. It is expected that short to medium term actions addressing the key drivers will reduce the overall assessed unit 1 criticality, thus discarding unit 1 as the most critical unit.

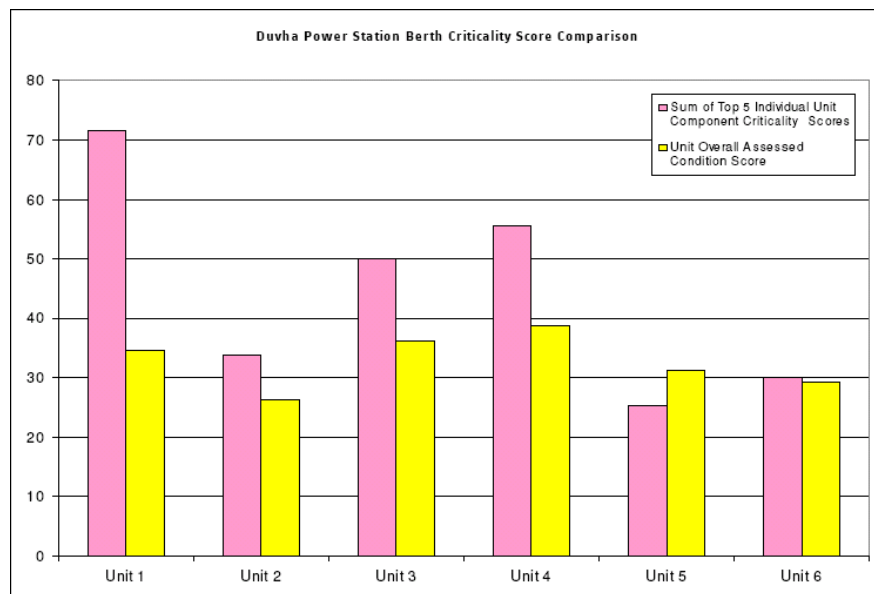


Figure 18. Duvha Power Station Unit Criticality Score Comparison [17]

The second highest unit criticality is unit 4 (taken as the highest/worst unit). The general outage planned for 2010 will provide an opportunity to reduce the unit criticality. While not the highest main stator criticality assessed condition score, highest being unit 5, unit 4 represents the highest Overall Assessed Condition score.

This score aligns with Duvha Power Station's proposed stator exchange program with the unit being designated as the first to undergo an exchange, proposed for 2012.

Only two of the 28 criticality ranked aspects have been regarded as not significant by the author and should not have appeared in the Criticality Review Table. These being criticality ranked aspects 16 and 17. The rest of the ranked aspects are accepted as justifiable and do align with the authors assessment findings. This implies that the analytical tool can be used to facilitate the assessment findings in order to display the Condition Assessed Scores graphically for easy interpretation purposes; - provided that the input data for the Process, Inspection and Feature findings are entered with consistency, based on the individual unit's findings relative to each other.

8. Duvha Maintenance Review

The future maintenance requirements based on the Plant Integrity Assessment data and analysis has been compared by the author to the supplied future outage plan for Duvha Power Station [29]. The key differences are presented in Table 3, with additional comments following thereafter:

Table 3: Duvha Outage/Main Generator Maintenance Plan Comparison

Unit/Year	2008	2009	2010	2011	2012	2013	2014	2015	2016
Duvha 1									
Assessment Based	mO Mar 08			MO Mar 11			mO Mar 14		
Duvha Plan	Interim	Inspection		GO Main Stator	Inspection		Interim Main Rotor	Inspection	
Stator Rewind?							4		
Rotor deployed (yrs)	3	4	5	6	7	8	9		
Comparison	No mO planned						Rotor revalidation		
Duvha 2									
Assessment Based		mO Apr 09		mO Apr 11		MO Apr 13			mO Apr 16
Duvha Plan	Inspection		Interim Main Stator Classified as MO	Inspection		GO Exciter Rotor	Inspection		Interim Main Stator Main Rotor
Stator Rewind?						2			
Rotor deployed (yrs)	2	3	4	5	6	7	8	9	
Comparison		Plant Condition Report recommends 2 yr mO	No work planned for 2010		Plant Condition recommends 2 yr mO	No Main Stator No Main Rotor Inspection planned			Classified as a MO, noting critical project path
Duvha 3									
Assessment Based	MO Sep 08			mO Sep 11			MO Sep 14		
Duvha Plan	GO Main Stator Main Rotor		Inspection	Interim		Inspection	GO Main Stator		Inspection
Stator Rewind?							5		
Rotor deployed (yrs)	Rotor exchange	1	2	3	4	5	6	7	8
Comparison				No Gen work planned					
Duvha 4									
Assessment Based		MO Oct 09			mO Oct 12			MO Oct 15	
Duvha Plan	Inspection	Interim Main Stator		Inspection	GO Main Rotor		Inspection	Interim Main Stator Exciter Rotor	
Stator Rewind?					1				
Rotor deployed (yrs)	5	6	7	8	9				
Comparison					Minor based on 2009 Major			Major based on 2009 outage	
Duvha 5									
Assessment Based			MO Apr 10			mO Apr 13			MO Apr 16
Duvha Plan	Inspection		GO Main Stator	Inspection		Interim	Inspection		GO Main Stator Main Rotor Exciter Rotor
Stator Rewind?									6
Rotor deployed (yrs)	10	11	12						
Comparison	Age of Rotor!		No work planned for 2010			No work planned for 2013			
Duvha 6									
Assessment Based			mO Jan 10			MO Jan 13			mO Jan 16
Duvha Plan		Inspection	Interim		Inspection	GO Main Rotor Exciter Rotor	Inspection		Interim
Stator Rewind?						3			
Rotor deployed (yrs)	1	2	3	4	5	6	7	8	9
Comparison			No work planned for 2010			SOW to include Stator			Rotor revalidation?

8.1. Plant integrity Assessment based Outage Plans

The recommended outages are based on the last known outage, based on Plant Integrity Assessment analysis and a future proposed maintenance strategy of minor outage every 3 years and major outages every 6 years, where:

- A minor outage (mO) is work scope involving inspection and testing of a shut down generator containing all inspection outage work scope plus intrusive inspection and testing of hydrogen seals and generator bearings.
- A major outage (MO) is a work scope involving inspection and testing of a shut down generator containing all minor outage work scope plus the rotor is removed from the stator bore, allowing increased inspection and testing of the rotor and stator core.

8.2. Duvha Long Term Outage Plan

The future outage planning for comparison has been taken from [29], noting that a Duvha General Outage (GO), standard duration is 45 days and the Duvha Interim Outage duration is 28 days.

From this and using the ALSTOM standard, best practice, planning time for a Major Outage of 28 days, it is assessed that a Major Outage (MO) work scope could be conducted in a Duvha General Outage. A Major Outage work scope planned for a Duvha Interim Outage is possible but would likely result in the generator work scope being/or close on the critical path.

ALSTOM's standard best practice planning time for a Minor Outage (mO) is 22 days, which could be conducted in a Duvha Interim or General Outage (GO).

Duvha's main rotor outage policy presently for a revalidation/exchange window is 75,000 to 100,000 operating hours which is equivalent to 8.5 to 12 year intervals.

8.3. Duvha Stator Rewind Programme

A proposed main stator rewind programme is currently under discussion, with Duvha's stator rewind programme, revision 2 included into Table 3. A comparison between Duvha's stator rewind unit order to the Plant Assessment reveals the following:

Table 4: Comparison of Stator Rewind unit order

	Order of Stator Rewinds					
Duvha Plan	Unit 4	Unit 2	Unit 6	Unit 1	Unit 3	Unit 5
Plant Assessment	Unit 4	Unit 3	Unit 1	Unit 5	Unit 6	Unit 2

The only unit that aligns with the Plant Assessment findings for the stator rewind plan is the most critical unit 4, refer to table 4.

8.4. Duvha Future Outage Plan Discussion

The observations made from section 8.1 to 8.3 and included in Table 3 are discussed below:

Duvha unit 1 planned maintenance, after 2010, is in line with the assessment based expectation and Duvha's declared policy, noting that a Major Outage (MO) is due in 2011.

Duvha unit 2 assessment based and Duvha plan based outage plans are not in alignment with the assessment recommendation that Minor Outages (mO) are conducted every 2 years for the near future. The Duvha plan after the Major Outage planned for the Interim Outage in 2010 (not done), is not in alignment with declared Duvha policy, due to the Minor Outage on the main stator/rotor not being conducted in the 2013 General Outage. Minor Outages are key to reducing the operational risk of the unit, reducing the risk of further damage and maintaining the health of the hydrogen seals and bearings.

Duvha unit 3 is in alignment with both the assessment based expectation and Duvha policy plan, with the exception that no maintenance is planned for the intervening period between the General Outages. This planning implies that no maintenance will be conducted on the unit for six years.

Duvha unit 4 follows the best maintenance cycle of the Duvha units and is an example of best practice as applied to a unit on base load operations. It is assumed by the author that the main rotor scope of work in the General Outage in 2012 includes a rotor exchange or revalidation based on the operational hours/age of the rotor.

Duvha unit 5 is in alignment with both the assessment based outcomes and the Duvha proposed outage plan. The age of the rotor from known records and in alignment with the recorded Feature risk profile, will have seen 12 years in operation, since being rewound by a non-OEM in 1997, at the General Outage in 2010. Whilst not noted in the Duvha plan a rotor exchange should be conducted during this outage.

Duvha unit 6 follows the Duvha planned strategy of not planning to conduct any maintenance between General Outage (six years), similar to unit 3. The expected Major Outage scope of work for 2013 does not include for main stator inspections, as would be expected. The Interim Outage in 2016 represents the first opportunity for the main rotor revalidation/exchange window of 8.5 to 12 years for rotor revalidation/exchange.

9. Conclusion

A generator condition assessment conducted by the author on the 6 units at Duvha Power Station, involved a high level plant walk-down to be performed in order to gauge the present operational conditions of the units. Thereafter the station data from the VA system was obtained and analysed for the assessment input streams of Process, Inspection and Feature findings. The findings by the author were entered into an analytical tool for the sub-components of rotor, stator and bearings/exciter for all 6 units. This was done in order to facilitate the analysis process of the findings in a manner that would easily allow interpretation and presentation of the results. The output from the tool, for the Condition Assessed Scores, when presented graphically was judged by the author to accurately correlate with his expectations. The Condition Assessed Scores were then developed further to achieve a ranked Criticality order, across all 6 units that could be used to target corrective actions which included operational and maintenance risk, i.e. Consequence of Failure (CoF). Only two of the criticality ranked aspects are viewed by the author as not being significant and should not have been included in the Criticality Ranked output table, as they pose no operational risk to the units. The author then conducted a Maintenance Review which compared the Duvha outage declared policy to the outcomes from the Plant Integrity Assessment.

On reviewing the data collected from the station and the plant walk-down, it was noted that a number of concerns fall into the category of short term actions whilst others require a long term approach. It must be stated that a number of the issues found are common across all the units and are due to operational pressure at Duvha Power Station.

9.1. Immediate Recommended Actions

The following are issues that the author would not have expected to have been left un-addressed:

- Duvha unit 3 is operating with low hydrogen gas purity and should be restored to recommended operating parameters.

Analysis of the hydrogen cooler hot gas and cold gas temperatures, based on temperature differential, indicates a cooler load imbalance on unit 2 with the left hand side front end cooler indicated to be carrying away minimal losses.

- Unit 2 hydrogen cooler load imbalance should be investigated.

9.2. Short Term Recommended Actions

The discrepancies of the process parameters between plant gauges and the operators mimic were common across all units and must be corrected, as adequate and consistent plant data is required in order to fully understand the plant condition and to provide the operators with consistent and accurate process parameters on which to base their actions on.

A number of systems were not set up or running to optimum conditions or maintaining the plant within the operational design specifications, for example: stator water cooling temperatures, seal oil/gas differential pressure. A short term remedy to the issue of the process parameters being close to alarm or marginally out of permissible settings can be implemented whilst the unit is on load with low risk of trip and limited interference to the balance of the systems.

- Corrective action to restore the plant to within the defined design operating specifications is considered best practice and any under lying or hidden defect/s preventing this should be found and rectified.

- Regular plant checks and monitoring should be conducted to identify short term discrepancies and corrective actions performed.
- A commissioning and/or re-base to the optimum settings for temperature control valves etc. should be conducted.
- Operating with standing alarms is not considered operational best practice. Hence standing alarms and instrumentation defects should be ranked for importance and rectified.

9.3. Long Term Recommended Actions

From the reviewed data, all the units' stator water inlet temps are high, affecting the efficiency of the cooling water. On investigating, it was found that the problem is due to the cooling water heat exchanger efficiency. Considering the generally high outputs being generated by the units, any reduction in efficiency of the cooling systems needs to be considered a serious deficiency. Increased component temperature levels results in an acceleration of long term degradation mechanisms. Note: for the stator and rotor insulation systems, a 10° Celsius increase in temperature results in halving the insulation life.

- Considering the operational outputs, cooling systems should be optimised and any long term performance deterioration mechanisms rectified.
- A review of the performance and efficiency of the ACW system and in particular the hydrogen coolers should be undertaken.
- A review of the hydrogen coolers set up and performance should be conducted.

In conclusion, the action bullets "→" from section 5: the Plant Process Parameters Assessment and the bulleted points from section 7, Plant Integrity Assessment Criticality Review should be actioned in conjunction with the Criticality Review Table 2 to prioritise the actions.

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Appendices

A1. Running data snapshot & plant data captured during walk-down Duvha Unit 1 Running data snapshot

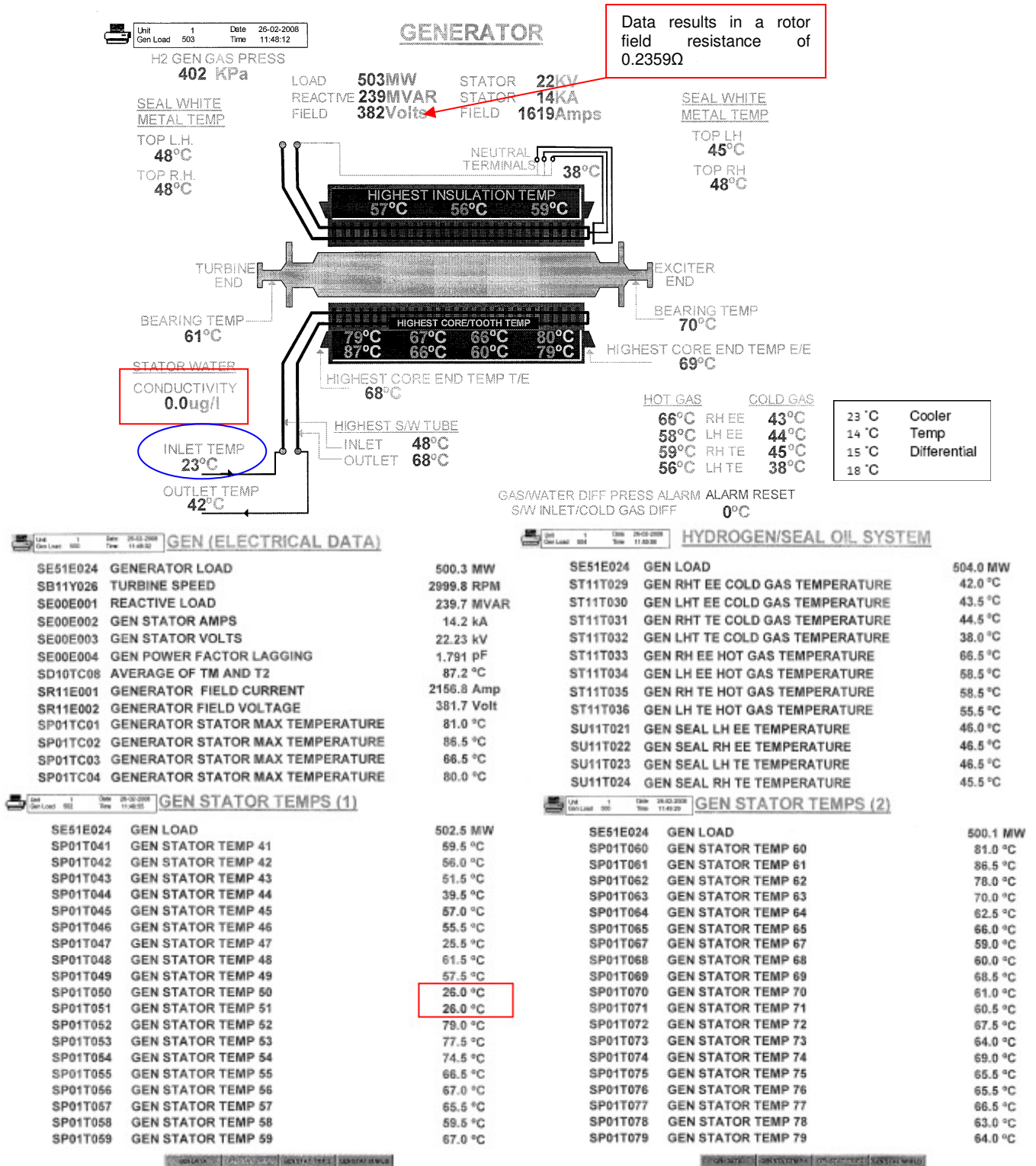


Figure 19. Duvha Unit 1 Running Data Snapshot

Duvha Unit 1 running data snapshot (cont):

Unit	1	Date	20-02-2018	Time	11:49:42	GEN STATOR WATER MANIFOLD TEMPS
SE51E024	GEN LOAD					502.1 MW
SP01T080	GEN STATOR WATER INLET MANIFOLD					48.5 °C
SP01T081	GEN STATOR WATER INLET MANIFOLD					47.8 °C
SP01T082	GEN STATOR WATER OUTLET MANIFOLD					66.0 °C
SP01T083	GEN STATOR WATER OUTLET MANIFOLD					67.5 °C
SP01T084	GEN STATOR WATER OUTLET MANIFOLD					26.0 °C
SP01T085	GEN STATOR WATER OUTLET MANIFOLD					66.0 °C
SP01T086	GEN STATOR WATER OUTLET MANIFOLD					62.5 °C
SP01T087	GEN STATOR WATER OUTLET MANIFOLD					64.0 °C
SP01T088	GEN STATOR WATER OUTLET MANIFOLD					66.0 °C
SP01T089	GEN STATOR WATER OUTLET MANIFOLD					66.0 °C
SP01T090	GEN STATOR WATER OUTLET MANIFOLD					55.0 °C
SP01T091	GEN STATOR WATER OUTLET MANIFOLD					55.5 °C
SP01T092	GEN STATOR WATER OUTLET MANIFOLD					55.0 °C
SP01T093	GEN STATOR WATER OUTLET MANIFOLD					54.5 °C
SP01T094	GEN STATOR WATER OUTLET MANIFOLD					51.0 °C
SP01T095	GEN STATOR WATER OUTLET MANIFOLD					53.5 °C
SP01T096	GEN STATOR WATER OUTLET MANIFOLD					53.5 °C
SP01T097	GEN STATOR WATER OUTLET MANIFOLD					48.0 °C
SP01T098	GEN STATOR WATER OUTLET MANIFOLD					55.0 °C

Unit	1	Date	20-02-2018	Time	11:50:22	STATOR WATER & CORE TOOTH
SP01T099	GEN STATOR WATER OUTLET MANIFOLD					56.0 °C
SP01T100	GEN STATOR WATER OUTLET MANIFOLD					55.0 °C
SP01T101	GEN STATOR WATER OUTLET MANIFOLD					55.0 °C
SP01T102	GEN STATOR WATER OUTLET MANIFOLD					53.5 °C
SP01T103	GEN STATOR WATER OUTLET MANIFOLD					54.5 °C
SP01T104	GEN STATOR WATER OUTLET MANIFOLD					56.5 °C
SP01T105	GEN STATOR WATER OUTLET MANIFOLD					56.0 °C
SP11T013	STATOR WATER GEN OUTLET TEMP					43.0 °C
SP11T014	STATOR WATER GEN INLET TEMP					24.0 °C
SP26T015	STATOR WATER GEN NEUT OUTLET TEMP					36.0 °C
SP01T110	GEN STATOR TOOTH TEMP					65.0 °C
SP01T112	GEN STATOR TOOTH TEMP					80.0 °C
SP01T114	GEN STATOR TOOTH TEMP					66.0 °C
SP01T116	GEN STATOR CORE TEMP					22.0 °C
SP01T118	GEN STATOR CORE TEMP					78.0 °C
SP01T117	GEN STATOR CORE TEMP					22.0 °C
SP01T111	GEN STATOR TEMP 111					70.0 °C
SP01T113	GEN STATOR TEMP 113					22.5 °C
SP01T115	GEN STATOR TEMP 115					61.5 °C

Running Data Snapshot key

 Parameter referenced in Unit Report Section

 Parameter data questionable

50 °C Parameter normal

40 °C Parameter outside expected value

40 °C Parameter outside normal operating zone

Plant Data Captured during Walk-Down		
Parameter	Unit 1	Design/Spec/Alarm/Recommended
Hydrogen System		
Hydrogen Range Pressure	555 kPa	600 kPa
Oil/Gas Diff Pressure TE	120 kPa	140 kPa
Gen Casing Pressure	400 kPa	min 400 max 450kPa
Oil/Gas Diff Pressure EE	145 kPa	140 kPa
Gas/Stator Water Diff Pressure	35 kPa	Design 35kPa
Hydrogen Purity %	98.3	95
Electro Gas Drier		
Inlet Dew Point (Gen Dew Point)	-32	-25°C to +10°C
Outlet Dew Point	-56	-25°C to +10°C
Alarm	No	
Stator Water System		
Gen Inlet Pressure	370 kPa	365 kPa
Gen Outlet Pressure	130 kPa	110 kPa
Pump Suction Pressure	195 kPa	
Pump Delivery Pressure	595 kPa	
Gen Stator Water Flow l/sec	20.2 l/sec	21 l/sec
Stator Water pH	9.95	8 - 8.5
Conductivity	1.718	2µS
Oxygen Content	35.2ppb	
Stator Water Inlet Temp	51°C	Design spec: >20°C/<43°C
Stator Water Outlet Temp	68°C	
Stator Water Terminal Outlet Temp	68°C	Design spec: <72°C
H2 seal temps		50°C - 60°C
Stator bar insulation, class F limit		155°C
Bearing temps expected		65°C - 85°C

Duvha Unit 2 running data snapshot

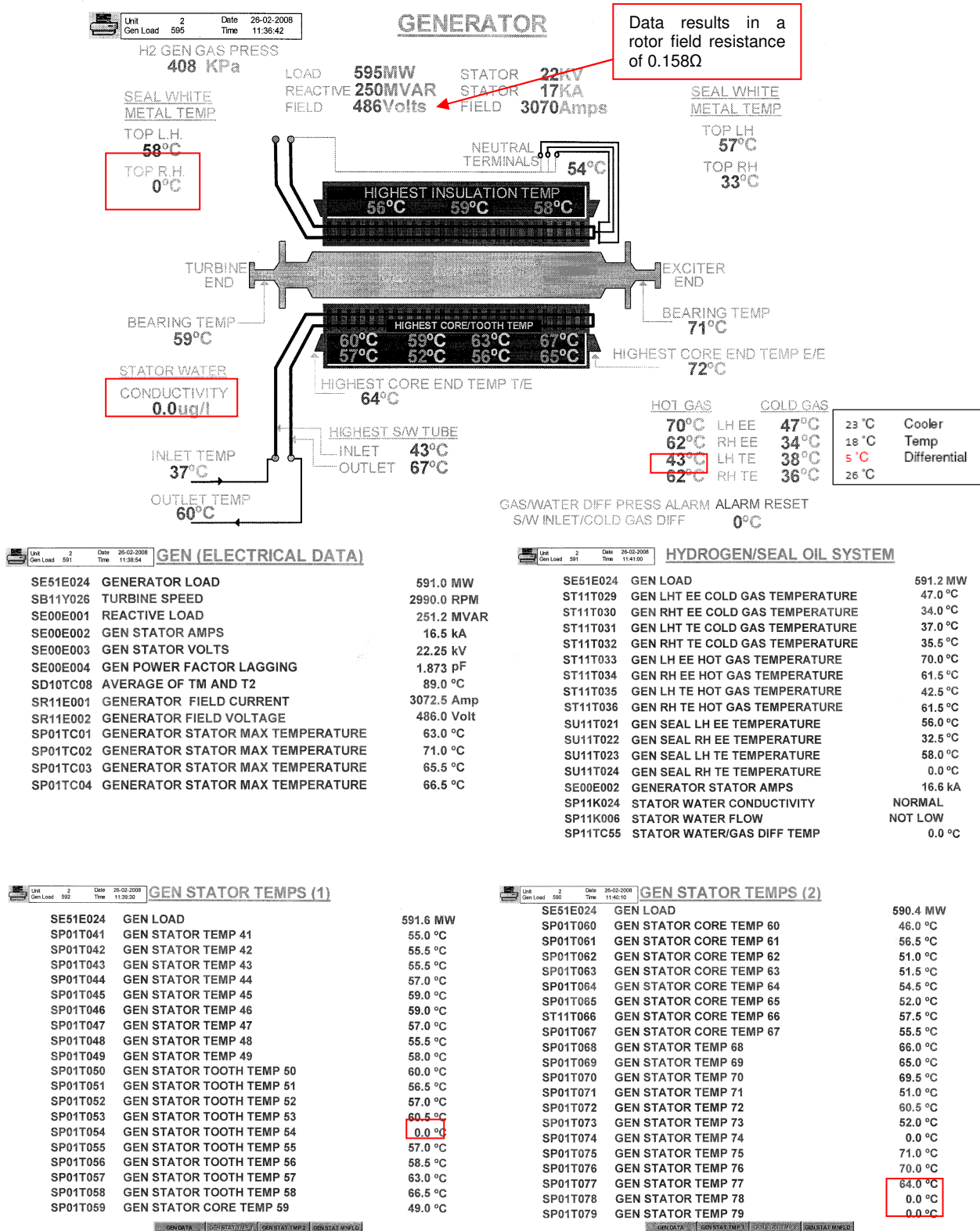


Figure 20. Duvha Unit 2 Running Data Snapshot

Duvha Unit 2 running data snapshot (cont)

Unit	2	Date	26-02-2008	GEN STATOR WATER MANIFOLD TEMPS	
Gen Load	592	Time	11:40:29		
SE51E024	GEN LOAD		591.7 MW		
SP01T080	GEN STATOR WATER INLET MANIFOLD		43.0 °C		
SP01T081	GEN STATOR WATER INLET MANIFOLD		43.0 °C		
SP01T082	GEN STATOR WATER OUTLET MANIFOLD		64.0 °C		
SP01T083	GEN STATOR WATER OUTLET MANIFOLD		63.5 °C		
SP01T084	GEN STATOR WATER OUTLET MANIFOLD		63.5 °C		
SP01T085	GEN STATOR WATER OUTLET MANIFOLD		63.5 °C		
SP01T086	GEN STATOR WATER OUTLET MANIFOLD		59.5 °C		
SP01T087	GEN STATOR WATER OUTLET MANIFOLD		62.0 °C		
SP01T088	GEN STATOR WATER OUTLET MANIFOLD		64.5 °C		
SP01T089	GEN STATOR WATER OUTLET MANIFOLD		64.0 °C		
SP01T090	GEN STATOR WATER OUTLET MANIFOLD		62.5 °C		
SP01T091	GEN STATOR WATER OUTLET MANIFOLD		63.5 °C		
SP01T092	GEN STATOR WATER OUTLET MANIFOLD		63.0 °C		
SP01T093	GEN STATOR WATER OUTLET MANIFOLD		63.0 °C		
SP01T094	GEN STATOR WATER OUTLET MANIFOLD		61.5 °C		
SP01T095	GEN STATOR WATER OUTLET MANIFOLD		58.5 °C		
SP01T096	GEN STATOR WATER OUTLET MANIFOLD		65.0 °C		
SP01T097	GEN STATOR WATER OUTLET MANIFOLD		64.0 °C		
SP01T098	GEN STATOR WATER OUTLET MANIFOLD		63.5 °C		

GEN DATA GEN STATOR TMP 1 GEN STATOR TMP 2 GEN STATOR TMP 3

Unit	2	Date	26-02-2008	STATOR WATER & CORE TOOTH	
Gen Load	590	Time	11:41:26		
SP01T099	GEN STATOR WATER OUTLET MANIFOLD		65.5 °C		
SP01T100	GEN STATOR WATER OUTLET MANIFOLD		65.0 °C		
SP01T101	GEN STATOR WATER OUTLET MANIFOLD		65.0 °C		
SP01T102	GEN STATOR WATER OUTLET MANIFOLD		61.0 °C		
SP01T103	GEN STATOR WATER OUTLET MANIFOLD		0.0 °C		
SP01T104	GEN STATOR WATER OUTLET MANIFOLD		63.5 °C		
SP01T105	GEN STATOR WATER OUTLET MANIFOLD		66.5 °C		
SP11T013	STATOR WATER GEN OUTLET TEMP		59.5 °C		
SP11T014	STATOR WATER GEN INLET TEMP		37.0 °C		
SP26T015	STATOR WATER GEN NEUT OUTLET TEMP		53.5 °C		
SP01T110	GEN STATOR TOOTH TEMP		0.0 °C		
SP01T112	GEN STATOR TOOTH TEMP		0.0 °C		
SP01T114	GEN STATOR TOOTH TEMP		0.0 °C		
SP01T116	GEN STATOR CORE TEMP		0.0 °C		
SP01T118	GEN STATOR CORE TEMP		0.0 °C		
SP01T117	GEN STATOR CORE TEMP		0.0 °C		
SP01T111	GEN STATOR TEMP 111		0.0 °C		
SP01T113	GEN STATOR TEMP 113		0.0 °C		
SP01T115	GEN STATOR TEMP 115		0.0 °C		

H2 & SEAL OIL STATOR & CORE

Plant Data Captured during Walk-Down	
Parameter	Unit 2
Hydrogen System	
Hydrogen Range Pressure	540 kPa
Oil/Gas Diff Pressure TE	160 kPa
Gen Casing Pressure	410 kPa
Oil/Gas Diff Pressure EE	145 kPa
Gas/Stator Water Diff Pressure	OC
Hydrogen Purity %	98.3
Electro Gas Drier	
Inlet Dew Point (Gen Dew Point)	Error
Outlet Dew Point	-63
Alarm	
Stator Water System	
Gen Inlet Pressure	370 kPa
Gen Outlet Pressure	110 kPa
Pump Suction Pressure	200 kPa
Pump Delivery Pressure	585 kPa
Gen Stator Water Flow l/sec	20 l/sec
Stator Water pH	OC
Conductivity	1.35
Oxygen Content	27.9 ppb
Stator Water Inlet Temp	43 °C
Stator Water Outlet Temp	64 °C
Stator Water Terminal Outlet Temp	38 °C

Running Data Snapshot key	
	Parameter referenced in Unit Report Section
	Parameter data questionable
50 °C	Parameter normal
40 °C	Parameter outside expected value
40 °C	Parameter outside normal operating zone

Duvha Unit 3 running data snapshot

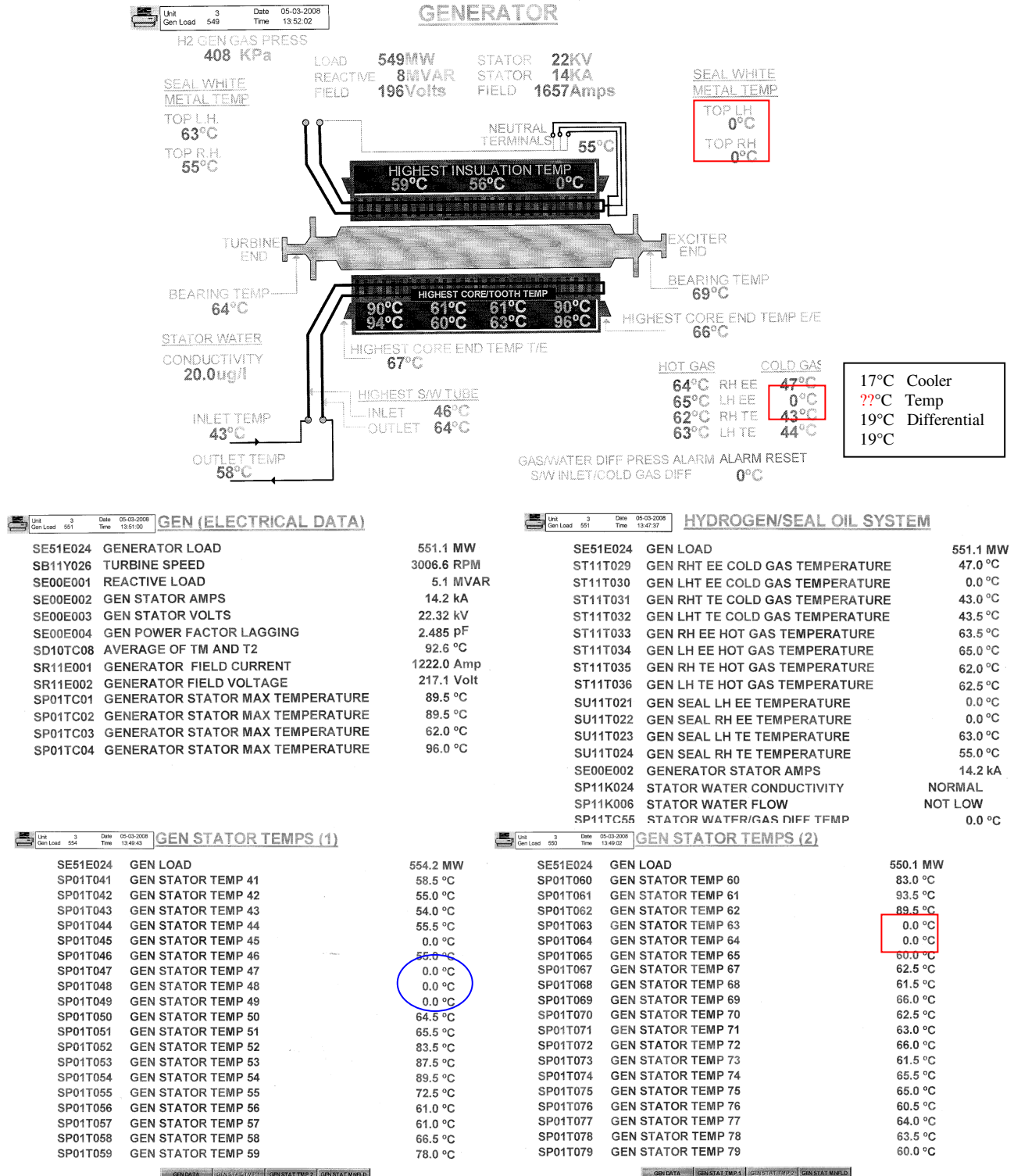


Figure 21. Duvha Unit 3 Running Data Snapshot

Duvha Unit 3 running data snapshot (cont)

Unit	3	Date	05-03-2008	Time	13:48:19	GEN STATOR WATER MANIFOLD TEMPS
Gen Load	547					547.2 MW
SE51E024	GEN LOAD					46.0 °C
SP01T080	GEN STATOR WATER INLET MANIFOLD					46.0 °C
SP01T081	GEN STATOR WATER INLET MANIFOLD					58.5 °C
SP01T082	GEN STATOR WATER OUTLET MANIFOLD					30.5 °C
SP01T083	GEN STATOR WATER OUTLET MANIFOLD					60.0 °C
SP01T084	GEN STATOR WATER OUTLET MANIFOLD					60.0 °C
SP01T085	GEN STATOR WATER OUTLET MANIFOLD					61.0 °C
SP01T086	GEN STATOR WATER OUTLET MANIFOLD					61.0 °C
SP01T087	GEN STATOR WATER OUTLET MANIFOLD					61.0 °C
SP01T088	GEN STATOR WATER OUTLET MANIFOLD					58.5 °C
SP01T089	GEN STATOR WATER OUTLET MANIFOLD					57.0 °C
SP01T090	GEN STATOR WATER OUTLET MANIFOLD					0.0 °C
SP01T091	GEN STATOR WATER OUTLET MANIFOLD					60.0 °C
SP01T092	GEN STATOR WATER OUTLET MANIFOLD					60.5 °C
SP01T093	GEN STATOR WATER OUTLET MANIFOLD					61.5 °C
SP01T094	GEN STATOR WATER OUTLET MANIFOLD					61.0 °C
SP01T095	GEN STATOR WATER OUTLET MANIFOLD					62.0 °C
SP01T096	GEN STATOR WATER OUTLET MANIFOLD					59.5 °C
SP01T097	GEN STATOR WATER OUTLET MANIFOLD					60.5 °C
SP01T098	GEN STATOR WATER OUTLET MANIFOLD					

Plant Data Captured during Walk-Down	
Parameter	Unit 3
Hydrogen System	
Hydrogen Range Pressure	540 kPa
Oil/Gas Diff Pressure TE	160 kPa
Gen Casing Pressure	420 kPa
Oil/Gas Diff Pressure EE	158 kPa
Gas/Stator Water Diff Pressure	35 kPa
Hydrogen Purity %	96.5
Electro Gas Drier	
Inlet Dew Point (Gen Dew Point)	-42
Outlet Dew Point	-86
Alarm	
Stator Water System	
Gen Inlet Pressure	365 kPa
Gen Outlet Pressure	90 kPa
Pump Suction Pressure	200 kPa
Pump Delivery Pressure	600 kPa
Gen Stator Water Flow	22 l/sec
Stator Water pH	6.31
Conductivity	1.66
Oxygen Content	92ppb
Stator Water Inlet Temp	46 °C
Stator Water Outlet Temp	60 °C
Stator Water Terminal Outlet Temp	60 °C

Unit	3	Date	05-03-2008	Time	13:48:37	STATOR WATER & CORE TOOTH
Gen Load	554					
SP01T099	GEN STATOR WATER OUTLET MANIFOLD					62.0 °C
SP01T100	GEN STATOR WATER OUTLET MANIFOLD					62.0 °C
SP01T101	GEN STATOR WATER OUTLET MANIFOLD					0.0 °C
SP01T102	GEN STATOR WATER OUTLET MANIFOLD					63.5 °C
SP01T103	GEN STATOR WATER OUTLET MANIFOLD					62.0 °C
SP01T104	GEN STATOR WATER OUTLET MANIFOLD					62.0 °C
SP01T105	GEN STATOR WATER OUTLET MANIFOLD					59.0 °C
SP11T013	STATOR WATER GEN OUTLET TEMP					58.0 °C
SP11T014	STATOR WATER GEN INLET TEMP					42.5 °C
SP26T015	STATOR WATER GEN NEUT OUTLET TEMP					54.5 °C
SP01T110	GEN STATOR TOOTH TEMP					80.5 °C
SP01T112	GEN STATOR TOOTH TEMP					89.5 °C
SP01T114	GEN STATOR TOOTH TEMP					68.5 °C
SP01T116	GEN STATOR CORE TEMP					87.0 °C
SP01T118	GEN STATOR CORE TEMP					84.5 °C
SP01T117	GEN STATOR CORE TEMP					96.0 °C
SP01T111	GEN STATOR TEMP 111					78.0 °C
SP01T113	GEN STATOR TEMP 113					66.0 °C
SP01T115	GEN STATOR TEMP 115					85.5 °C

Running Data Snapshot key	
	Parameter referenced in Unit Report Section
	Parameter data questionable
50 °C	Parameter normal
40 °C	Parameter outside expected value
40 °C	Parameter outside normal operating zone

Duvha Unit 4 running data snapshot

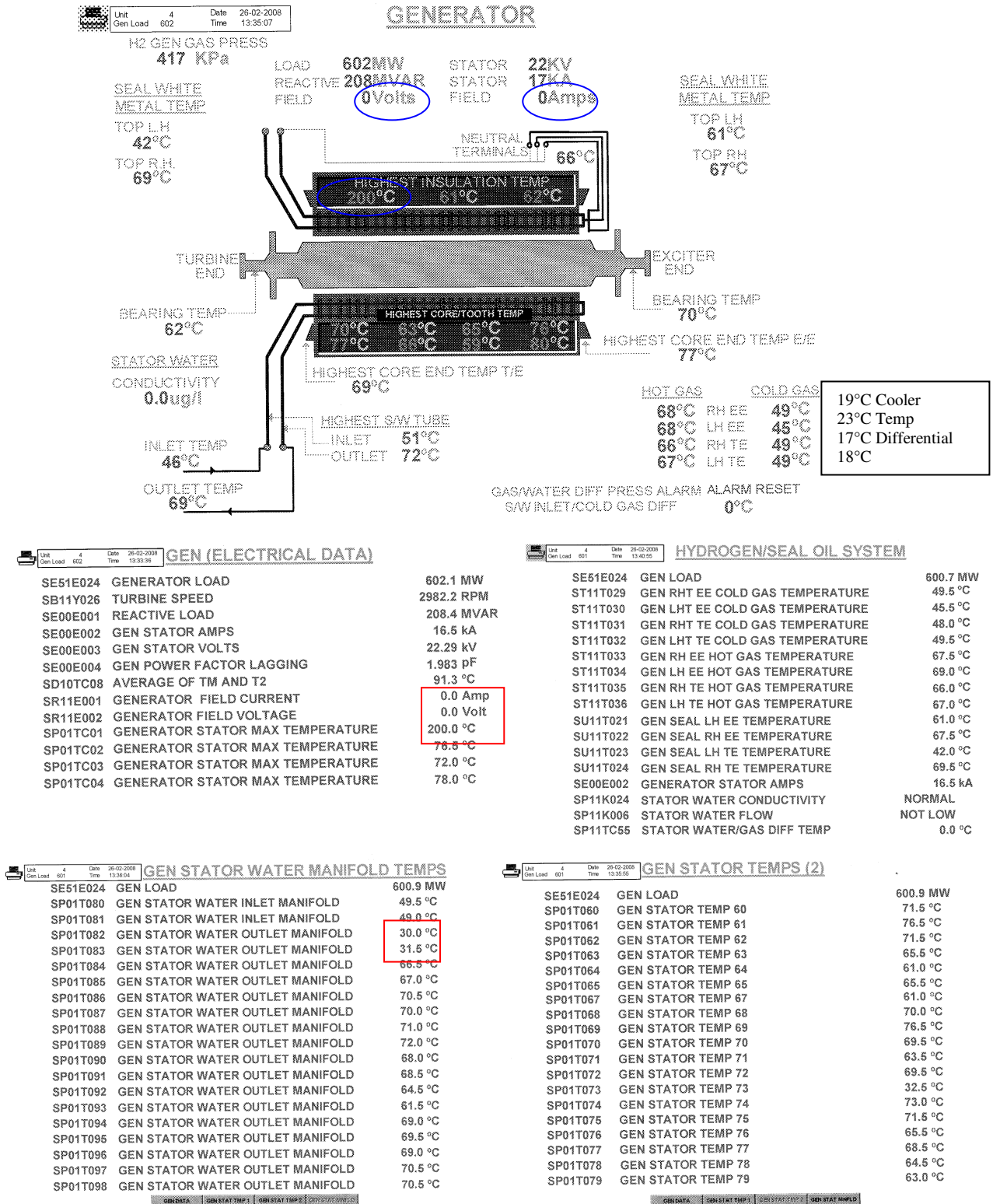


Figure 22. Duvha Unit 4 Running Data Snapshot

Duvha Unit 4 running data snapshot (cont)

Unit	4	Date	26-02-2008
Gen Load	601	Time	13:36:04
GEN STATOR WATER MANIFOLD TEMPS			
SE51E024	GEN LOAD		600.9 MW
SP01T080	GEN STATOR WATER INLET MANIFOLD		49.5 °C
SP01T081	GEN STATOR WATER INLET MANIFOLD		49.0 °C
SP01T082	GEN STATOR WATER OUTLET MANIFOLD		30.0 °C
SP01T083	GEN STATOR WATER OUTLET MANIFOLD		31.5 °C
SP01T084	GEN STATOR WATER OUTLET MANIFOLD		66.5 °C
SP01T085	GEN STATOR WATER OUTLET MANIFOLD		67.0 °C
SP01T086	GEN STATOR WATER OUTLET MANIFOLD		70.5 °C
SP01T087	GEN STATOR WATER OUTLET MANIFOLD		70.0 °C
SP01T088	GEN STATOR WATER OUTLET MANIFOLD		71.0 °C
SP01T089	GEN STATOR WATER OUTLET MANIFOLD		72.0 °C
SP01T090	GEN STATOR WATER OUTLET MANIFOLD		68.0 °C
SP01T091	GEN STATOR WATER OUTLET MANIFOLD		68.5 °C
SP01T092	GEN STATOR WATER OUTLET MANIFOLD		64.5 °C
SP01T093	GEN STATOR WATER OUTLET MANIFOLD		61.5 °C
SP01T094	GEN STATOR WATER OUTLET MANIFOLD		69.0 °C
SP01T095	GEN STATOR WATER OUTLET MANIFOLD		69.5 °C
SP01T096	GEN STATOR WATER OUTLET MANIFOLD		69.0 °C
SP01T097	GEN STATOR WATER OUTLET MANIFOLD		70.5 °C
SP01T098	GEN STATOR WATER OUTLET MANIFOLD		70.5 °C

GEN DATA | GEN STAT TMP 1 | GEN STAT TMP 2 | GEN STAT TMP 3

Plant Data Captured during Walk-Down	
Parameter	Unit 4
Hydrogen System	
Hydrogen Range Pressure	530 kPa
Oil/Gas Diff Pressure TE	165 kPa
Gen Casing Pressure	400 kPa
Oil/Gas Diff Pressure EE	178 kPa
Gas/Stator Water Diff Pressure	40 kPa
Hydrogen Purity %	99.4
Electro Gas Drier	
Inlet Dew Point (Gen Dew Point)	-11
Outlet Dew Point	20
Alarm	
Stator Water System	
Gen Inlet Pressure	350 kPa
Gen Outlet Pressure	140 kPa
Pump Suction Pressure	195 kPa
Pump Delivery Pressure	597 kPa
Gen Stator Water Flow	20.2 l/sec
Stator Water pH	9.92
Conductivity	1.012
Oxygen Content	84.5ppb
Stator Water Inlet Temp	41 °C
Stator Water Outlet Temp	55 °C
Stator Water Terminal Outlet Temp	55 °C

Unit	4	Date	26-02-2008
Gen Load	603	Time	13:35:44
GEN STATOR TEMPS (1)			
SE51E024	GEN LOAD		603.1 MW
SP01T041	GEN STATOR TEMP 41		61.5 °C
SP01T042	GEN STATOR TEMP 42		2047. °C
SP01T043	GEN STATOR TEMP 43		59.5 °C
SP01T044	GEN STATOR TEMP 44		59.0 °C
SP01T045	GEN STATOR TEMP 45		59.5 °C
SP01T046	GEN STATOR TEMP 46		59.0 °C
SP01T047	GEN STATOR TEMP 47		60.0 °C
SP01T048	GEN STATOR TEMP 48		62.0 °C
SP01T049	GEN STATOR TEMP 49		61.0 °C
SP01T050	GEN STATOR TEMP 50		62.0 °C
SP01T051	GEN STATOR TEMP 51		55.0 °C
SP01T052	GEN STATOR TEMP 52		25.5 °C
SP01T053	GEN STATOR TEMP 53		69.0 °C
SP01T054	GEN STATOR TEMP 54		66.0 °C
SP01T055	GEN STATOR TEMP 55		60.5 °C
SP01T056	GEN STATOR TEMP 56		62.0 °C
SP01T057	GEN STATOR TEMP 57		65.0 °C
SP01T058	GEN STATOR TEMP 58		60.5 °C
SP01T059	GEN STATOR TEMP 59		75.0 °C

GEN DATA | GEN STAT TMP 1 | GEN STAT TMP 2 | GEN STAT TMP 3

Running Data Snapshot key	
	Parameter referenced in Unit Report Section
	Parameter data questionable
50 °C	Parameter normal
40 °C	Parameter outside expected value
40 °C	Parameter outside normal operating zone

Duvha Unit 5 running data snapshot

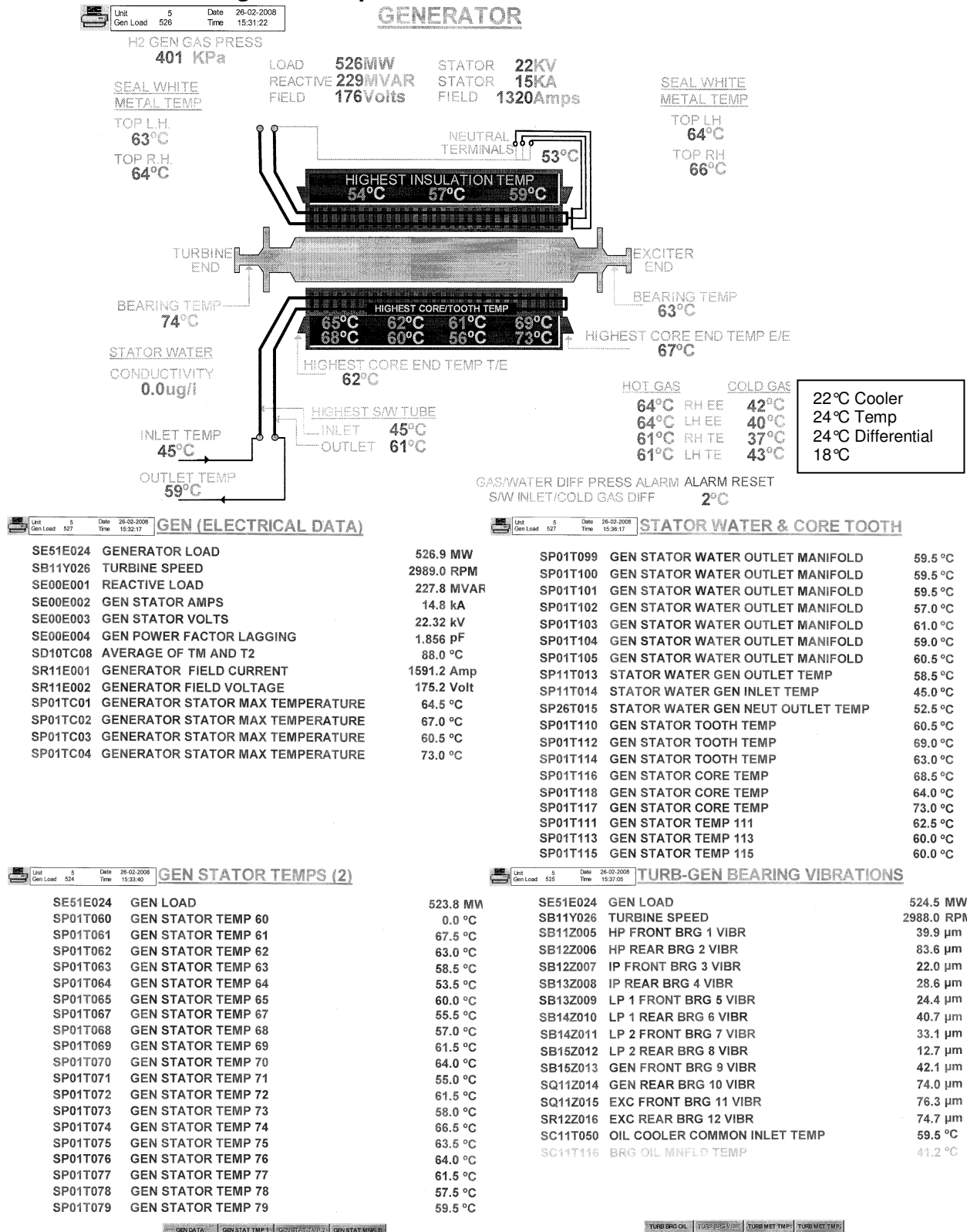


Figure 23. Duvha Unit 5 Running Data Snapshot

Duvha Unit 5 running data snapshot (cont)

Unit	5	Date	26-02-2008	TURB-GEN BEARING VIBRATIONS
Gen Load	525	Time	15:37:05	
SE51E024	GEN LOAD		524.5 MW	
SB11Y026	TURBINE SPEED		2988.0 RPM	
SB11Z005	HP FRONT BRG 1 VIBR		39.9 µm	
SB12Z006	HP REAR BRG 2 VIBR		83.6 µm	
SB12Z007	IP FRONT BRG 3 VIBR		22.0 µm	
SB13Z008	IP REAR BRG 4 VIBR		28.6 µm	
SB13Z009	LP 1 FRONT BRG 5 VIBR		24.4 µm	
SB14Z010	LP 1 REAR BRG 6 VIBR		40.7 µm	
SB14Z011	LP 2 FRONT BRG 7 VIBR		33.1 µm	
SB15Z012	LP 2 REAR BRG 8 VIBR		12.7 µm	
SB15Z013	GEN FRONT BRG 9 VIBR		42.1 µm	
SQ11Z014	GEN REAR BRG 10 VIBR		74.0 µm	
SQ11Z015	EXC FRONT BRG 11 VIBR		76.3 µm	
SR12Z016	EXC REAR BRG 12 VIBR		74.7 µm	
SC11T050	OIL COOLER COMMON INLET TEMP		59.5 °C	
SC11T116	BRG OIL MNFLD TEMP		41.2 °C	

TURB BRG OIL TURB BRG VIBR TURB MET TMP TURB MET TMP

Plant Data Captured during Walk-Down	
Parameter	Unit 5
Hydrogen System	
Hydrogen Range Pressure	520 kPa
Oil/Gas Diff Pressure TE	165 kPa
Gen Casing Pressure	400 kPa
Oil/Gas Diff Pressure EE	150 kPa
Gas/Stator Water Diff Pressure	35 kPa
Hydrogen Purity %	
Electro Gas Drier	
Inlet Dew Point (Gen Dew Point)	25
Outlet Dew Point	-55
Alarm	
Stator Water System	
Gen Inlet Pressure	350 kPa
Gen Outlet Pressure	95 kPa
Pump Suction Pressure	200 kPa
Pump Delivery Pressure	605 kPa
Gen Stator Water Flow	21 l/sec
Stator Water pH	9.47
Conductivity	1.08
Oxygen Content	4.7ppb
Stator Water Inlet Temp	38 °C
Stator Water Outlet Temp	63 °C
Stator Water Terminal Outlet Temp	55 °C

Running Data Snapshot key

 Parameter referenced in Unit Report Section

 Parameter data questionable

50 °C Parameter normal
 40 °C Parameter outside expected value
 40 °C Parameter outside normal operating zone

Duvha Unit 6 running data snapshot

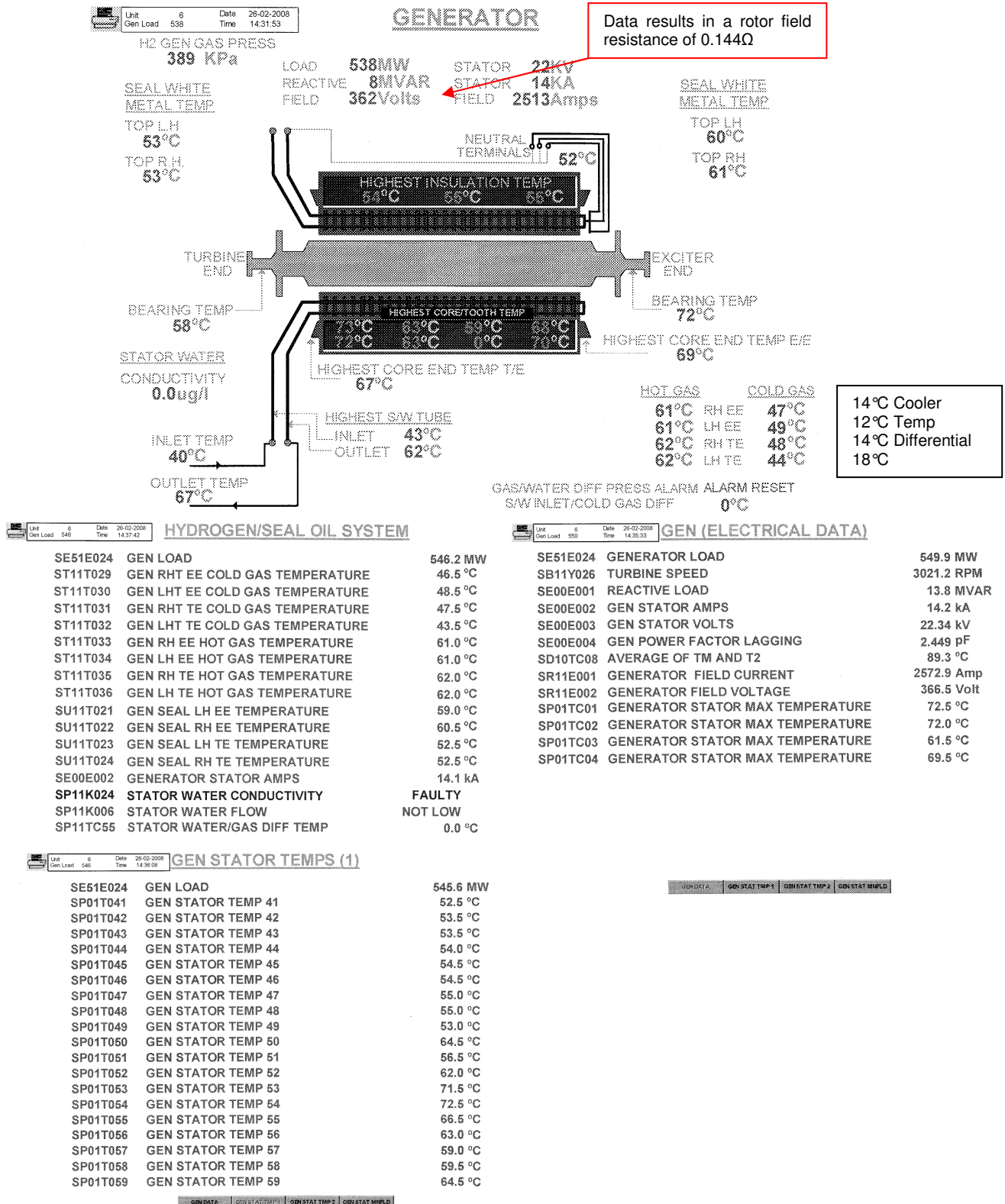


Figure 24. Duvha Unit 6 Running Data Snapshot

Duvha Unit 6 running data (cont)

Unit	6	Date	26-02-2008	GEN STATOR WATER MANIFOLD TEMPS	
Gen Load	544	Time	14:36:59		
SE51E024	GEN LOAD		544.1 MW		
SP01T080	GEN STATOR WATER INLET MANIFOLD		42.5 °C		
SP01T081	GEN STATOR WATER INLET MANIFOLD		43.0 °C		
SP01T082	GEN STATOR WATER OUTLET MANIFOLD		59.5 °C		
SP01T083	GEN STATOR WATER OUTLET MANIFOLD		61.0 °C		
SP01T084	GEN STATOR WATER OUTLET MANIFOLD		60.0 °C		
SP01T085	GEN STATOR WATER OUTLET MANIFOLD		59.5 °C		
SP01T086	GEN STATOR WATER OUTLET MANIFOLD		59.0 °C		
SP01T087	GEN STATOR WATER OUTLET MANIFOLD		56.5 °C		
SP01T088	GEN STATOR WATER OUTLET MANIFOLD		60.0 °C		
SP01T089	GEN STATOR WATER OUTLET MANIFOLD		59.5 °C		
SP01T090	GEN STATOR WATER OUTLET MANIFOLD		58.0 °C		
SP01T091	GEN STATOR WATER OUTLET MANIFOLD		59.0 °C		
SP01T092	GEN STATOR WATER OUTLET MANIFOLD		59.0 °C		
SP01T093	GEN STATOR WATER OUTLET MANIFOLD		55.5 °C		
SP01T094	GEN STATOR WATER OUTLET MANIFOLD		59.0 °C		
SP01T095	GEN STATOR WATER OUTLET MANIFOLD		57.0 °C		
SP01T096	GEN STATOR WATER OUTLET MANIFOLD		0.0 °C		
SP01T097	GEN STATOR WATER OUTLET MANIFOLD		0.0 °C		
SP01T098	GEN STATOR WATER OUTLET MANIFOLD		59.0 °C		
GEN DATA		GEN STAT TMP 1	GEN STAT TMP 2	GEN STAT MANIFOLD	

Plant Data Captured during Walk-Down	
Parameter	Unit 6
Hydrogen System	
Hydrogen Range Pressure	550 kPa
Oil/Gas Diff Pressure TE	155 kPa
Gen Casing Pressure	390 kPa
Oil/Gas Diff Pressure EE	182 kPa
Gas/Stator Water Diff Pressure	25 kPa
Hydrogen Purity %	98.3
Electro Gas Drier	
Inlet Dew Point (Gen Dew Point)	-3
Outlet Dew Point	3
Alarm	Standing
Stator Water System	
Gen Inlet Pressure	365 kPa
Gen Outlet Pressure	110 kPa
Pump Suction Pressure	200 kPa
Pump Delivery Pressure	595 kPa
Gen Stator Water Flow l/sec	20.5 l/sec
Stator Water pH	8.6
Conductivity	0.782
Oxygen Content	19.9ppb
Stator Water Inlet Temp	40 °C
Stator Water Outlet Temp	68 °C
Stator Water Terminal Outlet Temp	50 °C

Running Data Snapshot key	
	Parameter referenced in Unit Report Section
	Parameter data questionable
50 °C	Parameter normal
40 °C	Parameter outside expected value
40 °C	Parameter outside normal operating zone

A2. Summary Extract from Reports S180/05/040/a & S180/06/029/a:

(a) ALSTOM Power Service Generator On/Off Line Assessment Report S180/05/040/a Summary Extract – On line Duvha Unit 4 Rotor S2079/05

“An on-line rotor slot flux measurement was conducted on Duvha unit 4 generator in accordance with ALSTOM Power Service procedures. The results of the analysis indicate that the coil 1 (lagging) had an apparent fault indication of 1 shorted turn (14% of coil). After further analysis of the measurement data and other associated information detailed in this report this is probably due to the presence of an aluminium plug in a balance weight hole on the pole face rather than the actual inter-turn fault presented as our preliminary findings. This interpretation is detailed in pages 4 and 5. For a reactive load swing the apparent indication on coil 1 (leading) of 0.05 to 0.4 of a shorted turn (0.5 to 6% of coil) for the radial measurement and 0.05 to 0.95 of shorted turn (0.5 to 14% of coil) for the tangential measurement. This exhibits an unusual characteristic, which may be a combination of the aluminium plug in a balance weight hole on the pole and a possible inter-turn fault on the opposite pole. Further investigation is necessary to fully establish the presence of an inter-turn fault as detailed in the recommended section.”

(b) ALSTOM Power Service Generator On-Line Assessment Report S180/06/029/a Summary Extract – On line Duvha Unit 4 Rotor S2079/05

“The maximum apparent fault indication recorded from the slot type probe on coil 1 is 0.77 shorted turns on the leading edge of pole A. The fault indication level varies in load to a minimum of 0.05 shorted turns (noise levels) and varies in a manner that is not consistent with a current carrying fault.

The maximum apparent fault indication recorded from the rod type probe on coil 1 is 2.0 shorted turns on the leading edge of pole A. This level does not vary with load. This is again not consistent with the behaviour expected from a real fault.

The slot 1 fault indication from the slot type probe can be related to rotor heating and hence the position of the probe with respect to the balance weights in the slot 1 regions. This indicates that this behaviour is caused by the magnetic effect of the balance weights adjacent to slot 1. The shape of the waveform in this region is also indicative of a magnetic anomaly.

Other effects is expected if a real fault were present such as increased vibration and indications on the latest RSO tests have not been observed.

It is concluded from the data gathered that the rotor is free from current carrying shorts.”

A3. Plant Assessment Process Overview Extract

Plant Integrity Assessment

The ALSTOM Asset Management Process [30] (Figure 25) aims to develop a systematic and coordinated approach to activities and practices, through which an organisation can optimally manage its assets and their associated performance, risks and expenditures over the life cycle, for the purposes of achieving its organisational strategy plan.

The Plant Integrity Assessment Process forms the key element to Stage 1 Asset Condition Assessment of the Asset Management Process.

The Plant Integrity Assessment (Figure 26) is an analytical process used to provide a full understanding of the condition of the plant. The approach is built on failure mode analysis at sub component level identifying failure modes and associated operational driver supported by the following key input streams.

The Monitored Condition as determined by Process Indicators such as on-line condition monitoring data. The Inspection Condition as determined by reviewing the results of off-line inspections and tests.

The Feature score captures Operational Experience, include expert opinion and capture experience from across similar unit designs, based on the key groups of Family – Any problems seen on sister plant, Expert Knowledge – Any known or foreseeable problems based on design knowledge and as advised by experts and Stable – Any problems seen on plant that utilises the same technology/component design.

These input streams values are combined to develop an assessment of the sub component condition that is then summed to express an overall Assessed Condition of the sub component. The individually Assessed Condition component scores are then utilised to develop an understanding the overall unit and hence plant condition.

Criticality Review

The Criticality Review develops the sub component analysis and Assessed Condition Score to achieve a ranked sub component score which can be utilised to support and inform station personnel in their assessment of the unit operational and maintenance risk.

A minimum sub component threshold level score of 1.5 is set for the criticality process; this reduces the sensitivity to single data point entries and ensures that the criticality review is based on scores developed from the interaction of multiple entries and across scoring sections. The criticality list is drawn up from sub component assessed condition scores of greater than 1 to ensure capture of any sub component falling just below the set threshold level of 1.5 which would post Consequence of Failure (CoF) analysis be elevated in the criticality ranked listing.

During the Criticality Review the sub component scores are amended for the Consequence of Failure analysis based on defect driver and significance.

The Consequence of Failure is developed from three key aspects coded S, W and D:

S- Whether the failure would cause machine shutdown, i.e. a breakdown requiring immediate attention. 1 no shutdown required, 10 instant machine shutdown.

W- The amount of work required to rectify the problem, i.e. including cost and downtime. 1 no work required, 10 major replacement > 2 months.

D- Damage to other parts of the machine. 1 no damage to other components, 10 catastrophic failure/major damage to turbine generator/plant.

The three key aspects are given equal weighting with the resulting CoF calculated as the average of the S, W and D scores.

The original ranked sub component score is combined with the associated CoF to produce a ranked criticality where:

- Criticality Score = Assessed Condition Score x CoF

The Criticality Review then steps through a structured review of mitigation options and their applicability.

With the ranked criticality list being supported at sub component level the key drivers to the overall unit Assessed Condition Score are clearly identified and the resolution enables targeted actions to be identified.

The results of the criticality review are presented in the Criticality Review Table with supporting criticality discussion of significant finding arising during the analysis process.

This understanding of plant condition is then combined with other plant considerations such as the effects of future maintenance plans and spares holding to develop a criticality assessment within the Plant Assessment Report.



Figure 25. ALSTOM Asset Management Process [30]

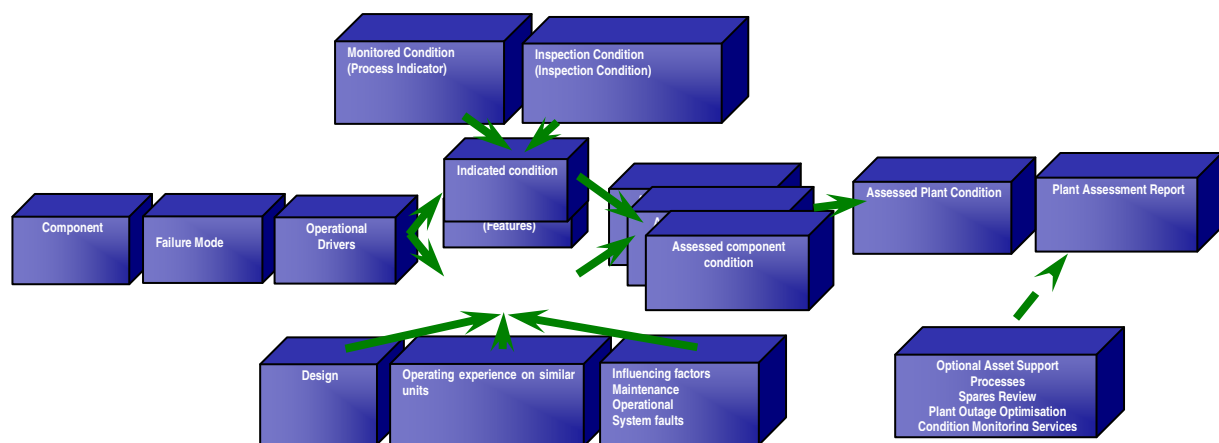


Figure 26. ALSTOM Plant Assessment Process [30]

A4. Sub Component Analysis and Assessed Condition Score

Duvha Unit 1:

Sub Component	Failure Mode	Due To	Process Indicator	Inspection Condition	Features	The Final Assessed Condition Status Score
ROTORS:						
Rotor body ends (Endring seating/Comp fixing holes, etc.):						
Comb Fixing Holes	Cracking				1.00	1.00
Rotor Shaft Ends:						
Shaft ends general	Cracking		2.00	0.78		2.15
Splines					1.00	1.00
Rotor: Coils insulation packing wedges:						
Pole slot wedges	Cracking	Fatigue		0.75		0.75
Rotor coils	Crack at braze	Bad brazing			0.50	0.50
Pole slot dampers & associated packing & fixing	Overheating	Unbalanced faults		0.75		0.75
Field leads & connections	Cracking	Thermal & centrifugal expansion forces		0.75	0.50	0.90
Radial stalks	Cracking	Fatigue		0.79		0.79
STATORS:						
Stator Annular Core Stator Frame Core:						
Stator frame/casing	H2 leakage	Incorrect frame sealing	1.50			1.50
Core plate & insulation	Melting (circulating current)	Loss of cooling	0.20	0.58		0.62
Core finger plates, clamp plates & endplates	Melting (circulating current)	Over fluxing			1.00	1.00
Core support system	Weld failure	Fatigue			1.00	1.00
Stator Windings: Coils, insulation, wndgs :						
LNB coil- slot portion	Earth fault	Therm.aging (blockages)			1.00	1.00
LFB coil- slot portion	Earth fault	Therm.aging (blockages)		0.89	1.00	1.29
LNB coil- overhang portion	Earth fault	Therm.aging (Blockages)			1.00	1.00
LFB coil- Overhang portion	Earth fault	Therm.aging (Blockages)		0.61	1.00	1.17
Stator WNDGS- CONNS & TERMLS incl TERML boxes:						
Coil to phase ring connections	Cracking	Stress (thermal expansion)		0.78		0.78
Phase ring & extensions	Cracking	Stress (thermal expansion)			0.50	0.50
Flexible connections to terminals	Cracking	Vibration		0.78		0.78
Stator WNDGS-Water cooling manifold & hoses:						
PTFE hoses				0.33		0.33
Manifolds	Cracking	High vibration		0.50	2.00	2.06
Stator INSTMTN/core coil cooling & heater:						
Core & endplate thermocouples	Open/short circuit	Mechanical overload	0.33	0.56		0.65
Inlet & outlet Manifold temperatures			2.50	0.33		2.52
Gas temperature monitoring	Overheating	Loss of coolant	1.00			1.00
VNTLTN & CLRS-STR ENCL-E/SHLD.F/SHLD & AIR BFLS:						
Hydrogen coolers	Tube erosion	Poor water quality	0.10			0.10
Pedestals & Bearings:						
Bearing liners			3.50			3.50
Bearing Brackets & Bearings:						
Bearing Liners			3.50			3.50
Oil Wipers				0.33		0.33
Gland Seals. Oil Baffles etc:						
Seal Carrier	Loss of insulation	Contamination	0.25	0.50		0.56
Seal Oil System:						
Instrumentation			1.00			1.00
Exciters:						
Exciter cubicle polarity bar				0.67		0.67
			15.88	10.60	11.50	34.69

Duvha Unit 2:

Sub Component	Failure Mode	Due To	Process Indicator	Inspection Condition	Features	The Final Assessed Condition Status Score
ROTORS:						
ROTOR: BODY, SHAFT, CPLING, COMP						
Shaft ends general	Cracking		1.00			1.00
Bearing Journal	Cracking			0.75		0.75
Face Collar				0.78		0.78
Splines					1.00	1.00
ROTOR: COILS, INSUL, PKNG & WDGES						
Rotor coils	Crack at braze	Bad brazing		0.78		0.78
Pole slot dampers & associated packing & fixing	Overheating	Unbalanced faults			1.00	1.00
Endwinding Retaining Rings	Cracking	Stress corrosion		0.56		0.56
Field leads & connections	Cracking	Thermal & centrifugal			0.50	0.50
STATORS:						
STATOR ANNULAR CORE: STATOR FRAME & CORE						
Stator frame/casing	H2 leakage	Incorrect frame sealing	1.50	0.78		1.69
Core plate & insulation	Melting (circulating current)	Loss of cooling			0.50	0.50
STATOR WINDINGS: COIL & INSUL + WNDGS						
LNB coil- slot portion	Earth fault	Therm.aging (blockages)			1.00	1.00
LFB coil- slot portion	Earth fault	Therm.aging (blockages)			1.00	1.00
LNB coil- overhang portion	Earth fault	Therm.aging (Blockages)			1.00	1.00
LFB coil- Overhang portion	Earth fault	Therm.aging (Blockages)			1.00	1.00
STATOR WNDGS: SUPPORT PACKINGS & WEDGES						
Endwinding support structure	Looseness	Decohesion			1.00	1.00
STATOR WNDGS, CONNS & TERMLS incl TERML boxes:						
Coil to phase ring connections	Cracking	Stress (thermal expansion)		0.11		0.11
Phase ring & extensions	Cracking	Stress (thermal expansion)			1.00	1.00
Terminals & flanges	Flashover	Oil ingress		0.04		0.04
Stator WNDGS-Water cooling manifold & hoses:						
Manifolds	Cracking	High vibration		0.75	1.00	1.25
Manifold connection pipes (bellows, etc.)	Cracking	High vibration		0.75		0.75
STATOR INSTMTN(CORE, COIL, COOLING & HEATER)						
Gas temperature monitoring	Overheating	Loss of coolant	1.00			1.00
VNTLTN & CLRS-STR ENCL-E/SHLD.F/SHLD & AIR BFLS:						
Hydrogen coolers	Tube erosion	Poor water quality	2.00			2.00
PEDESTALS & BEARINGS:						
Bearing liners			1.00			1.00
Pads & insulation				0.67		0.67
Jacking oil hoses/pipes	Fracture	Hot oil		1.67	1.00	1.94
BEARING BRACKETS & BEARINGS:						
Bearing Liners			1.00			1.00
Oil Wipers				0.33		0.33
GLAND SEALS. OIL BAFFELS ETC.:						
Aux						
GENERAL ARRANGEMENT OF MACHINES & WORKS TEST:						
Alignment				0.67		0.67
Exciters:						
Exciter bearing				1.00		1.00
			9.50	9.63	11.00	26.31

Duvha Unit 3:

Sub Component	Failure Mode	Due To	Process Indicator	Inspection Condition	Features	The Final Assessed Condition Status Score
ROTORS:						
ROTOR: BODY, SHAFT, CPLING, COMP						
Endring Sealings	Cracking	High compressive stress			1.00	1.00
Comb fixing holes	Cracking				1.00	1.00
Rotor Shaft Ends						
Shaft ends general	Cracking		1.00			1.00
F.E. Seal Journal	Cracking		2.00			2.00
R.E. Seal Journal	Cracking		2.00			2.00
ROTOR: COILS, INSUL, PKNG & WDGS						
Rotor coils	Crack at braze	Bad brazing			1.00	1.00
Pole to Pole connections	Crack at braze	Bad brazing			1.00	1.00
Main Slot Cells & Slot Bridge Pieces	Earth Fault	Coil movement (thermal)			1.00	1.00
Pole slot dampers & associated packing & fixing	Overheating	Unbalanced faults			2.00	2.00
Endwinding Retaining Rings	Cracking	Stress corrosion			1.00	1.00
Endwinding Retaining Ring Insulation	Inter-turn/coil short	Overheating			1.00	1.00
Field leads & connections	Cracking	Thermal & centrifugal			0.50	0.50
STATORS:						
STATOR ANNULAR CORE: STATOR FRAME & CORE						
Stator frame/casing	H2 leakage	Incorrect frame sealing	1.00			1.00
STATOR WINDINGS: COIL & INSUL + WNDGS						
LNB coil- slot portion	Earth fault	Therm.aging (blockages)		0.81	1.00	1.29
LFB coil- slot portion	Earth fault	Therm.aging (blockages)			1.00	1.00
LNB coil- overhang portion	Earth fault	Therm.aging (Blockages)			1.00	1.00
LFB coil- Overhang portion	Earth fault	Therm.aging (Blockages)		0.81	1.00	1.28
STATOR WNDGS: SUPPORT PACKINGS & WEDGES						
Endwinding support structure	Looseness	Decohesion		0.67		0.67
Endwinding support bolting & lashing	Looseness	Decohesion		0.67		0.67
STATOR WNDGS, CONNS & TERMLS incl TERML boxes:						
Phase ring & extensions	Cracking	Stress (thermal expansion)		0.78	0.50	0.92
Terminals & flanges	Flashover	Oil ingress		0.79		0.79
Terminal boxes & mounting plates	Cracking	Fatigue		0.75		0.75
Stator WNDGS-Water cooling manifold & hoses:						
PTFE Hoses				2.00		2.00
Manifolds	Cracking	High vibration		0.75		0.75
Manifold Vent Pipes		High vibration		0.67		0.67
STATOR INSTMTN(CORE, COIL, COOLING & HEATER)						
Inlet & Outlet Manifold temperatures			2.50			2.50
VNTLTN & CLRS-STR ENCL-E/SHLD.F/SHLD & AIR BFLS:						
Hydrogen coolers	Tube erosion	Poor water quality	1.67			1.67
Internal Seals (e.g. Inner to outer frame seal)	Broken sealing gaskets	Embrittlement		1.00		1.00
PEDESTALS & BEARINGS:						
Bearing liners			1.00			1.00
BEARING BRACKETS & BEARINGS:						
Bearing Liners			1.00			1.00
GLAND SEALS, OIL BAFFELS ETC.:						
Seal Ring	Wear	Oil Starvation		0.67		0.67
Exciters:						
Exciter bearing					1.00	1.00
			7.50	9.64	11.00	26.72

Duvha Unit 4:

Sub Component	Failure Mode	Due To	Process Indicator	Inspection Condition	Features	The Final Assessed Condition Status Score
ROTORS:						
Rotor Body						
Base of slot/subslot	Cracking			0.50		0.50
Rotor Body Ends (Endring Seating/comb Fixing Holes etc.)						
Endring Sealings	Cracking	High compressive stress		0.75	1.00	1.25
Comb fixing holes	Cracking				1.00	1.00
Rotor Shaft Ends						
Shaft ends general	Cracking		2.00	0.78		2.15
Bearing Journal	Cracking			0.50		0.50
F.E. Seal Journal	Cracking		2.00			2.00
R.E. Seal Journal	Cracking		2.00			2.00
Spines					1.00	1.00
Front End Coupling and fixing details						
Shrunk on Coupling	Slip of Coupling	High Torque event		0.78		0.78
ROTOR: COILS, INSUL, PKNG & WDGES						
Rotor coils	Crack at braze	Bad brazing		0.67		0.67
Inter-turn insulation	Short circuit	Pollution		0.78		0.78
Coil to coil connections	Crack at braze	Bad brazing		0.78	1.00	1.27
Top of slot packing inclu. Inverted troughs	Earth fault	Copper dusting		0.78		0.78
Pole slot dampers & associated packing & fixing	Overheating	Unbalanced faults		0.75	2.00	2.14
Field leads & connections	Cracking	Thermal & centrifugal		0.67	1.00	1.20
STATORS:						
STATOR ANNULAR CORE: STATOR FRAME & CORE						
Core Finger plates. Clamp plates and Endplates	Melting (circulating current)	Over fluxing			1.00	1.00
STATOR WINDINGS: COIL & INSUL + WNDGS						
LNB coil- slot portion	Earth fault	Therm.aging (blockages)		0.60	1.00	1.16
LFB coil- slot portion	Earth fault	Therm.aging (blockages)		0.62	1.00	1.18
LNB coil- overhang portion	Earth fault	Therm.aging (Blockages)		0.61	1.00	1.17
LFB coil- Overhang portion	Earth fault	Therm.aging (Blockages)		0.61	1.00	1.17
STATOR WNDGS: SUPPORT PACKINGS & WEDGES						
Endwinding support structure	Looseness	Decohesion		0.75		0.75
STATOR WNDGS, CONNS & TERMLS incl TERML boxes:						
Phase ring & extensions	Cracking	Stress (thermal expansion)		0.78	1.00	1.27
Flexible connections to terminals	Cracking	Vibration		0.78		0.78
STATOR INSTMTN(CORE, COIL, COOLING & HEATER)						
Inlet & Outlet Manifold temperatures			2.00			2.00
VNTLTN & CLRS-STR ENCL-E/SHLD.F/SHLD & AIR BFLS:						
Hydrogen coolers	Tube erosion	Poor water quality	1.67			1.67
PEDESTALS & BEARINGS:						
Bearing liners			2.00			2.00
Jacking Oil Hoses/pipes	Fracture	Hot Oil			1.00	1.00
BEARING BRACKETS & BEARINGS:						
Bearing Liners			2.00			2.00
COOLING AND LUBRICATION: GAS SYSTEM						
Gas drier & Changeover valves	Resin collapse	Wetting	1.00			1.00
Dew point monitoring equipment	Loss of calibration	Contamination	1.00			1.00
C & I Sequence & Protection						
Stator Earth Fault (51N)				0.33		0.33
			15.67	12.82	14.00	37.50

Duvha Unit 5:

Sub Component	Failure Mode	Due To	Process Indicator	Inspection Condition	Features	The Final Assessed Condition Status Score
ROTORS:						
Rotor Body Ends (Endring Seating/comb Fixing Holes etc.)						
Endring Sealings	Cracking	High comp stress			1.00	1.00
Rotor Shaft Ends						
Shaft ends general	Cracking		1.00			1.00
Spines					1.00	1.00
Rear end coupling and fixing details				0.78		0.78
ROTOR: COILS, INSUL, PKNG & WDGS						
Rotor coils	Crack at braze	Bad brazing			1.00	1.00
Inter-turn insulation	Short circuit	Pollution			1.00	1.00
Coil to coil connections	Crack at braze	Bad brazing			1.00	1.00
Top of slot packing inclu. Inverted troughs	Earth fault	Copper dusting			1.00	1.00
Field leads & connections	Cracking	Thermal & centrifugal			0.50	0.50
STATORS:						
STATOR ANNULAR CORE: STATOR FRAME & CORE						
Stator Frame/Casing	H2 leakage	Incorrect frame sealing		0.78		0.78
Core plate & insulation	Melting (circulating current)	Loss of cooling			0.50	0.50
Core vent plates & spacers	Detachment	Vibration			1.00	1.00
Core Finger plates. Clamp plates and Endplates	Melting (circulating current)	Over fluxing			0.67	0.67
Screening Shield	Overheating of plate (circulating currents)	Leading power factor			1.00	1.00
STATOR WINDINGS: COIL & INSUL + WNDGS						
LNB coil- slot portion	Earth fault	Therm.aging (blockages)		0.21	1.00	1.02
LFB coil- slot portion	Earth fault	Therm.aging (blockages)		0.19	1.00	1.02
LNB coil- overhang portion	Earth fault	Therm.aging (Blockages)		0.28	1.00	1.04
LFB coil- Overhang portion	Earth fault	Therm.aging (Blockages)		0.22	1.00	1.02
STATOR WNDGS: SUPPORT PACKINGS & WEDGES						
Wedges	Wedge wear	Fretting		0.50		0.50
Endwinding Support Structure	Looseness	Decohesion		0.75		0.75
STATOR WNDGS, CONNS & TERMLS incl TERML boxes:						
Phase ring & extensions	Cracking	Stress (thermal expansion)			1.00	1.00
Terminals & flanges	E/F (flashover)	Oil ingress		0.79		0.79
Terminal boxes & mounting plates	Cracking	Vibration		0.75		0.75
STATOR WINDINGS- WATER COOLING: MANIFOLD & HOSES						
Manifolds	Cracking	High vibration		0.75		0.75
Manifold connection pipes (Bellows, etc.)	Cracking	High vibration			1.00	1.00
Manifold clamping		High vibration		0.67		0.67
STATOR INSTMTN(CORE, COIL, COOLING & HEATER)						
Inlet & Outlet Manifold temperatures			2.00			2.00
VNTLTN & CLRS-STR ENCL- E/SHLD.F/SHLD & AIR BFLS:						
Hydrogen coolers	Tube erosion	Poor water quality	2.00		0.50	2.06
PEDESTALS & BEARINGS:						
Bearing liners			1.00			1.00
Jacking Oil Hoses/pipes	Fracture	Hot Oil			1.00	1.00
BEARING BRACKETS & BEARINGS:						
Bearing Liners			1.00			1.00
Bearing support ring				0.33		0.33
Oil wipers				0.67		0.67
Exciters						
Exciter bearings				0.67		0.67
			7.00	8.34	17.17	31.27

Duvha Unit 6:

Sub Component	Failure Mode	Due To	Process Indicator	Inspection Condition	Features	The Final Assessed Condition Status Score
ROTORS:						
Rotor Body Ends (Endring Seating/comb Fixing Holes etc.)						
Comb fixing holes	Cracking				1.00	1.00
Finger blocks	Cracking				1.00	1.00
Rotor Shaft Ends						
Shaft ends general	Cracking		1.00			1.00
Bearing journal	Cracking		1.00			1.00
Spines					1.00	1.00
ROTOR: COILS, INSUL, PKNG & WDGES						
Inter-turn insulation	Short circuit	Pollution	0.33			0.33
Main slot cells & slot bridge pieces	Earth fault	Coil movement (thermal)	1.00			1.00
Pole slot dampers & associated packings & fixings	Overheating	Unbalanced faults			2.00	2.00
Endwinding retaining ring insulation	Inter-turn/coil short	Overheating	0.33			0.33
STATORS:						
STATOR ANNULAR CORE: STATOR FRAME & CORE						
Stator Frame/Casing	H2 leakage	Incorrect frame sealing		0.78		0.78
Screening Shield	Overheating of plate (circulating currents)	Leading power factor			1.00	1.00
STATOR WINDINGS: COIL & INSUL + WNDGS						
LNB coil- slot portion	Earth fault	Therm.aging (blockages)		0.31	1.00	1.05
LFB coil- slot portion	Earth fault	Therm.aging (blockages)		0.31	1.00	1.05
LNB coil- overhang portion	Earth fault	Therm.aging (Blockages)		0.36	1.00	1.06
LFB coil- Overhang portion	Earth fault	Therm.aging (Blockages)		0.36	1.00	1.06
STATOR WNDGS: SUPPORT PACKINGS & WEDGES						
Wedges	Wedge wear	Fretting		0.50		0.50
Endwinding support system (complete)		Structural resonance		1.33		1.33
Endwinding Support Structure	Looseness	Decohesion		0.67		0.67
STATOR WNDGS, CONNS & TERMLS incl TERML boxes:						
Phase ring & extensions	Cracking	Stress (thermal expansion)		0.76	1.00	1.27
Terminals & flanges	E/F (flashover)	Oil ingress		0.79		0.79
Terminal boxes & mounting plates	Cracking	Vibration		0.50		0.50
STATOR WINDINGS- WATER COOLING: MANIFOLD & HOSES						
PTFE Hoses				0.78		0.78
Manifolds	Cracking	High vibration	1.00	0.50		1.12
Manifold connection pipes (Bellows, etc.)	Cracking	High vibration		0.75	1.00	1.25
Manifold vent pipes		High vibration		0.67		0.67
STATOR INSTMTN(CORE, COIL, COOLING & HEATER)						
Inlet & Outlet Manifold temperatures			1.00			1.00
VNTLTN & CLRS-STR ENCL- E/SHLD.F/SHLD & AIR BFLS:						
Hydrogen coolers	Tube erosion	Poor water quality	1.57		0.50	1.74
PEDESTALS & BEARINGS:						
Bearing liners			1.00			1.00
Jacking Oil Hoses/pipes	Fracture	Hot Oil			1.00	1.00
BEARING BRACKETS & BEARINGS:						
Bearing Liners			1.00			1.00
			9.33	9.38	13.50	29.28

A5.Duvha Unit 1 Process Parameters Data

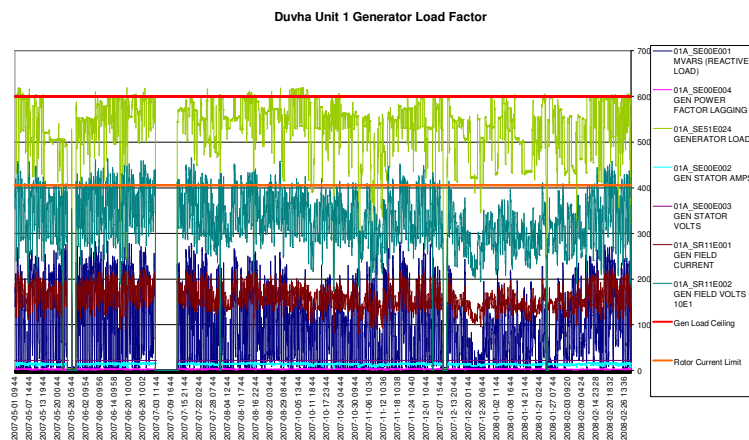


Figure 27. Generator Load Factor

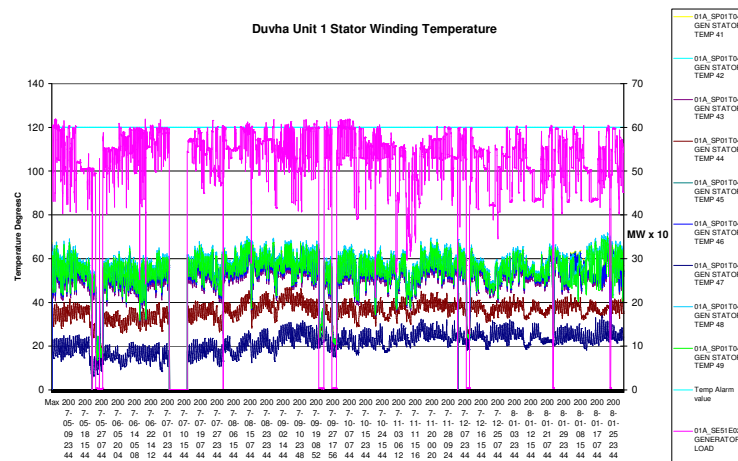


Figure 28. Stator Winding Temperatures

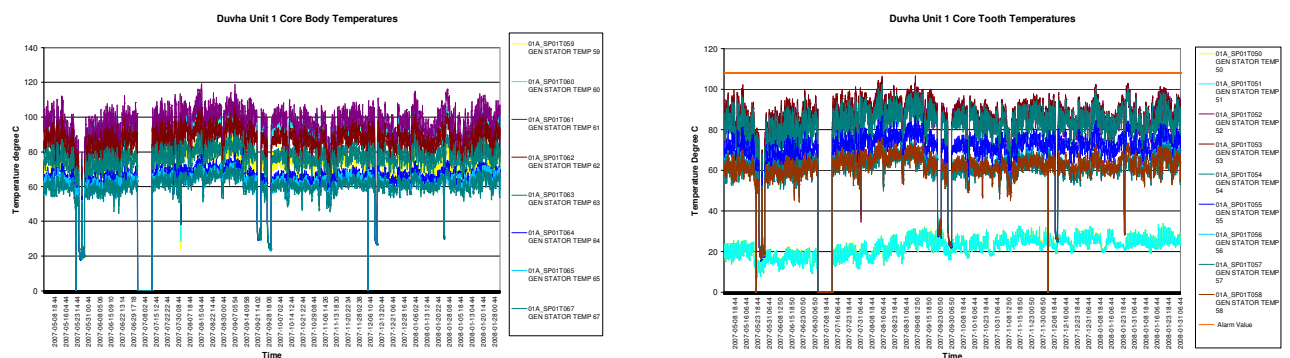


Figure 29. Core Body & Tooth Temperatures

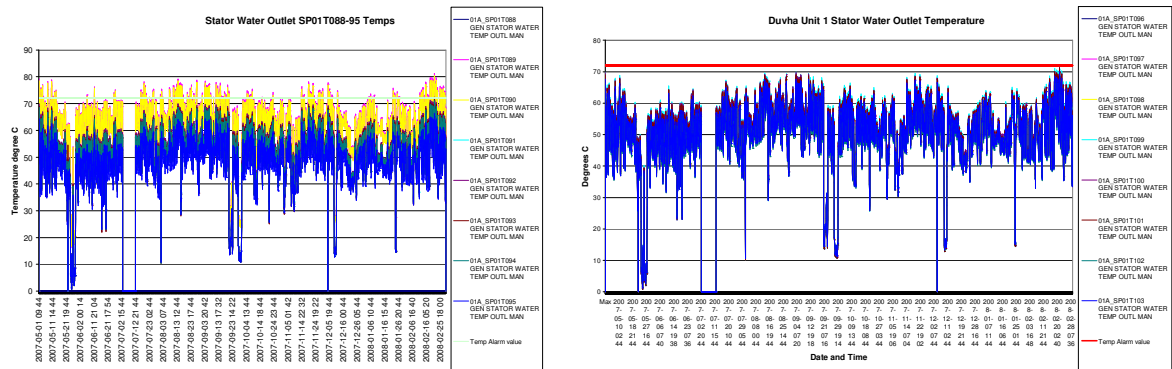


Figure 30. Stator Water Outlet Temperatures

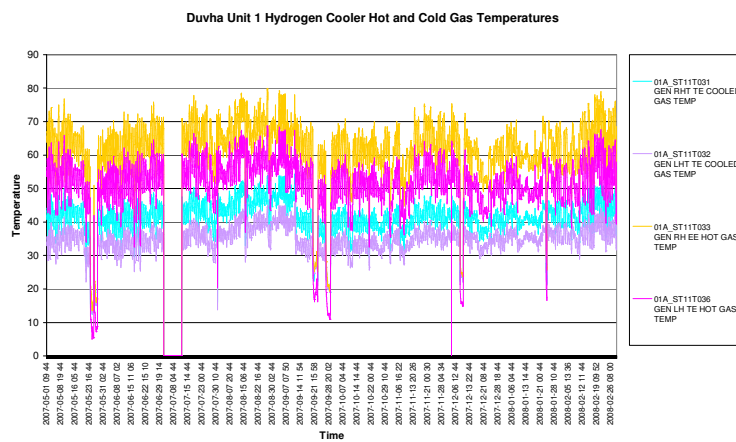


Figure 31. Hydrogen Gas Temperatures

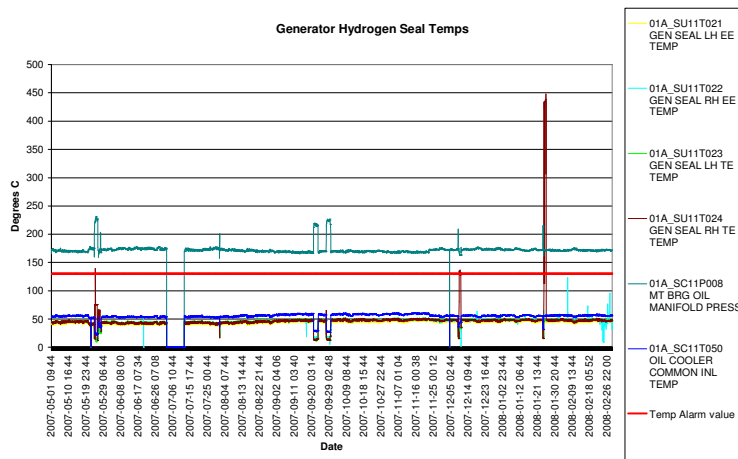


Figure 32. Hydrogen Seal Temperatures

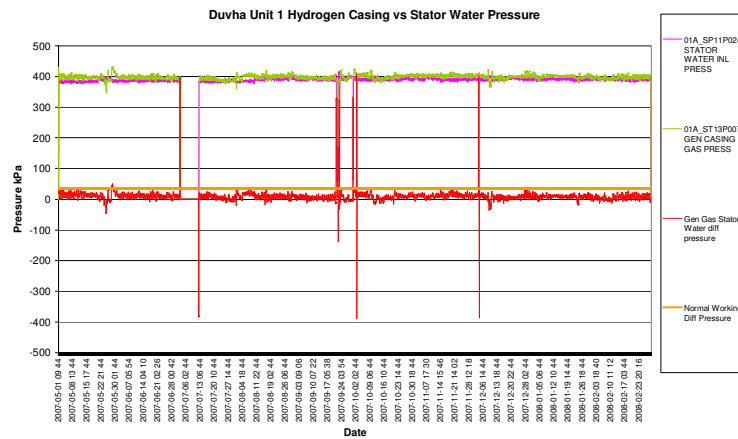


Figure 33. Hydrogen Casing versus Stator Water Pressure

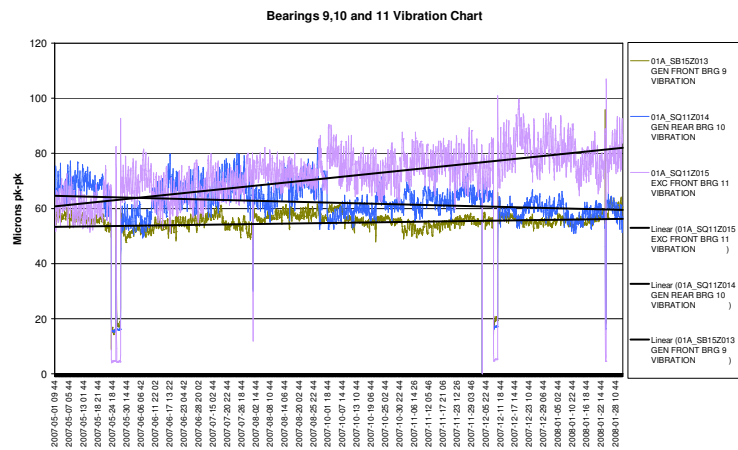


Figure 34. Bearing Vibration 9, 10 and 11

A6. Duvha Unit Design Feature and Assessment

Duvha Unit 1 Main Rotor Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) on Failure	Cause of Failure	S	D	Repair/Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk										
Rotor Body Length	Long (270") Short (260")						n/a	n/a	n/a			n/a		
Forging Properties	PS30/076-1982	PS30/076 1972-1982	PS30/076 <1972				n/a	n/a	n/a			n/a		
Winding	Consolidated Coils	Unconsolidated Coils			Barring Hours		Electrical short	Coil-coil-earth electrical breakdowns	Fretting	3	8		1	4
Rotor Shaft Diameter/fan splines	Large 24" fan spline mod 8 fan splines	Small 24" fan spline mod 8 fan splines					Cracking	Increased vibration/catastrophic failure	High cycle fatigue	2	8		5	5
Endwinding Retaining Ring Liner Material	Nomex Asbestos or Kevlar Coated Epoxy Glass	Asbestos (ii) Faced Epoxy Glass		Glass (i)			Electrical short	Coil-coil-earth electrical breakdowns	Tracking of Cu debris created by abrasion of top turns by glass fibres	8	8	Use Nomex asbestos glass liner	8	8
Top Cross Over Bottom Cross Over Turn to Turn Step Ups	db Oxygen Free Cu (i)	Low Oxygen Content Cu	1a, 2b				Hydrogen embrittlement	Hydrogen embrittlement	Oxygen in Cu	7	7	Replace with oxygen free copper	7	7
Slot Cell Restraint	Packing block mods and bonded slot cell	Finger Block Insert with reinforcing dowels (ii)	Finger Block Insert (ii)	No Special Restraint (i)			Migration of slot cells	Earth fault	Insufficient bonding and/or support, thermal expansion	7	7	Bonding of slot cells and/or packing block mods	5	6
Endwinding Retaining Ring Material	18/18 (ii)	18/4 (i)			Moisture		Cracks	Explosion of retaining ring	Stress Corrosion Cracking	8	7	Replacement of 18/18 rings	4	6
Field Lead	T Head ERMA T Head Cu/Cr/Mg Alloy	T Head H.H Cu with lip L Head H.H Cu (i) with lip	T Head H.H Cu L Head H.H Cu (i)	Symmetrical radial connector			Distortion and bending of field lead	Distortion leading to cracking	Prevailing bending moment	5	6	Replace with T Head design (ERM3A)	5	5
Field Lead Riser Insulation	Restraint lip machined into the riser		No Restraint lip on Riser (i)		Load		Degradation of insulation on riser as well as migration of insulation	Loss of insulation	No restraint lip	2	2	Machine restraint lip on riser	2	2
Inter-turn Insulation	Epoxy Glass	Rub, Asbestos (ii)	Nomex (i)		Time		Degradation of insulation	Paralysis and failure of insulation leading to shorted turns	Cu particles puncturing insulation	3	7	Replace with epoxy glass insulation	4	5
Pole-pole flexible connect Restraint	"Omega" Type Connection	"L" Shaped with packing block	Original "L" Shaped Support (i)		Starts, Hours		Distortion and subsequent cracking	Worst case rotor Earth Fault	"L" shape design unsuitable	5	6	Replace with "omega" pole to pole connector	3	5
Endring Seating Arrangement	Type 3 3 Land	Type 2 2 Land (i)	Type 1 Screwed Ring		Starts		Cracks	Cracking of dovetail load bearing flanks	LCF	3	3	3 land seating arrangement	6	4
Packing Blocks	Spigot mounted Finger Blocks						n/a	n/a	n/a			n/a		
Coil Restraint Design	Axial Restraint	No Axial Restraint					Migration of packings	Overheating	Restricted cooling gas channels	3	5	Use of lamb chop packings	3	4
Top Packer Finish	PTFE coated Nomex	PTFE Coated Glass (ii)	Nomex Glass	Ground Glass (i)	Load		Turn to turn fretting	Inter-turn short	Ground glass high friction interface	4	3	Use of PTFE coated nomex top packer	3	3
Finger Blocks/Support Comb	Finger blocks		Winding Comb (i)				Cracks	Cracking of winding comb & shearing of fixed bolts	Inability to withstand imposed hoop stresses	2	2	Introduce finger blocks	3	2
Finger block fixing	New finger block design no fixing holes	Upper and lower fixing holes					Cracking	Increased vibration/forging revalidation risk	HCF/LCF/Starts	2	8	NDT Inspection	5	5
D Lead	Laminated flexible and relief machined Glass Tube Insulated	Solid D lead, no machined relief, resin insulated					Electrical short	Worst case rotor earth fault	Insulation breakdown due to fretting	8	8	Full revalidation/repair during rotor refurbishments	8	8
Damper Link Type	Cad Cu Ag Plated	Glass Bead Peened	Cad Cu	Cu Cr Zr			Cracking	Reduced neg sequence capability	Fretting	1	8	Inspection at MO	1	3
Damper link configuration	2+2 damper links	Full+2 damper links	Original 20+2 damper links				n/a	n/a	n/a			n/a		
Coil End Relief	Fully relieved Coil 1-8	Limited relief Coils 1-4 only	No relief				Coil fretting	Rotor earth fault	Breakdown in insulation system	8	8	Original build quality	8	8
H2 seal Type	Face Type Double Flow				Running Hours		Degradation of sealing	Hydrogen leakage	Wear	3	5	Inspection repair at mO/MO monitor seal temps gas replenishment rate	2	3

Duvha Unit 1 Main Stator Features

Features	Risk of Failure				Failure Drivers	Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S	D	Repair/Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk									
Core End Packets	Mark 3	Mark 1, Mark 2			Leading PF operation Overfluxing	Thermal fatigue	Core fault	Reduced cooling	6	9	Temp Cond Monitoring	10	8
Core Tooth Spills	Mark A, Mark B Mark a, Mark B, Mark v				None known	n/a	n/a	n/a			n/a		
Core Plates Material	Insuline Totanin Totanin/Red Oxide Wanin				None known	n/a	n/a	n/a			n/a		
Core Plate Insulation					None Known	n/a	n/a	n/a			n/a		
Vent Spacers/Plates	Mark D	Mark A, Mark B, Mark C				Local reduced cooling	Overheating	Local reduced cooling gas flow	2	5	None	5	4
Screening Shield Form	U shape	Short L Extended L			Leading PF operation	Overheating	End of core Core fault	Increased local heating due to eddie current losses	2	5	Inspection, modified screening shield	5	4
Screening Shielded Thickness	(xx) mm				None known	n/a	n/a	n/a			n/a		
Press Phan Material	Press phan material at each end of core None				None known	n/a	n/a	n/a			n/a		
Core Bars	Insulated core bars	Un-insulated core bars			Overfluxing	Back of core burning	Core melting	Recirculating currents	2	5	Monitor at outages find core fault root cause	5	4
Spring Mounted Core	Leat Springs Tangential Rods Longitudinal None				None known	n/a	n/a	n/a			n/a		
Core Cooling	Radial conventional Radial reverse flow Radial multipass				None known	n/a	n/a	n/a			n/a		
Coil Type	Full				None known	n/a	n/a	n/a			n/a		
Coil Insulation Slot	System 1-6				None known	n/a	n/a	n/a			n/a		
Coil Insulation Overhang	System A-F				None known	n/a	n/a	n/a			n/a		
Coil Cooling	Direct water go 3 Direct water single pass Direct gas single pass Indirect gas				None known	n/a	n/a	n/a			n/a		
Wedge Type	Plain Plain with tapered slides Top hay with tapered slides				None known	n/a	n/a	n/a			n/a		
PTFE Hose Joints	Fluorocarbon rubber "O" rings	Nitrile originals, fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Water Manifold Position	FE & RE FE RE None				None known	n/a	n/a	n/a			n/a		
Water Manifold Fixing	Mounted on core Mounted on frame				None known	n/a	n/a	n/a			n/a		
Manifold Balance Pipe	PTFE hose	Rigid pipe			Operating hours	Gas into water leak	Relaxation/ Fatigue	Running hours high Cycle fatigue	2	6	Mod to change to flexible hose	5	4
Manifold Type (Stainless/copper & thickness)	Stainless Thick copper (0.125")	Medium copper	Thin Cu			Gas into water leaks	Relaxation/ Fatigue		6	6		5	6
Manifold Bellows	Controlled filament	Uncontrolled filament			Alignment sensitivity	High cycle fatigue	Gas into water	Mis-alignment	6	6	Replace/realign	3	5
Manifold Flanged Joints	Fluorocarbon rubber "O" rings	Nitrile originals, Fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Stator Coils	Stainless steel	Copper			Chemical control	Blockage of coolant channels with Cu oxide	Overheating	Cu oxide build up poor water chemistry	6	9	Core bar change Chemical clean	7	8
Hydrogen Cooler tube Supports	Closed cell rubber	Open cell rubber			Age	Breakdown of rubber inserts	Tube vibrations Stator contamination	Fatigue	1	1	No repair possible. Clean up debris when possible	3	2
Winding Support Brackets	Epoxy glass	Permalin			Operating hours	Relaxation	Wear/fretting	Relaxation	10	9	MO inspection every 6 years	8	9
Phase Ring Position	FE RE				None known	n/a	n/a	n/a			n/a		
Phase Ring Type	Multiconductor hollow Multiconductor solid Tube Direct water Indirect gas				None known	n/a	n/a	n/a			n/a		
Phase Ring Cooling					None known	n/a	n/a	n/a			n/a		
Phase Ring Ends & Droppers		Original design			Operating hours	Gas into water leaks	Relaxation/ fatigue	High Cycle Fatigue	6	5	MO inspections, tap testing	6	6
Phase Conn Type/Supports	Revised type	Original Type (a)			None known	n/a	n/a	n/a			n/a		
Inner Stator Jacking Studs	Key plate reprofiled, jacking plate, full penetration weld Original profile and original weld detail Original design					Looseness of inner stator jacking studs	Fatigue/ fretting	Relaxation	2	8	MO checks on radial jacking load and NDT of keyplate/ jacking plate welds	4	5
Slot Wedges	Enhanced					Relaxation	Wear/ fretting	Material creep. Core vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Support	Blades Blocked & Bent Blades Rings & Studs Full Core				Operating hours	Relaxation	Wear/ fretting	Material creep. Core Vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Structure	With papered Original design					Relaxation	Fatigue/ fretting	Operating Hrs High Cycle fatigue	2	6	MO inspections	5	4
Hydrogen Seal Type	Face type Double flow				None known	n/a	n/a	n/a			n/a		

Duvha Unit 1 Exciter Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S
	0 No known Risk	1 Low Risk	2 Medium Risk	3 High Risk						
Excitation Method	Brushless	Slip rings			Operating hours		Slip ring wear	Increased brush wear	Operating hours/friction	2
Rectification Type	Rotating Mk 1 Rotating Mk 2 Static									
PMG Type	Salient Pole	Heteropolar					Relaxation	Pole block looseness	High Cycle Fatigue	2
Main Exciter EWRR	18 Mn 18 Cr	18 Mn 4 Cr			Moisture		Cracks	Explosion of retaining ring	Stress corrosion cracking	8
Pedestals	GEC Mitchell									

Duvha Unit 2 Main Rotor Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) on Failure	Cause of Failure	S	D	Repair/ Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk										
Rotor Body Length	Long (270" Short (260"))						n/a	n/a	n/a			n/a		
Forging Properties	PS30/076-1982	PS30/076 1972-1982	PS30/076 <1972				n/a	n/a	n/a			n/a		
Winding	Consolidated Coils	Unconsolidated Coils			Barring Hours		Electrical short	Coil-coil-earth electrical breakdowns	Fretting	3	8		1	4
Rotor Shaft Diameter/fan splines	Large 24" fan spline mod 8 fan splines	Small 24" fan spline mod 8 fan splines					Cracking	Increased vibration/catastrophic failure	High cycle fatigue	2	8		5	5
Endwinding Retaining Ring Liner Material	Nomex Asbestos or Kevlar Coated Epoxy Glass	Asbestos (ii) Faced Epoxy Glass		Glass (i)			Electrical short	Coil-coil-earth electrical breakdowns	Tracking of Cu debris created by abrasion of top turns by glass fibres	8	8	Use Nomex asbestos glass liner	8	8
Top Cross Over Bottom Cross Over Turn to Turn Step Ups	8b Oxygen Free Cu (i)	Low Oxygen Content Cu	1a, 2b				Hydrogen embrittlement	Hydrogen embrittlement	Oxygen in Cu	7	7	Replace with oxygen free copper	7	7
Slot Cell Restraint	Packing block mods and bonded slot cell	Finger Block Insert with reinforcing dowels (ii)	Finger Block Insert (ii)	No Special Restraint (i)			Migration of slot cells	Earth fault	Insufficient bonding and/or support, thermal expansion	7	7	Bonding of slot cells and/or packing block mods	5	6
Endwinding Retaining Ring Material	18/18 (i)	18/4 (i)			Moisture		Cracks	Explosion of retaining ring	Stress Corrosion Cracking	8	7	Replacement of 18/18 rings	4	6
Field Lead	T Head ERM3A T Head CuCrMg Alloy	T Head H,H Cu with lip L Head H,H Cu (i) with lip	T Head H,H Cu L Head H,H Cu (i)	Symmetrical radial connector			Distortion and bending of field lead	Distortion leading to cracking	Prevailing bending moment	5	6	Replace with T Head design (ERM3A)	5	5
Field Lead Riser Insulation	Restraint lip machined into the riser		No Restraint lip on Riser (i)		Load		Degradation of insulation on riser as well as migration of insulation	Loss of insulation	No restraint lip	2	2	Machine restraint lip on riser	2	2
Inter-turn Insulation	Epoxy Glass	Rub, Asbestos (ii)	Nomex (i)		Time		Degradation of insulation	Paralysis and failure of insulation leading to shorted turns	Cu particles puncturing insulation	3	7	Replace with epoxy glass insulation	4	5
Pole-pole flexible connect Restraint	"Omega" Type Connection	"L" Shaped with packing block	Original "L" Shaped Support (i)		Starts, Hours		Distortion and subsequent cracking	Worst case rotor Earth Fault	"L" shape design unsuitable	5	6	Replace with "omega" pole to pole connector	3	5
Endring Seating Arrangement	Type 3 3 Land	Type 2 2 Land (i)	Type 1 Screwed Ring		Starts		Cracks	Cracking of dovetail load bearing flanks	LCF	3	3	3 land seating arrangement	6	4
Packing Blocks	epigot mounted Finger Blocks						n/a	n/a	n/a			n/a		
Coil Restraint Design	Axial Restraint	No Axial Restraint					Migration of packings	Overheating	Restricted cooling gas channels	3	5	Use of lambchop packings	3	4
Top Packer Finish	PTFE coated Nomex	PTFE Coated Glass (ii)	Nomex Glass	Ground Glass (i)	Load		Turn to turn fretting	Inter-turn short	Ground glass high friction interface	4	3	Use of PTFE coated nomex top packer	3	3
Finger Blocks/Support Comb	Finger blocks		Winding Comb (i)				Cracks	Cracking of winding comb & shearing of fixed bolts	Inability to withstand imposed hoop stresses	2	2	Introduce finger blocks	3	2
Finger block fixing	New finger block design no fixing holes	Upper and lower fixing holes					Cracking	Increased vibration/forging revalidation risk	HCF/LCF/Starts	2	8	NDT Inspection	5	5
D Lead	Laminated flexible and relief machined Glass Tube Insulated	Solid D lead, no machined relief, resin insulated					Electrical short	Worst case rotor earth fault	Insulation breakdown due to fretting	8	8	Full revalidation/repair during rotor refurbishments	8	8
Damper Link Type	Cad Cu Ag Plated	Glass Bead Peened	Cad Cu	Cu Cr Zr			Cracking	Reduced neg sequence capability	Fretting	1	8	Inspection at MO	1	3
Damper link configuration	2+2 damper links	Full+2 damper links	Original 26+2 damper links				n/a	n/a	n/a			n/a		
Coil End Relief	Fully relieved Coil 1-8	Limited relief Coils 1-4 only	No relief				Coil fretting	Rotor earth fault	Breakdown in insulation system	8	8	Original build quality	8	8
H2 seal Type	Face Type Double Flow				Running Hours		Degradation of sealing	Hydrogen leakage	Wear	3	5	Inspection repair at mO/MO monitor seal temps gas replenishment rate	2	3

Duvha Unit 2 Main Stator Features

Features	Risk of Failure				Failure Drivers	Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S	D	Repair/Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk									
Core End Packets	Mark 3	Mark 1, Mark 2			Leading PF operation Overfluxing	Thermal fatigue	Core fault	Reduced cooling	6	9	Temp Cond Monitoring	10	8
Core Tooth Splits	Mark A, Mark B Mark a, Mark B, Mark v				None known	n/a	n/a	n/a			n/a		
Core Plates Material	Insuline Totanin Totanin/Red Oxide Wanin				None known	n/a	n/a	n/a			n/a		
Core Plate Insulation					None Known	n/a	n/a	n/a			n/a		
Vent Spacers/Plates	Mark D	Mark A, Mark B, Mark C				Local reduced cooling	Overheating	Local reduced cooling gas flow	2	5	None	5	4
Screening Shield Form	U shape	Short L Extended L			Leading PF operation	Overheating	End of core Core fault	Increased local heating due to eddie current losses	2	5	Inspection, modified screening shield	5	4
Screening Shielded Thickness	(xx) mm				None known	n/a	n/a	n/a			n/a		
Press Phan Material	Press phan material at each end of core None				None known	n/a	n/a	n/a			n/a		
Core Bars	Insulated core bars	Un-insulated core bars			Overfluxing	Back of core burning	Core melting	Recirculating currents	2	5	Monitor at outages find core fault root cause	5	4
Spring Mounted Core	Leat Springs Tangential Rods Longitudinal Axial				None known	n/a	n/a	n/a			n/a		
Core Cooling	Radial conventional Radial reverse flow Radial multipass				None known	n/a	n/a	n/a			n/a		
Coil Type	Full				None known	n/a	n/a	n/a			n/a		
Coil Insulation Slot	System 1-6				None known	n/a	n/a	n/a			n/a		
Coil Insulation Overhang	System A-F				None known	n/a	n/a	n/a			n/a		
Coil Cooling	Direct water go to Direct water single pass Direct gas single pass Indirect gas				None known	n/a	n/a	n/a			n/a		
Wedge Type	Plain Plain with tapered slides Top hay with tapered slides				None known	n/a	n/a	n/a			n/a		
PTFE Hose Joints	Fluorocarbon rubber "O" rings	Nitrile originals, fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Water Manifold Position	FE & RE FE RE				None known	n/a	n/a	n/a			n/a		
Water Manifold Fixing	Mounted on-ends Mounted on frame				None known	n/a	n/a	n/a			n/a		
Manifold Balance Pipe	PTFE hose	Rigid pipe			Operating hours	Gas into water leak	Relaxation/ Fatigue	Running hours high Cycle fatigue	2	6	Mod to change to flexible hose	5	4
Manifold Type (Stainless/copper & thickness)	Stainless Thick copper (0.125")	Medium copper	Thin Cu			Gas into water leaks	Relaxation/ Fatigue		6	6		5	6
Manifold Bellows	Controlled filament	Uncontrolled filament			Alignment sensitivity	High cycle fatigue	Gas into water	Mis-alignment	6	6	Replace/realign	3	5
Manifold Flanged Joints	Fluorocarbon rubber "O" rings	Nitrile originals, Fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Stator Coils	Stainless steel	Copper			Chemistry control	Blockage of coolant channels with Cu oxide	Overheating	Cu oxide build up poor water chemistry	6	9	Core bar change Chemical clean	7	8
Hydrogen Cooler tube Supports	Closed cell rubber	Open cell rubber			Age	Breakdown of rubber inserts	Tube vibrations Stator contamination	Fatigue	1	1	No repair possible. Clean up debris when possible	3	2
Winding Support Brackets	Epoxy glass	Permalin			Operating hours	Relaxation	Wear/fretting	Relaxation	10	9	MO inspection every 6 years	8	9
Phase Ring Position	FE RE				None known	n/a	n/a	n/a			n/a		
Phase Ring Type	Multiconductor hollow Multiconductor solid Tube				None known	n/a	n/a	n/a			n/a		
Phase Ring Cooling	Direct water Indirect gas				None known	n/a	n/a	n/a			n/a		
Phase Ring Ends & Droppers		Original design			Operating hours	Gas into water leaks	Relaxation/ fatigue	High Cycle Fatigue	6	5	MO inspections, tap testing	6	6
Phase Conn Type/Supports	Revised type	Original Type (a)			None known	n/a	n/a	n/a			n/a		
Inner Stator Jacking Studs	Key plate reprofiled, jacking plate, full penetration weld Original profile and jacking stud detail					Looseness of inner stator jacking studs	Fatigue/ fretting	Relaxation	2	8	MO checks on radial jacking load and NDT of keyplate/ jacking plate welds	4	5
Slot Wedges	Original design/ Enhanced					Relaxation	Wear/ fretting	Material creep. Core vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Support	Blades Blocked & Banded Blades Rings & Studs Full Core				Operating hours	Relaxation	Wear/ fretting	Material creep. Core Vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Structure	Wet papered Original design					Relaxation	Fatigue/ fretting	Operating Hrs High Cycle fatigue	2	6	MO inspections	5	4
Hydrogen Seal Type	Face type Double flow				None known	n/a	n/a	n/a			n/a		

Duvha Unit 2 Exciter Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S
	0 No known Risk	1 Low Risk	2 Medium Risk	3 High Risk						
Excitation Method	Brushless	Slip rings			Operating hours		Slip ring wear	Increased brush wear	Operating hours/friction	2
Rectification Type	Rotating Mk 1 Rotating Mk 2 Static									
PMG Type	Salient Pole	Heteropolar					Relaxation	Pole block looseness	High Cycle Fatigue	2
Main Exciter EWRR	18 Mn 18 Cr	18 Mn 4 Cr			Moisture		Cracks	Explosion of retaining ring	Stress corrosion cracking	8
Pedestals	GEC Mitchell									

Duvha Unit 3 Main Rotor Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) on Failure	Cause of Failure	S	D	Repair/ Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk										
Rotor Body Length	Long (270") Short (260")						n/a	n/a	n/a			n/a		
Forging Properties	PS30/076-1982	PS30/076 1972-1982	PS30/076 <1972				n/a	n/a	n/a			n/a		
Winding	Consolidated Coils	Unconsolidated Coils			Barring Hours		Electrical short	Coil-coil-earth electrical breakdowns	Fretting	3	8		3	5
Rotor Shaft Diameter/fan splines	Large 24" fan spline mod 8 fan splines	Small 21" fan spline mod 6 fan spline					Cracking	Increased vibration/catastrophic failure	High cycle fatigue	2	6		5	4
Endwinding Retaining Ring Liner Material	Nomex Asbestos or Kevlar Coated Epoxy Glass	Asbestos (ii) Faced Epoxy Glass		Glass (i)			Electrical short	Coil-coil-earth electrical breakdowns	Tracking of Cu debris created by abrasion of top turns by glass fibres	8	8	Use Nomex asbestos glass liner	9	8
Top Cross Over Bottom Cross Over Turn to Turn Step Ups	5b Oxygen Free Cu (i)	Low Oxygen Content Cu	1a, 2b				Hydrogen embrittlement	Hydrogen embrittlement	Oxygen in Cu	7	7	Replace with oxygen free copper	7	7
Slot Cell Restraint	Packing block mods and bonded slot cell	Finger Block Insert with reinforcing dowels (ii)	Finger Block Insert (ii)	No Special Restraint (i)			Migration of slot cells	Earth fault	Insufficient bonding and/or support, thermal expansion	7	7	Bonding of slot cells and/or packing block mods	7	7
Endwinding Retaining Ring Material	18/18 (i)	18/4 (i)			Moisture		Cracks	Explosion of retaining ring	Stress Corrosion Cracking	8	10	Replacement of 18/18 rings	6	8
Field Lead	T Head ERM3A T Head CuCrMg Alloy	T Head H,H Cu with lip L Head H,H Cu (i) with lip	T Head H,H Cu L Head H,H Cu (i)	Symmetrical radial connector			Distortion and bending of field lead	Distortion leading to cracking	Prevailing bending moment	5	6	Replace with T Head design (ERM3A)	5	5
Field Lead Riser Insulation	Restraint lip machined into the riser		No Restraint lip on Riser (ii)		Load		Degradation of insulation on riser as well as migration of insulation	Loss of insulation	No restraint lip	5	5	Machine restraint lip on riser	5	5
Inter-turn Insulation	Epoxy Glass	Rub, Asbestos (ii)	Nomex (i)		Time		Degradation of insulation	Paralysis and failure of insulation leading to shorted turns	Cu particles puncturing insulation	3	7	Replace with epoxy glass insulation	4	5
Pole-pole flexible connect Restraint	"Omega" Type Connection	"L" Shaped with packing block	Original "L" Shaped Support (i)		Starts, Hours		Distortion and subsequent cracking	Worst case rotor Earth Fault	"L" shape design unsuitable	5	7	Replace with "omega" pole to pole connector	5	6
Endring Seating Arrangement	Type 3 3 Land	Type 2 2 Land (i)	Type 1 Screwed Ring		Starts		Cracks	Cracking of dovetail lead bearing flanks	LCF	3	5	3 land seating arrangement	6	5
Packing Blocks	Spigot mounted Finger Blocks						n/a	n/a	n/a			n/a		
Coil Restraint Design	Axial Restraint	No Axial Restraint					Migration of packings	Overheating	Restricted cooling gas channels	3	5	Use of lambchop packings	3	4
Top Packer Finish	PTFE coated Nomex	PTFE Coated Glass (ii)	Nomex Glass	Ground Glass (i)	Load		Turn to turn fretting	Inter-turn short	Ground glass high friction interface	6	5	Use of PTFE coated nomex top packer	5	5
Finger Blocks/Support Comb	Finger blocks		Winding Comb (i)				Cracks	Cracking of winding comb & shearing of fixed bolts	Inability to withstand imposed hoop stresses	2	2	Introduce finger blocks	3	2
Finger block fixing	New finger block design no fixing holes	Upper and lower fixing holes					Cracking	Increased vibration/forging revalidation risk	HCF/LCF/Starts	2	8	NDT Inspection	5	5
D Lead	Laminated flexible and relief machined Glass Tube Insulated	Solid D lead, no machined relief, resin insulated					Electrical short	Worst case rotor earth fault	Insulation breakdown due to fretting	8	8	Full revalidation/repair during rotor refurbishments	8	8
Damper Link Type	Cad Cu Ag Plated	Glass Bead Peened	Cad Cu	Cu Cr Zr			Cracking	Reduced neg sequence capability	Fretting	1	8	Inspection at MO	1	3
Damper link configuration	2+2 damper links	Full+2 damper links	Original 26+2 damper links				n/a	n/a	n/a			n/a		
Coil End Relief	Fully relieved Coils 1-8	Limited relief Coils 1-4 only	No relief				Coil fretting	Rotor earth fault	Breakdown in insulation system	7	7	Original build quality	7	7
H2 seal Type	Face Type Double Flow				Running Hours		Degradation of sealing	Hydrogen leakage	Wear	3	5	Inspection repair at mO/MO monitor seal temps gas replenishment rate	2	3

Duvha Unit 3 Main Stator Features

Features	Risk of Failure				Failure Drivers	Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S	D	Repair/Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk									
Core End Packets	Mark 3	Mark 1, Mark 2			Leading PF operation Overfluxing	Thermal fatigue	Core fault	Reduced cooling	6	9	Temp Cond Monitoring	10	8
Core Tooth Splits	Mark A, Mark B Mark a, Mark B, Mark v				None known	n/a	n/a	n/a			n/a		
Core Plates Material	Insuline Totanin Totanin/Red Oxide Wanin				None known	n/a	n/a	n/a			n/a		
Core Plate Insulation					None Known	n/a	n/a	n/a			n/a		
Vent Spacers/Plates	Mark D	Mark A, Mark B, Mark C				Local reduced cooling	Overheating	Local reduced cooling gas flow	2	5	None	5	4
Screening Shield Form	U shape	Short L Extended L			Leading PF operation	Overheating	End of core Core fault	Increased local heating due to eddie current losses	2	5	Inspection, modified screening shield	5	4
Screening Shielded Thickness	(xx) mm				None known	n/a	n/a	n/a			n/a		
Press Phan Material	Press phan material at each end of core None				None known	n/a	n/a	n/a			n/a		
Core Bars	Insulated core bars	Un-insulated core bars			Overfluxing	Back of core burning	Core melting	Recirculating currents	2	5	Monitor at outages find core fault root cause	5	4
Spring Mounted Core	Leat Springs Tangential Rods Longitudinal Axial None				None known	n/a	n/a	n/a			n/a		
Core Cooling	Radial conventional Radial reverse flow Radial multipass Half Full				None known	n/a	n/a	n/a			n/a		
Coil Type	System 1-6				None known	n/a	n/a	n/a			n/a		
Coil Insulation Slot Overhang	System A, F				None known	n/a	n/a	n/a			n/a		
Coil Cooling	Direct water go to return Direct water single pass Direct gas single pass Indirect gas				None known	n/a	n/a	n/a			n/a		
Wedge Type	Plain Plain with tapered sides Solid Top hay with tapered sides				None known	n/a	n/a	n/a			n/a		
PTFE Hose Joints	Fluorocarbon rubber "O" rings	Nitrile originals, fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Water Manifold Position	FE & RE FE RE None				None known	n/a	n/a	n/a			n/a		
Water Manifold Fixing	Mounted on core Mounted on frame				None known	n/a	n/a	n/a			n/a		
Manifold Balance Pipe	PTFE hose	Rigid pipe			Operating hours	Gas into water leak	Relaxation/ Fatigue	Running hours high Cycle fatigue	2	6	Mod to change to flexible hose	5	4
Manifold Type (Stainless/copper & thickness)	Stainless Thick copper (0.125")	Medium copper	Thin Cu			Gas into water leaks	Relaxation/ Fatigue		6	6		5	6
Manifold Bellows	Controlled filment	Uncontrolled filment			Alignment sensitivity	High cycle fatigue	Gas into water	Mis-alignment	6	6	Replace/realign	3	5
Manifold Flanged Joints	Fluorocarbon rubber "O" rings	Nitrile originals, Fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Stator Coils	Stainless steel	Copper			Chemical control	Blockage of coolant channels with Cu oxide	Overheating	Cu oxide build up poor water chemistry	6	9	Core bar change Chemical clean	7	8
Hydrogen Cooler tube Supports	Closed cell rubber	Open cell rubber			Age	Breakdown of rubber inserts	Tube vibrations Stator contamination	Fatigue	1	1	No repair possible. Clean up debris when possible	3	2
Winding Support Brackets	Epoxy glass	Permal			Operating hours	Relaxation	Wear/fretting	Relaxation	10	9	MO inspection every 6 years	8	9
Phase Ring Position	FE RE				None known	n/a	n/a	n/a			n/a		
Phase Ring Type	Multiconductor hollow Multiconductor solid Tube Direct water Indirect gas				None known	n/a	n/a	n/a			n/a		
Phase Ring Cooling					None known	n/a	n/a	n/a			n/a		
Phase Ring Ends & Droppers		Original design			Operating hours	Gas into water leaks	Relaxation/ fatigue	High Cycle Fatigue	6	5	MO inspections, tap testing	6	6
Phase Conn Type/Supports	Revised type	Original Type (a)			None known	n/a	n/a	n/a			n/a		
Inner Stator Jacking Studs	Key plate reprofiled, jacking plate, full penetration weld Original profile and jacking stud detail					Looseness of inner stator jacking studs	Fatigue/ fretting	Relaxation	2	8	MO checks on radial jacking load and NDT of keyplate/ jacking plate welds	4	5
Slot Wedges	Original design/ Enhanced					Relaxation	Wear/ fretting	Material creep. Core vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Support	Blades Blocked & Bent Blades Rings & Studs Full Core				Operating hours	Relaxation	Wear/ fretting	Material creep. Core Vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Structure	Half papered Original design					Relaxation	Fatigue/ fretting	Operating Hrs High Cycle fatigue	2	6	MO inspections	5	4
Hydrogen Seal Type	Face type Double flow				None known	n/a	n/a	n/a			n/a		

Duvha Unit 3 Exciter Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S
	0 No known Risk	1 Low Risk	2 Medium Risk	3 High Risk						
Excitation Method	Brushless	Slip rings			Operating hours		Slip ring wear	Increased brush wear	Operating hours/friction	2
Rectification Type	Rotating Mk 1 Rotating Mk 2 Static									
PMG Type	Salient Pole	Heteropolar					Relaxation	Pole block looseness	High Cycle Fatigue	2
Main Exciter EWRR	18 Mn 18 Cr	18 Mn 4 Cr			Moisture		Cracks	Explosion of retaining ring	Stress corrosion cracking	8
Pedestals	GEC Mitchell									

Duvha Unit 4 Main Rotor Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) on Failure	Cause of Failure	S	D	Repair/ Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk										
Rotor Body Length	Long (270") Short (260")						n/a	n/a	n/a			n/a		
Forging Properties	PS30/076-1982	PS30/076 1972-1982	PS30/076 <1972				n/a	n/a	n/a			n/a		
Winding	Consolidated Coils	Unconsolidated Coils			Barring Hours		Electrical short	Coil-coil-earth electrical breakdowns	Fretting	3	8		1	4
Rotor Shaft Diameter/fan splines	Large 24" fan spline mod 8 fan splines	Small 24" fan spline mod 8 fan splines					Cracking	Increased vibration/catastrophic failure	High cycle fatigue	2	8		5	5
Endwinding Retaining Ring Liner Material	Nomex Asbestos or Kevlar Coated Epoxy Glass	Asbestos (ii) Faced Epoxy Glass		Glass (i)			Electrical short	Coil-coil-earth electrical breakdowns	Tracking of Cu debris created by abrasion of top turns by glass fibres	8	8	Use Nomex asbestos glass liner	8	8
Top Cross Over Bottom Cross Over Turn to Turn Step Ups	3b Oxygen Free Cu (i)	Low Oxygen Content Cu	1a, 2b				Hydrogen embrittlement	Hydrogen embrittlement	Oxygen in Cu	7	7	Replace with oxygen free copper	7	7
Slot Cell Restraint	Packing block mods and bonded slot cell	Finger Block Insert with reinforcing dowels (ii)	Finger Block Insert (ii)	No Special Restraint (i)			Migration of slot cells	Earth fault	Insufficient bonding and/or support, thermal expansion	7	7	Bonding of slot cells and/or packing block mods	5	6
Endwinding Retaining Ring Material	18/18 (i)	18/4 (i)			Moisture		Cracks	Explosion of retaining ring	Stress Corrosion Cracking	8	7	Replacement of 18/18 rings	4	6
Field Lead	T Head ERM3A T Head CuCrMg Alloy	T Head H,H Cu with lip L Head H,H Cu (i) with lip	T Head H,H Cu L Head H,H Cu (i)	Symmetrical radial connector			Distortion and bending of field lead	Distortion leading to cracking	Prevailing bending moment	5	6	Replace with T Head design (ERM3A)	5	5
Field Lead Riser Insulation	Restraint lip machined into the riser		No Restraint lip on Riser (i)		Load		Degradation of insulation on riser as well as migration of insulation	Loss of insulation	No restraint lip	2	2	Machine restraint lip on riser	2	2
Inter-turn Insulation	Epoxy Glass	Rub, Asbestos (ii)	Nomex (i)		Time		Degradation of insulation	Paralysis and failure of insulation leading to shorted turns	Cu particles puncturing insulation	3	7	Replace with epoxy glass insulation	4	5
Pole-pole flexible connect Restraint	"Omega" Type Connection	"L" Shaped with packing block	Original "L" Shaped Support (i)		Starts, Hours		Distortion and subsequent cracking	Worst case rotor Earth Fault	"L" shape design unsuitable	5	6	Replace with "omega" pole to pole connector	3	5
Endring Seating Arrangement	Type 3 3 Land	Type 2 2 Land (i)	Type 1 Screwed Ring		Starts		Cracks	Cracking of dovetail load bearing flanks	LCF	3	3	3 land seating arrangement	6	4
Packing Blocks	Spot mounted Finger Blocks						n/a	n/a	n/a			n/a		
Coil Restraint Design	Axial Restraint	No Axial Restraint					Migration of packings	Overheating	Restricted cooling gas channels	3	5	Use of lambchop packings	3	4
Top Packer Finish	PTFE coated Nomex	PTFE Coated Glass (ii)	Nomex Glass	Ground Glass (i)	Load		Turn to turn fretting	Inter-turn short	Ground glass high friction interface	4	3	Use of PTFE coated nomex top packer	3	3
Finger Blocks/Support Comb	Finger blocks		Winding Comb (i)				Cracks	Cracking of winding comb & shearing of fixed bolts	Inability to withstand imposed hoop stresses	2	2	Introduce finger blocks	3	2
Finger block fixing	New finger block design no fixing holes	Upper and lower fixing holes					Cracking	Increased vibration/forging revalidation risk	HCF/LCF/Starts	2	8	NDT Inspection	5	5
D Lead	Laminated flexible and relief machined Glass Tube Insulated	Solid D lead, no machined relief, resin insulated					Electrical short	Worst case rotor earth fault	Insulation breakdown due to fretting	8	8	Full revalidation/repair during rotor refurbishments	8	8
Damper Link Type	Cad Cu Ag Plated	Glass Bead Peened	Cad Cu	Cu Cr Zr			Cracking	Reduced neg sequence capability	Fretting	1	8	Inspection at MO	1	3
Damper link configuration	2+2 damper links	Full+2 damper links	Original 26+2 damper links				n/a	n/a	n/a			n/a		
Coil End Relief	Fully relieved Coil 1-8	Limited relief Coils 1-4 only	No relief				Coil fretting	Rotor earth fault	Breakdown in insulation system	8	8	Original build quality	8	8
H2 seal Type	Face Type Double Flow				Running Hours		Degradation of sealing	Hydrogen leakage	Wear	3	5	Inspection repair at mO/MO monitor seal temps gas replenishment rate	2	3

Duvha Unit 4 Main Stator Features

Features	Risk of Failure				Failure Drivers	Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S	D	Repair/Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk									
Core End Packets	Mark 3	Mark 1, Mark 2			Leading PF operation Overfluxing	Thermal fatigue	Core fault	Reduced cooling	6	9	Temp Cond Monitoring	10	8
Core Tooth Splits	Mark A, Mark B Mark a, Mark B, Mark v				None known	n/a	n/a	n/a			n/a		
Core Plates Material	Insuline Totanin Totanin/Red Oxide Wanin				None known	n/a	n/a	n/a			n/a		
Core Plate Insulation					None Known	n/a	n/a	n/a			n/a		
Vent Spacers/Plates	Mark D	Mark A, Mark B, Mark C				Local reduced cooling	Overheating	Local reduced cooling gas flow	2	5	None	5	4
Screening Shield Form	U shape	Short L Extended L			Leading PF operation	Overheating	End of core Core fault	Increased local heating due to eddie current losses	2	5	Inspection, modified screening shield	5	4
Screening Shielded Thickness	(xx) mm				None known	n/a	n/a	n/a			n/a		
Press Phan Material	Press phan material at each end of core None				None known	n/a	n/a	n/a			n/a		
Core Bars	Insulated core bars	Un-insulated core bars			Overfluxing	Back of core burning	Core melting	Recirculating currents	2	5	Monitor at outages find core fault root cause	5	4
Spring Mounted Core	Leat Springs Tangential Rods Longitudinal Axial				None known	n/a	n/a	n/a			n/a		
Core Cooling	Radial conventional Radial reverse flow Radial multipass				None known	n/a	n/a	n/a			n/a		
Coil Type	Full				None known	n/a	n/a	n/a			n/a		
Coil Insulation Slot	System 1-6				None known	n/a	n/a	n/a			n/a		
Coil Insulation Overhang	System A-F				None known	n/a	n/a	n/a			n/a		
Coil Cooling	Direct water go to Direct water single pass Direct gas single pass Indirect gas				None known	n/a	n/a	n/a			n/a		
Wedge Type	Plain Plain with tapered slides Top hay with tapered slides				None known	n/a	n/a	n/a			n/a		
PTFE Hose Joints	Fluorocarbon rubber "O" rings	Nitrile originals, fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Water Manifold Position	FE & RE FE RE None				None known	n/a	n/a	n/a			n/a		
Water Manifold Fixing	Mounted on frame				None known	n/a	n/a	n/a			n/a		
Manifold Balance Pipe	PTFE hose	Rigid pipe			Operating hours	Gas into water leak	Relaxation/ Fatigue	Running hours high Cycle fatigue	2	6	Mod to change to flexible hose	5	4
Manifold Type (Stainless/copper & thickness)	Stainless Thick copper (0.125")	Medium copper	Thin Cu			Gas into water leaks	Relaxation/ Fatigue		6	6		5	6
Manifold Bellows	Controlled filament	Uncontrolled filament			Alignment sensitivity	High cycle fatigue	Gas into water	Mis-alignment	6	6	Replace/realign	3	5
Manifold Flanged Joints	Fluorocarbon rubber "O" rings	Nitrile originals, Fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Stator Coils	Stainless steel	Copper			Chemical control	Blockage of coolant channels with Cu oxide	Overheating	Cu oxide build up poor water chemistry	6	9	Core bar change Chemical clean	7	8
Hydrogen Cooler tube Supports	Closed cell rubber	Open cell rubber			Age	Breakdown of rubber inserts	Tube vibrations Stator contamination	Fatigue	1	1	No repair possible. Clean up debris when possible	3	2
Winding Support Brackets	Epoxy glass	Permalin			Operating hours	Relaxation	Wear/fretting	Relaxation	10	9	MO inspection every 6 years	8	9
Phase Ring Position	FE RE				None known	n/a	n/a	n/a			n/a		
Phase Ring Type	Multiconductor hollow Multiconductor solid Tube Direct water Indirect gas				None known	n/a	n/a	n/a			n/a		
Phase Ring Cooling					None known	n/a	n/a	n/a			n/a		
Phase Ring Ends & Droppers		Original design			Operating hours	Gas into water leaks	Relaxation/ fatigue	High Cycle Fatigue	6	5	MO inspections, tap testing	6	6
Phase Conn Type/Supports	Revised type	Original Type (a)			None known	n/a	n/a	n/a			n/a		
Inner Stator Jacking Studs	Key plate reprofiled, jacking plate, full penetration weld Original profile and original weld detail Original design					Looseness of inner stator jacking studs	Fatigue/ fretting	Relaxation	2	8	MO checks on radial jacking load and NDT of keyplate/ jacking plate welds	4	5
Slot Wedges	Enhanced					Relaxation	Wear/ fretting	Material creep. Core vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Support	Blades Blocked & Bent Blades Rings & Studs Full Core				Operating hours	Relaxation	Wear/ fretting	Material creep. Core Vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Structure	With papered Original design					Relaxation	Fatigue/ fretting	Operating Hrs High Cycle fatigue	2	6	MO inspections	5	4
Hydrogen Seal Type	Face type Double flow				None known	n/a	n/a	n/a			n/a		

Duvha Unit 4 Exciter Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S
	0 No known Risk	1 Low Risk	2 Medium Risk	3 High Risk						
Excitation Method	Brushless	Slip rings			Operating hours		Slip ring wear	Increased brush wear	Operating hours/friction	2
Rectification Type	Rotating Mk 1 Rotating Mk 2 Static									
PMG Type	Salient Pole	Heteropolar					Relaxation	Pole block looseness	High Cycle Fatigue	2
Main Exciter EWRR	18 Mn 18 Cr	18 Mn 4 Cr			Moisture		Cracks	Explosion of retaining ring	Stress corrosion cracking	8
Pedestals	GEC Mitchell									

Duvha Unit 5 Main Rotor Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) on Failure	Cause of Failure	S	D	Repair/ Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk										
Rotor Body Length	Long (270" Short (260"))						n/a	n/a	n/a			n/a		
Forging Properties	PS30/076-1982	PS30/076 1972-1982	PS30/076 <1972				n/a	n/a	n/a			n/a		
Winding	Consolidated Coils	Unconsolidated Coils			Barring Hours		Electrical short	Coil-coil-earth electrical breakdowns	Fretting	3	8		1	4
Rotor Shaft Diameter/fan splines	Large 24" fan spline mod 8 fan splines	Small 24" fan spline mod 8 fan splines					Cracking	Increased vibration/catastrophic failure	High cycle fatigue	2	8		5	5
Endwinding Retaining Ring Liner Material	Nomex Asbestos or Kevlar Coated Epoxy Glass	Asbestos (ii) Faced Epoxy Glass		Glass (i)			Electrical short	Coil-coil-earth electrical breakdowns	Tracking of Cu debris created by abrasion of top turns by glass fibres	8	8	Use Nomex asbestos glass liner	8	8
Top Cross Over Bottom Cross Over Turn to Turn Step Ups	3b Oxygen Free Cu (i)	Low Oxygen Content Cu	1a, 2b				Hydrogen embrittlement	Hydrogen embrittlement	Oxygen in Cu	7	7	Replace with oxygen free copper	7	7
Slot Cell Restraint	Packing block mods and bonded slot cell	Finger Block Insert with reinforcing dowels (ii)	Finger Block Insert (ii)	No Special Restraint (i)			Migration of slot cells	Earth fault	Insufficient bonding and/or support, thermal expansion	7	7	Bonding of slot cells and/or packing block mods	5	6
Endwinding Retaining Ring Material	18/18 (ii)	18/4 (i)			Moisture		Cracks	Explosion of retaining ring	Stress Corrosion Cracking	8	7	Replacement of 18/18 rings	4	6
Field Lead	T Head ERM3A T Head CuCrMg Alloy	T Head H,H Cu with lip L Head H,H Cu (i) with lip	T Head H,H Cu L Head H,H Cu (i)	Symmetrical radial connector			Distortion and bending of field lead	Distortion leading to cracking	Prevailing bending moment	5	6	Replace with T Head design (ERM3A)	5	5
Field Lead Riser Insulation	Restraint lip machined into the riser		No Restraint lip on Riser (i)		Load		Degradation of insulation on riser as well as migration of insulation	Loss of insulation	No restraint lip	2	2	Machine restraint lip on riser	2	2
Inter-turn Insulation	Epoxy Glass	Rub, Asbestos (ii)	Nomex (i)		Time		Degradation of insulation	Paralysis and failure of insulation leading to shorted turns	Cu particles puncturing insulation	3	7	Replace with epoxy glass insulation	4	5
Pole-pole flexible connect Restraint	"Omega" Type Connection	"L" Shaped with packing block	Original "L" Shaped Support (i)		Starts, Hours		Distortion and subsequent cracking	Worst case rotor Earth Fault	"L" shape design unsuitable	5	6	Replace with "omega" pole to pole connector	3	5
Endring Seating Arrangement	Type 3 3 Land	Type 2 2 Land (ii)	Type 1 Screwed Ring		Starts		Cracks	Cracking of dovetail load bearing flanks	LCF	3	3	3 land seating arrangement	6	4
Packing Blocks	Spigot mounted Finger Blocks						n/a	n/a	n/a			n/a		
Coil Restraint Design	Axial Restraint	No Axial Restraint					Migration of packings	Overheating	Restricted cooling gas channels	3	5	Use of lambchop packings	3	4
Top Packer Finish	PTFE coated Nomex	PTFE Coated Glass (ii)	Nomex Glass	Ground Glass (i)	Load		Turn to turn fretting	Inter-turn short	Ground glass high friction interface	4	3	Use of PTFE coated nomex top packer	3	3
Finger Blocks/Support Comb	Finger blocks		Winding Comb (i)				Cracks	Cracking of winding comb & shearing of fixed bolts	Inability to withstand imposed hoop stresses	2	2	Introduce finger blocks	3	2
Finger block fixing	New finger block design no fixing holes	Upper and lower fixing holes					Cracking	Increased vibration/forging revalidation risk	HCF/LCF/Starts	2	8	NDT Inspection	5	5
D Lead	Laminated flexible and relief machined Glass Tube Insulated	Solid D lead, no machined relief, resin insulated					Electrical short	Worst case rotor earth fault	Insulation breakdown due to fretting	8	8	Full revalidation/repair during rotor refurbishments	8	8
Damper Link Type	Cad Cu Ag Plated	Glass Bead Peened	Cad Cu	Cu Cr Zr			Cracking	Reduced neg sequence capability	Fretting	1	8	Inspection at MO	1	3
Damper link configuration	2+2 damper links	Full+2 damper links	Original 28+2 damper links				n/a	n/a	n/a			n/a		
Coil End Relief	Fully relieved Coil 1-8	Limited relief Coils 1-4 only	No relief				Coil fretting	Rotor earth fault	Breakdown in insulation system	8	8	Original build quality	8	8
H2 seal Type	Face Type Double Flow				Running Hours		Degradation of sealing	Hydrogen leakage	Wear	3	5	Inspection repair at mO/MO monitor seal temps gas replenishment rate	2	3

Duvha Unit 5 Main Stator Features

Features	Risk of Failure				Failure Drivers	Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S	D	Repair/Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk									
Core End Packets	Mark 3	Mark 1, Mark 2			Leading PF operation Overfluxing	Thermal fatigue	Core fault	Reduced cooling	6	9	Temp Cond Monitoring	10	8
Core Tooth Splits	Mark A, Mark B Mark a, Mark B, Mark v				None known	n/a	n/a	n/a			n/a		
Core Plates Material	Insuline Totanin Totanin/Red Oxide Wanin				None known	n/a	n/a	n/a			n/a		
Core Plate Insulation					None Known	n/a	n/a	n/a			n/a		
Vent Spacers/Plates	Mark D	Mark A, Mark B, Mark C				Local reduced cooling	Overheating	Local reduced cooling gas flow	2	5	None	5	4
Screening Shield Form	U shape	Short L Extended L			Leading PF operation	Overheating	End of core Core fault	Increased local heating due to eddie current losses	2	5	Inspection, modified screening shield	5	4
Screening Shielded Thickness	(xx) mm				None known	n/a	n/a	n/a			n/a		
Press Phan Material	Press phan material at each end of core None				None known	n/a	n/a	n/a			n/a		
Core Bars	Insulated core bars	Un-insulated core bars			Overfluxing	Back of core burning	Core melting	Recirculating currents	2	5	Monitor at outages find core fault root cause	5	4
Spring Mounted Core	Leat Springs Tangential Rods Longitudinal Axial None				None known	n/a	n/a	n/a			n/a		
Core Cooling	Radial conventional Radial reverse flow Radial multipass				None known	n/a	n/a	n/a			n/a		
Coil Type	Half Full				None known	n/a	n/a	n/a			n/a		
Coil Insulation Slot	System 1-6				None known	n/a	n/a	n/a			n/a		
Coil Insulation Overhang	System A-F				None known	n/a	n/a	n/a			n/a		
Coil Cooling	Direct water go 3 return Direct water single pass Direct gas single pass Indirect gas				None known	n/a	n/a	n/a			n/a		
Wedge Type	Plain Plain with tapered slides Half Top hay with tapered slides				None known	n/a	n/a	n/a			n/a		
PTFE Hose Joints	Fluorocarbon rubber "O" rings FE & RE FE RE None	Nitrile originals, fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Water Manifold Position	Mounted on frame				None known	n/a	n/a	n/a			n/a		
Water Manifold Fixing	PTFE hose	Rigid pipe			Operating hours	Gas into water leak	Relaxation/ Fatigue	Running hours high Cycle fatigue	2	6	Mod to change to flexible hose	5	4
Manifold Type (Stainless/copper & thickness)	Stainless Thick copper (0.125")	Medium copper	Thin Cu			Gas into water leaks	Relaxation/ Fatigue		6	6		5	6
Manifold Bellows	Controlled filament	Uncontrolled filament			Alignment sensitivity	High cycle fatigue	Gas into water	Mis-alignment	6	6	Replace/realign	3	5
Manifold Flanged Joints	Fluorocarbon rubber "O" rings	Nitrile originals, Fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Stator Coils	Stainless steel	Copper			Chemical control	Blockage of coolant channels with Cu oxide	Overheating	Cu oxide build up poor water chemistry	6	9	Core bar change Chemical clean	7	8
Hydrogen Cooler tube Supports	Closed cell rubber	Open cell rubber			Age	Breakdown of rubber inserts	Tube vibrations Stator contamination	Fatigue	1	1	No repair possible. Clean up debris when possible	3	2
Winding Support Brackets	Epoxy glass	Permalin			Operating hours	Relaxation	Wear/fretting	Relaxation	10	9	MO inspection every 6 years	8	9
Phase Ring Position	FE RE				None known	n/a	n/a	n/a			n/a		
Phase Ring Type	Multi-conductor hollow Multi-conductor solid Tube Direct water Indirect gas				None known	n/a	n/a	n/a			n/a		
Phase Ring Cooling					None known	n/a	n/a	n/a			n/a		
Phase Ring Ends & Droppers		Original design			Operating hours	Gas into water leaks	Relaxation/ fatigue	High Cycle Fatigue	6	5	MO inspections, tap testing	6	6
Phase Conn Type/Supports	Revised type	Original Type (a)			None known	n/a	n/a	n/a			n/a		
Inner Stator Jacking Studs	Key plate reprofiled, jacking plate, full penetration weld Original profile and original weld detail Original design					Looseness of inner stator jacking studs	Fatigue/ fretting	Relaxation	2	8	MO checks on radial jacking load and NDT of keyplate/ jacking plate welds	4	5
Slot Wedges	Enhanced					Relaxation	Wear/ fretting	Material creep. Core vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Support	Blades Blocked & Bent Blades Rings & Studs Full Core				Operating hours	Relaxation	Wear/ fretting	Material creep. Core Vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Structure	Half tapered Original design					Relaxation	Fatigue/ fretting	Operating Hrs High Cycle fatigue	2	6	MO inspections	5	4
Hydrogen Seal Type	Face type Double flow				None known	n/a	n/a	n/a			n/a		

Duvha Unit 5 Exciter Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S
	0 No known Risk	1 Low Risk	2 Medium Risk	3 High Risk						
Excitation Method	Brushless	Slip rings			Operating hours		Slip ring wear	Increased brush wear	Operating hours/friction	2
Rectification Type	Rotating Mk 1 Rotating Mk 2 Static									
PMG Type	Salient Pole	Heteropolar					Relaxation	Pole block looseness	High Cycle Fatigue	2
Main Exciter EWRR	18 Mn 18 Cr	18 Mn 4 Cr			Moisture		Cracks	Explosion of retaining ring	Stress corrosion cracking	8
Pedestals	GEC Mitchell									

Duvha Unit 6 Main Rotor Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) on Failure	Cause of Failure	S	D	Repair/ Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk										
Rotor Body Length	Long (270") Short (260")						n/a	n/a	n/a			n/a		
Forging Properties	PS30/076<1982	PS30/076 1972-1982	PS30/076 <1972				n/a	n/a	n/a			n/a		
Winding	Consolidated Coils	Unconsolidated Coils			Barring Hours		Electrical short	Coil-coil-earth electrical breakdowns	Fretting	3	8		1	4
Rotor Shaft Diameter/fan splines	Large 24" fan spline mod 8 fan splines	Small 24" fan spline mod 8 fan splines					Cracking	Increased vibration/catastrophic failure	High cycle fatigue	2	8		5	5
Endwinding Retaining Ring Liner Material	Nomex Asbestos or Kevlar Coated Epoxy Glass	Asbestos (ii) Faced Epoxy Glass		Glass (i)			Electrical short	Coil-coil-earth electrical breakdowns	Tracking of Cu debris created by abrasion of top turns by glass fibres	8	8	Use Nomex asbestos glass liner	8	8
Top Cross Over Bottom Cross Over Turn to Turn Step Ups	3b Oxygen Free Cu (i)	Low Oxygen Content Cu	1a, 2b				Hydrogen embrittlement	Hydrogen embrittlement	Oxygen in Cu	7	7	Replace with oxygen free copper	7	7
Slot Cell Restraint	Packing block mods and bonded slot cell	Finger Block Insert with reinforcing dowels (ii)	Finger Block Insert (ii)	No Special Restraint (i)			Migration of slot cells	Earth fault	Insufficient bonding and/or support, thermal expansion	7	7	Bonding of slot cells and/or packing block mods	5	6
Endwinding Retaining Ring Material	18/18 (ii)	18/4 (i)			Moisture		Cracks	Explosion of retaining ring	Stress Corrosion Cracking	8	7	Replacement of 18/18 rings	4	6
Field Lead	T Head ERM3A T Head CuCrMg Alloy	Head H,H Cu with lip L Head H,H Cu (i) with lip	T Head H,H Cu L Head H,H Cu (i)	Symmetrical radial connector			Distortion and bending of field lead	Distortion leading to cracking	Prevailing bending moment	5	6	Replace with T Head design (ERM3A)	5	5
Field Lead Riser Insulation	Restraint lip machined into the riser		No Restraint lip on Riser (i)		Load		Degradation of insulation on riser as well as migration of insulation	Loss of insulation	No restraint lip	2	2	Machine restraint lip on riser	2	2
Inter-turn Insulation	Epoxy Glass	Rub, Asbestos (ii)	Nomex (i)		Time		Degradation of insulation	Paralysis and failure of insulation leading to shorted turns	Cu particles puncturing insulation	3	7	Replace with epoxy glass insulation	4	5
Pole-pole flexible connect Restraint	"Omega" Type Connection	"L" Shaped with packing block	Original "L" Shaped Support (i)		Starts, Hours		Distortion and subsequent cracking	Worst case rotor Earth Fault	"L" shape design unsuitable	5	6	Replace with "omega" pole to pole connector	3	5
Endring Seating Arrangement	Type 3 3 Land	Type 2 2 Land (i)	Type 1 Screwed Ring		Starts		Cracks	Cracking of dovetail load bearing flanks	LCF	3	3	3 land seating arrangement	6	4
Packing Blocks	epigot mounted Finger Blocks						n/a	n/a	n/a			n/a		
Coil Restraint Design	Axial Restraint	No Axial Restraint					Migration of packings	Overheating	Restricted cooling gas channels	3	5	Use of lambchop packings	3	4
Top Packer Finish	PTFE coated Nomex	PTFE Coated Glass (ii)	Nomex Glass	Ground Glass (i)	Load		Turn to turn fretting	Inter-turn short	Ground glass high friction interface	4	3	Use of PTFE coated nomex top packer	3	3
Finger Blocks/Support Comb	Finger blocks		Winding Comb (i)				Cracks	Cracking of winding comb & shearing of fixed bolts	Inability to withstand imposed hoop stresses	2	2	Introduce finger blocks	3	2
Finger block fixing	New finger block design no fixing holes	Upper and lower fixing holes					Cracking	Increased vibration/forging revalidation risk	HCF/LCF/Starts	2	8	NDT Inspection	5	5
D Lead	Laminated flexible and relief machined Glass Tube Insulated	Solid D lead, no machined relief, resin insulated					Electrical short	Worst case rotor earth fault	Insulation breakdown due to fretting	8	8	Full revalidation/repair during rotor refurbishments	8	8
Damper Link Type	Cad Cu Ag Plated	Glass Bead Peened	Cad Cu	Cu Cr Zr			Cracking	Reduced neg sequence capability	Fretting	1	8	Inspection at MO	1	3
Damper link configuration	2+2 damper links	Full+2 damper links	Original 28+2 damper links				n/a	n/a	n/a			n/a		
Coil End Relief	Fully relieved Coil 1-8	Limited relief Coils 1-4 only	No relief				Coil fretting	Rotor earth fault	Breakdown in insulation system	8	8	Original build quality	8	8
H2 seal Type	Face Type Double Flow				Running Hours		Degradation of sealing	Hydrogen leakage	Wear	3	5	Inspection repair at mO/MO monitor seal temps gas replenishment rate	2	3

Duvha Unit 6 Main Stator Features

Features	Risk of Failure				Failure Drivers	Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S	D	Repair/Mitigation	W	CoF
	0 No Known Risk	1 Low Risk	2 Medium Risk	3 High Risk									
Core End Packets	Mark 3	Mark 1, Mark 2			Leading PF operation Overfluxing	Thermal fatigue	Core fault	Reduced cooling	6	9	Temp Cond Monitoring	10	8
Core Tooth Spills	Mark A, Mark B Mark a, Mark B, Mark v				None known	n/a	n/a	n/a			n/a		
Core Plates Material	Insuline Totanin Totanin/Red Oxide Wanin				None known	n/a	n/a	n/a			n/a		
Core Plate Insulation	Mark D	Mark A, Mark B, Mark C				Local reduced cooling	Overheating	Local reduced cooling gas flow	2	5	None	5	4
Vent Spacers/Plates	U shape	Short L Extended L			Leading PF operation	Overheating	End of core Core fault	Increased local heating due to eddie current losses	2	5	Inspection, modified screening shield	5	4
Screening Shield Form	(xx) mm				None known	n/a	n/a	n/a			n/a		
Screening Shielded Thickness	Press phan material at each end of core None				None known	n/a	n/a	n/a			n/a		
Press Phan Material	Insulated core bars	Un-insulated core bars			Overfluxing	Back of core burning	Core melting	Recirculating currents	2	5	Monitor at outages find core fault root cause	5	4
Core Bars	Leat Springs Tangential Rods Longitudinal None				None known	n/a	n/a	n/a			n/a		
Spring Mounted Core	Radial conventional Radial reverse flow Radial multipass				None known	n/a	n/a	n/a			n/a		
Core Cooling	Coil Type Full				None known	n/a	n/a	n/a			n/a		
Coil Insulation Slot	System 1-6				None known	n/a	n/a	n/a			n/a		
Coil Insulation Overhang	System A-F				None known	n/a	n/a	n/a			n/a		
Coil Cooling	Direct water go to return Direct water single pass Direct gas single pass Indirect gas				None known	n/a	n/a	n/a			n/a		
Wedge Type	Plain Plain with tapered sides Solid Top hay with tapered sides				None known	n/a	n/a	n/a			n/a		
PTFE Hose Joints	Fluorocarbon rubber "O" rings	Nitrile originals, fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Water Manifold Position	FE & RE FE RE None				None known	n/a	n/a	n/a			n/a		
Water Manifold Fixing	Mounted on frame				None known	n/a	n/a	n/a			n/a		
Manifold Balance Pipe	PTFE hose	Rigid pipe			Operating hours	Gas into water leak	Relaxation/ Fatigue	Running hours high Cycle fatigue	2	6	Mod to change to flexible hose	5	4
Manifold Type (Stainless/copper & thickness)	Stainless Thick copper (0.125")	Medium copper	Thin Cu			Gas into water leaks	Relaxation/ Fatigue		6	6		5	6
Manifold Bellows	Controlled filament	Uncontrolled filament			Alignment sensitivity	High cycle fatigue	Gas into water	Mis-alignment	6	6	Replace/realign	3	5
Manifold Flanged Joints	Fluorocarbon rubber "O" rings	Nitrile originals, Fluorocarbon spares			Age	Failure of seal	Leaks	Relaxation	6	6	Material spec change	5	6
Stator Coils	Stainless steel	Copper			Chemical control	Blockage of coolant channels with Cu oxide	Overheating	Cu oxide build up poor water chemistry	6	9	Core bar change Chemical clean	7	8
Hydrogen Cooler tube Supports	Closed cell rubber	Open cell rubber			Age	Breakdown of rubber inserts	Tube vibrations Stator contamination	Fatigue	1	1	No repair possible. Clean up debris when possible	3	2
Winding Support Brackets	Epoxy glass	Permalin			Operating hours	Relaxation	Wear/fretting	Relaxation	10	9	MO inspection every 6 years	8	9
Phase Ring Position	FE RE				None known	n/a	n/a	n/a			n/a		
Phase Ring Type	Multiconductor hollow Multiconductor solid Tube Direct water Indirect gas				None known	n/a	n/a	n/a			n/a		
Phase Ring Cooling					None known	n/a	n/a	n/a			n/a		
Phase Ring Ends & Droppers		Original design			Operating hours	Gas into water leaks	Relaxation/ fatigue	High Cycle Fatigue	6	5	MO inspections, tap testing	6	6
Phase Conn Type/Supports	Revised type	Original Type (a)			None known	n/a	n/a	n/a			n/a		
Inner Stator Jacking Studs	Key plate reprofiled, jacking plate, full penetration weld Original profile and original weld detail Original design					Looseness of inner stator jacking studs	Fatigue/ fretting	Relaxation	2	8	MO checks on radial jacking load and NDT of keyplate/ jacking plate welds	4	5
Slot Wedges	Enhanced					Relaxation	Wear/ fretting	Material creep. Core vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Support	Blades Blocked & Bent Blades Rings & Studs Full Core				Operating hours	Relaxation	Wear/ fretting	Material creep. Core Vibration	10	9	MO inspection every 6 yrs	8	9
Endwinding Structure	Welded Original design					Relaxation	Fatigue/ fretting	Operating Hrs High Cycle fatigue	2	6	MO inspections	5	4
Hydrogen Seal Type	Face type Double flow				None known	n/a	n/a	n/a			n/a		

Duvha Unit 6 Exciter Features

Feature	Risk of Failure				Failure Drivers		Failure Mode	Potential Effect(s) of Failure	Cause of Failure	S
	0 No known Risk	1 Low Risk	2 Medium Risk	3 High Risk						
Excitation Method	Brushless	Slip rings			Operating hours		Slip ring wear	Increased brush wear	Operating hours/friction	2
Rectification Type	Rotating Mk 1 Rotating Mk 2 Static									
PMG Type	Salient Pole	Heteropolar					Relaxation	Pole block looseness	High Cycle Fatigue	2
Main Exciter EWRR	18 Mn 18 Cr	18 Mn 4 Cr			Moisture		Cracks	Explosion of retaining ring	Stress corrosion cracking	8
Pedestals	GEC Mitchell									