AVAILABILITY ANALYSIS OF HEAT RECOVERY STEAM GENERATORS USED IN COMBINED CYCLE THERMELECTRIC POWER PLANTS

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Abstract. *In a combined cycle thermelectric power station, the exhaust gas from the gas turbine is used to heat water in the steam generator, which is part of the steam cycle. In case of heat recovery steam generator failure the power plant is partially shut down once the steam cycle is unavailable, reducing the efficiency of the power plant, measured in terms of power output, and reducing the advantage of the combined cycle technology. Taking in view the great importance of the heat recovery steam generator (HRSG) for plant operation, its availability should be carefully evaluated.*
This paper presents a method for reliability and availability evaluation of HRSG installed in combined cycle thermelectric power station. The method is based on system reliability concepts and has three main steps: functional tree elaboration, Failure Mode and Effects Analysis implementation, including maintenance policy selection based on Reliability Centered Maintenance Concepts, and reliability analysis
The method is applied on the analysis of two HRSG installed in a 500MW combined cycle thermelectric power plant. The reliability and availability of the HRSGs are simulated based on a five-year failure database. The availability analysis shows different behaviors for each steam generator, one presenting 99% and the other 99,5% availability, indicating differences in their failure modes associated with the systems installation and operation. The use of RCM concepts allows the proposal of new maintenance procedures. The availability simulation indicates that the implementation of those procedures can improve the heat recovery steam generator availability.

Keywords*: availability, reliability, heat recovery steam generator.*

1. INTRODUCTION

The availability of the combined cycle thermoelectric power plants depends on the perfect operation of all its systems (gas turbine, heat recovery steam generator and steam turbine). In the combined cycle the gas turbine transforms the chemical energy generated by combustion in mechanical energy to rotate the generator's shaft. The exhaust gas is used to heat water in the steam generator allowing the operation of the steam cycle.

The HRSG is the link between the gas turbine and the steam turbine process, in Figure 1 is simplified flow diagram for combined cycle thermoelectric power plant is presented.

The function of HRSG is to convert the exhaust gas energy of the gas turbine into steam. After heating in the economizer, water enters the drum, slightly subcooled. From the drum, it is circulated to the evaporator and returns as a water/steam mixture to the drum where water and steam are separated. The saturated steam leaves the drum for the superheater where is reaches the maximum heat exchange temperature with the hottest exhaust-gas leaving the gas turbine. The heat exchange in an HRSG can take place on up to three pressure levels depending on the desired amount of the energy and exergy to be recovered. Today, two or three pressure levels of steam generation are most commonly used.

In case of heat recovery steam generator (HRSG) failure, the power plant has two possible operation conditions:

i) The gas turbine coupled to the failed HRSG may operate in open cycle if the power plant has an environmental license for that specific operation.

ii) The gas turbine coupled to the failed HRSG is shutdown for both cases there is a reduction of the power plant generation capacity.

Bearing in mind the great importance of the HRSG for plant operation, its availability should be carefully evaluated in order to foresee the performance – technical and economical - of the energy system. The availability of a complex system, such as the HRSG, is strongly associated with the parts reliability and maintenance policy. That policy not only has influence on the parts repair time but also on the parts reliability affecting the system degradation and availability.

This paper presents a system reliability-based method used to identify the most critical components in a HRSG. the criticality is associated with the component failure effect on the HRSG operation condition. The higher the criticality of the component more technical and economical resources should de used by the maintenance activities to keep the

HRSG available for operation. the reliability centered maintenance concepts are used as a guideline in ranking the maintenance policy priorities for the critical components aiming at the HRSG operation availability.

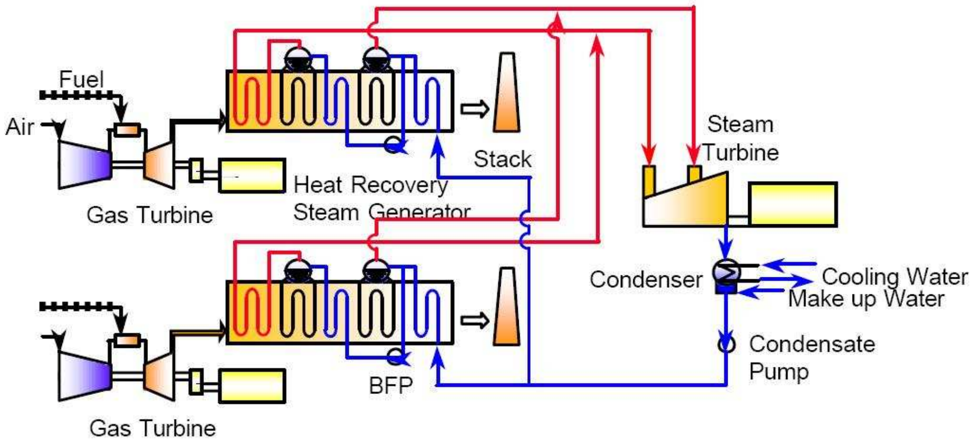

Figure 1. Simplified Flow Diagram of a Combined Cycle (Hitachi, 1998)

2. METHOD DEVELOMENT

The method for reliability and availability is based on system reliability concepts.

The method first step consists in the elaboration of the HRSG functional tree that allows the definition of the functional links between the equipment subsystems. Although all HRSG possess essentially the same subsystems, such as feedwater system, economizers and evaporators, there are differences between the technologies used by the manufacturers; therefore the functional tree must be developed for each specific HRSG model.

The next step is the development of the Failure Mode and Effects Analysis (usually referred to by the acronym FMEA) of each boiler component in order to define the most critical components for HRSG operation. This criticality is based on the evaluation of the component failure effect on the system operation, (Lewis, 1996). For the definition of the system degradation, the FMEA analysis uses a numerical code, usually varying between 1 and 10. The higher the number the higher is the criticality of the component that must be evaluated for each component failure mode. For the HRSG analysis a criticality scale between 1 and 9 is proposed. Values between 1 and 3 express minor effects on the system operation and values between 4 and 6 express significant effects on the system operation. Failures that cause the turbine unavailability or environmental degradation are classified with criticality values between 7 and 9.

The method third step involves a reliability analysis based on the 'time to failure' data recorded during the HRSG operation. The failures should be classified according to the subsystem presented on the functional tree. The reliability of each subsystem is calculated based on the failure data and the system reliability is simulated through the use of block diagram. Considering the 'time to repair' data and the preventive maintenance tasks associated with the equipment, the HRSG availability is evaluated using the block diagram.

Once the critical components are defined a maintenance policy can be proposed for those components, considering the Reliability Centred Maintenance (RCM) concepts. This maintenance policy philosophy has focus on the use of predictive or preventive maintenance tasks that aim at the reduction of unexpected failures during the component normal operation, (Smith and Hinchcliffe, 2003). For complex systems, the occurrence of unexpected components failures highly increases maintenance costs associated with corrective tasks not only for the direct corrective costs (spare parts, labour hours) but also for the system unavailability costs.

So, the use of predictive or preventive tasks allows the programming of maintenance tasks in advance and also reduces the component failure probability during a given operation period and consequently increasing the system availability.

The reliability block diagram analysis not only allows the evaluation of the actual maintenance policy but also allows the prediction of possible availability improvement considering the application of new maintenance procedures, expressed by the reduction of corrective maintenance repair time.

In Fig. 2 a flowchart is used to explain the method's main steps.

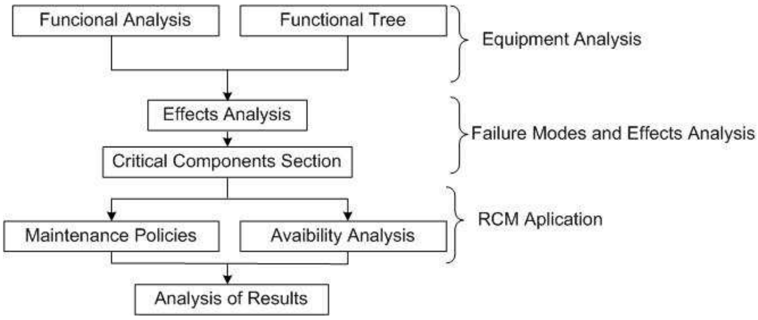

Figure 2. Flowchart for Complex System Availability Evaluation.

3. APPLICATION

The method is applied on the analysis of two identical HRSG, with tree pressure levels of steam generation, installed in a 500MW combined cycle thermoelectric power plant located in South America. The reliability and availability of the HRSGs is simulated based on a five-year failure database.

3.1. Functional Tree

The functional tree for the power plant is presented in Fig. 3 and was divided in seven main systems: gas turbine, steam turbine, electric generator, heat recovery steam generator, cooling water system, water treating system and electrical station.

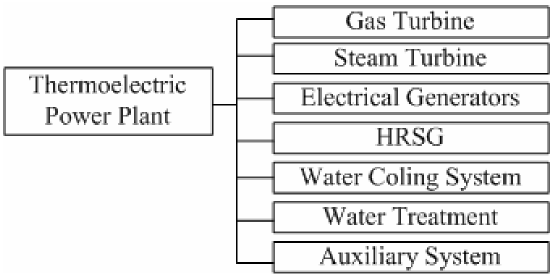

Figure 3. Combined –Cycle Thermoelectric Power Plant Functional Tree

The functional tree for the HRSG is presented in Fig. 4. The equipment is divided in nine main subsystems: feedwater system, three economizers, three evaporators and two superheaters. Those subsystems are divided in components, each one performing a specific function linked with the subsystem main function. A failure in a component at the bottom of the tree affects all subsystems above it, causing a possible degradation in the boiler operation, represented by any reduction in the nominal output or even environmental degradation. The tree was developed according to the operation manual furnished by the manufacturer.

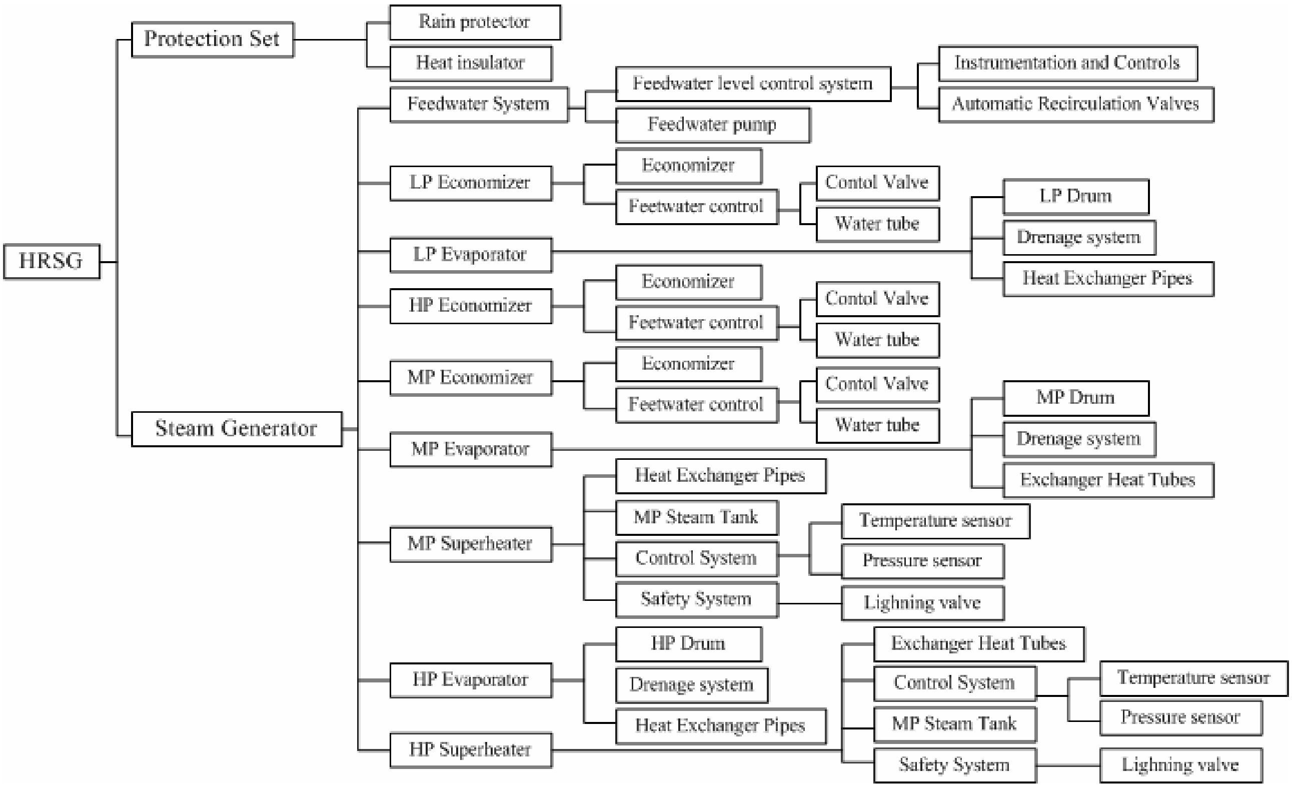

Figure 4. Heat Recovery Steam Generator Simplified Functional Tree

3.2. Failure Mode and Effects Analysis

The FMEA analysis is used to enumerate the possible modes by which components may fail and for tracking through the characteristics and consequences of each mode of failure on the boiler as a whole.

Although there are many variants of FMEA, it is always based on a table, as shown in Fig. 5. In the left-hand column the component under analysis is listed; then in the next column the physical modes by which the component may fail are given. This is followed, in the third column, by the possible causes of each of the failure modes.

The fourth column lists the effects of each failure mode that are classified according to the criticality scale, given the degradation degree in the boiler operation.

The FMEA analysis was performed for each component listed at the end of a given branch of the functional tree. In Fig. 5 the analysis for the feedwather pump support is partially presented as an example.

Function	Failure Model	Failure Causes	Failure effects	Severity
To transmit mechanical energy for the feed water	Incapacity to transmitter energy	Rupture of the blades Blockage of the line of suction. Shutdown of the electrical motor.	1. No water flow 2. Shutdown of the feedwater system. 3. Trip: low feedwater flow.	7

Figure 5. Failure Mode and Effects Analysis: Example – Feedwater Pump

The failure modes for the components were developed according to manufacturer's information and failures analysis presented in literature, Jovanovic, (2003); Srikanth *et al* (2002); Kehlhofer *at al* (1999); Lora and Nascimento, (2004); Ragland and Stenzel, (2000); Kim, Lee and Ro, (1999) and Burgazzi, (2004).

The analysis pointed that the most critical components for the HRSG are:

- Feedwater system: automatic recirculation valve (ARC); feedwater pump and feed system level control;
- Drenage system: to Low, Intermediate and high pressure;
- Low pressure: feed system level control; drain system;
- Intermediate pressure: feed system level control; drain system and heat exchanger pipes;
- High pressure: feed system level control; drain system, exchanger heat tubes and HP drum.

Those systems are submitted, according to manufacturer's recommendation, to a detailed maintenance policy based on predictive or preventive techniques, including annual inspections, for example: review available system prints and be familiar with the location of various major components; report any change in plant status to plant control room/supervisory personnel; slowly open manual valves to limit the pressure transients in piping systems, when opening vent and drain valves, be alert that hot liquid or steam may be present; always remain alert for safety valves to lift unexpectedly, (Siemens, 2000)

3.3. Reliability and Availability Analysis

Reliability can be defined as the probability that a system will perform properly for a specified period of time under a given set of operating conditions. Implied in this definition is a clear-cut criterion for failure, from which one may judge at what point the system is no longer functioning properly. For the HRSG the failure criterion is any component failure that causes incapacity of generating the nominal output.

The reliability analysis is performed for each of the two HRSGs installed in the power plant. The reliability analysis is based on the time to failure data analysis.

The HRSG block diagram, for normal operation condition, is a series system using all subsystems present in the first level of the functional tree, except for the protection set. Once the reliability of each component is defined, based on statistical analysis of their failure data, the boiler reliability is equal to the product of the subsystem reliability.

For the case under analysis there are not enough failures for all subsystems to estimate their reliability. So the boiler reliability will be calculated as a whole based on failure database.

Thus the reliability ($R(t)$) can be represented by a Weibull probability distribution, widely used in reliability calculations. The two-parameter Weibull distribution, typically used to model wear-out or fatigue failures, is represented by the following equation:

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

where $R(t)$ is the reliability, β called shape parameter and η called the characteristic life, are the distribution parameters.

The distribution parameters are estimated through the use of parametric estimation methods that fit the distribution to the "time to failure" data. There are procedures for estimating the Weibull distribution parameters from data, using what is known as the maximum likelihood estimation method. For the HRSG reliability analysis the software Weibull++, (Reliasoft, 2003), was used for parameter estimation.

Table I shows the Weibull distribution parameters for the HRSGs.

Table I**.** Weibull Distribution for HRSGS Reliability Calculations.

System	Parameters
HRSG 1	β = 0,4645 η = 461,2352
HRSG 2	β = 0,6484 η=1531,3139

Both HRSGs have reliability distribution with shape parameters less than one. When $0<\beta<1$, the distribution has a decreasing failure rate. This is referred to as the period of early failures where defective pieces of equipment, prone to failure because they were not manufactured or constructed properly, cause the high initial failure rates of engineering devices.

For the HRSG or other complex systems, in the beginning of the operational life, the early failure stage is also associated with the adjustment of control systems or/and operational crew learning.

The shape parameter of HRSG two reliability function is higher than the same parameter estimated for HRSG one. This fact indicates that the second boiler is getting close to the period of random failures, characterized by shape parameter equal to one ($\beta=1$).

The reliability distribution curve for HRSG 1, as an example, is presented in Fig. 6.

Once the boiler has failed a corrective maintenance procedure is performed to return the equipment to normal operation condition as soon as possible. The time to repair is also a random variable once it is dependent on the nature of failure, on the ability to diagnose the cause of failure and on the availability of equipment and skilled personnel to carry out the repair procedure

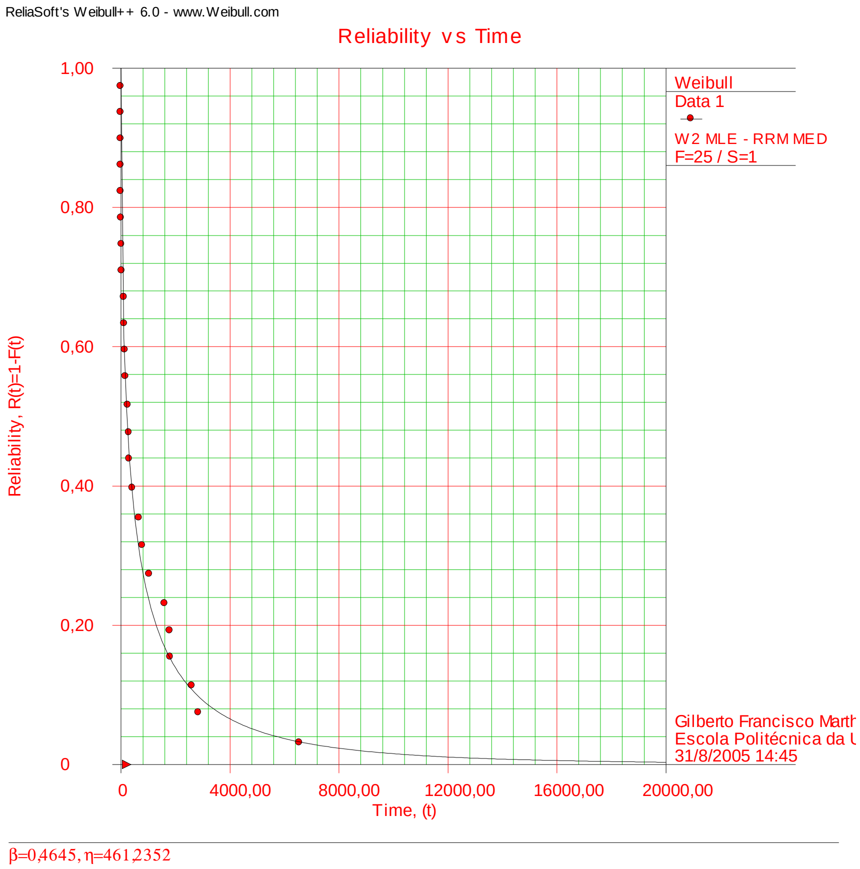

Figure 6. HRSG 1 Reliability Distribution.

The probability that equipment will be repaired in a given period of time is defined as maintainability and described by a probability distribution. Typically the lognormal distribution is used to model the time to repair distribution of complex systems. The maintainability can be expressed according to equation (2):

$$M(t) = 1 - \Phi\left(\frac{ln\,t - \mu}{\sigma}\right) \tag{2}$$

where $M(t)$ represents the maintainability, a measure of how fast a system can be repaired after a failure, $\Phi(\cdot)$ represents the standard normal distribution cumulative function, and μ and σ are respectively the mean and standard deviation in the logarithmic domain.

Based on the time to repair database for both gas turbines and using the software Weibull++, (Reliasoft, 2003), the lognormal distribution parameters for maintainability modelling were calculated and the results are presented in Table II.

The graphical representation of the maintainability probability distribution for HRSG 1 is presented in Fig. 7.

Table II**.** Lognormal Distribution for Turbines Maintainability Calculation

System	Parameters
HRSG 1	μ = 1,1148 σ = 1,1273
HRSG 2	μ = 0,7758 σ = 1,5957

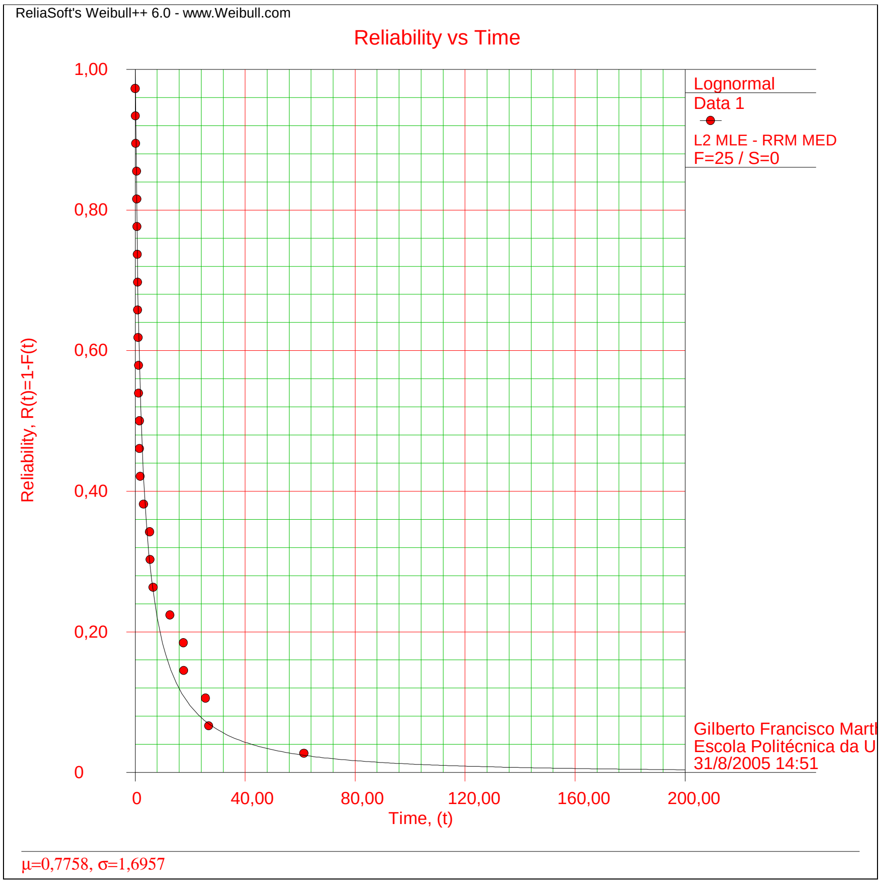

Figure 7. HGSR 1 Maintainability Distribution.

The HRSG 2 has a mean time to repair smaller than HRSG 1, (represented by μ). This fact is explained through the analysis of failure database.

The HRSGs presents not only faults related to the feedwater system, usually of sensors or control systems (the feedwater pump), devices that require small time to repair, but, also severe mechanic faults caused by lubrication problems that need a long time to repair. In relation to the feedwater level control, the faults are related to the automatic recirculation valve.

Once the reliability and maintainability parameters are calculated the system availability can be estimated. Availability is the probability that a system is available for use at a given time. Roughly, it may be viewed as a fraction of time that a system is in an operational state, (Smith and Hinchcliffe, 2003).

Applying the Monte Carlo simulation method, the availability can be estimated for an operation time. Considering that the HRSGs must operate during one year, corresponding to 8760 hours, and using the reliability and maintainability probability distribution presented in tables I and II, respectively, the availability for HRSG one is 99,6 % and for HRSG two is 99,7 % Availability is an index dependent on reliability and maintainability order although HRSG on has low reliability in comparison with HRSG two it has a low mean time to repair, that leads to a high availability.

The simulation results show that for complex electric-mechanical feedwater systems and control level flow, such as HRSG, the availability can be different for identical equipment located in the same site. This difference can be associated with the operational profile of the equipment, mainly the number of trips presented during the operational life, and the nature of failures – associated with mechanical or electrical devices.

3.4. Availability Improvement

The maintenance policy of HRSGs is typically based on five or six year's cycles, similar to the maintenance program of the gas turbines. During the first two years some annually based basic preventive tasks are performed. In the middle of the cycle a more complex inspection is performed. After that the basic tasks are annually performed and at the end of the cycle an overhaul maintenance is performed.

Considering that any boiler has complex monitoring and control systems; the preventive maintenance policy can be associated with some predictive tasks aiming at the reduction of the annually based maintenance activities. The time-history of a given sensor indication can be used to define the evolution of a failure mechanism that will cause a failure in a component. Based on historical records a maintenance analyst can foresee a future failure and define the necessity of maintenance intervention. This analysis is the basic principle of the predictive maintenance practice, strongly recommended by the Reliability Centered Maintenance Philosophy.

The amount and type of maintenance that is applied in a system depends on its costs as well as on the cost and safety implications of system failure. For a complex system concern would be with how much preventive or predictive maintenance can be afforded without affecting the system availability.

For the HRSG evaluated in this analysis the efforts applied in corrective tasks may be reduced with training of operators and maintenance crew and even the use of predictive analysis, for example a visual inspection using borescopes, to determine if the amount of remainders inlaid in the heat exchanger pipes is dangerous. They can be also used thermographic inspection that allows accompanying the behaviour by HRSG. Supposing that the consequence of those actions will be the reduction of mean time to repair, a new availability simulation is performed for each boiler, considering a reduction of ten minutes in the mean time to repair.

For HRSG 1 the availability is increased from 99,6% to 99,9%. For HRSG 2 that index increases from 99,7% to 99,9%

Those figures show that the use of predictive maintenance, allied to personnel training, can increase the HRSG availability and, as a consequence, the power plant availability.

4. CONCLUSIONS

The proposed method for reliability and availability analysis seems suitable for complex systems since it allows not only the identification of critical components for maintenance planning but also defines quantitatively the system's reliability and availability.

The development of the system functional tree is fundamental for the understanding of the functional relation between system components. Based on this tree a reliability block diagram can be easily constructed, representing the information flow through the components in accordance with a pre-defined system performance level.

Based on the functional hierarchy, the FMEA analysis is performed considering the failure modes associated with the components listed at the end of each branch of the functional tree, identifying the effects of component failure on the system under analysis. Once the critical components are identified, based on the failure effects classification, a maintenance policy can be formulated to reduce their occurrence probabilities.

The maintenance policy aims to reduce the system unavailability through the use of predictive or preventive maintenance tasks for critical components. This policy allows the reduction of unexpected failure occurrences that cause the system unavailability and are usually very expensive to repair.

For HRSGs the use of predictive or preventive tasks seems feasible providing better maintenance practices for the complex feedwather system or heat exchange system. A simple on conditions analyse could use flow sensor to check the operational condition, avoiding any trip due to pipes or valve obstruction.

Based on time to failure and time to repair data, the method allows system reliability, maintainability and availability analysis.

For the case under analysis, considering two identical heat recovery steam generators installed in the same power plant, the reliability was calculated considering a five-year operational database. Both boilers have their reliability represented by a Weibull probability function and are still presenting a decreasing failure rate. Due to the small operational time of each HRSG the operational crew is still learning how to operate the equipment and inducing some operational failures most of them associated with control system set-up.

The reliability and availability are different for both boilers. HRSG number two presented a great number of failures that were rapidly repaired having small effect on system availability. HRSG number one although presenting almost the same number of failures had a higher time to repair than HRSG two, reducing the system reliability.

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