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Availability analysis of heat recovery steam generators used in thermal power plants

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ABSTRACT

The combined-cycle gas and steam turbine power plant presents three main pieces of equipment: gas turbines, steam turbines and heat recovery steam generator (HRSG). In case of HRSG failure the steam cycle is shut down, reducing the power plant output. Considering that the technology for design, construction and operation of high capacity HRSGs is quite recent its availability should be carefully evaluated in order to foresee the performance of the power plant.

This study presents a method for reliability and availability evaluation of HRSGs installed in combined-cycle power plant. The method's first step consists in the elaboration of the steam generator functional tree and development of failure mode and effects analysis. The next step involves a reliability and availability analysis based on the time to failure and time to repair data recorded during the steam generator operation. The third step, aiming at availability improvement, recommends the fault-tree analysis development to identify components the failure (or combination of failures) of which can cause the HRSG shutdown. Those components maintenance policy can be improved through the use of reliability centered maintenance (RCM) concepts. The method is applied on the analysis of two HRSGs installed in a 500 MW combined-cycle power plant.

1. Introduction

The availability of combined-cycle gas and steam turbine power plants depends on the perfect operation of all its systems (gas turbine, HRSG and steam turbine).

The function of HRSG is to convert the exhaust gas energy of the gas turbine into steam. After a pre-heating step in the economizer, water enters into the drum, slightly sub cooled. From the drum, the water flows 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 to the superheater where it reaches the maximum temperature [10]. The heat exchange process in a 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 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 the consequence of the failure is the 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 such complex system 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.

Availability measures are concerned with the fraction of time a unit is capable of providing service. Most power plants use the index proposed by IEEE std. 762, [12], to define availability. That index represents the percentage of a given period of time, expressed in hours that the unit is in service hours (including reserve shutdown state). A reduction in availability is caused by planned maintenance and unplanned maintenance actions. The index, usually evaluated monthly, is reported in a generating availability data system (GADS) and can be used for comparison between different generating systems.

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Nomenclature

C	Larson–Miller equation constant depending on the material chemical composition
f_{model}	random variable expressing uncertainty in Larson–Miller parameter P
h	tube thickness [mm]
$M(t)$	maintainability at time t
MTTF	mean time to failure
MTTR	mean time to repair
p	tube internal pressure [MPa]
$p_{creepfailure}(t)$	probability of creep failure at time t
P	Larson–Miller equation parameter
$R(t)$	reliability at time t
$R_{HRSGlongterm}(t)$	HRSG long-term reliability at time t
$R_{longterm}(t)$	structural components long-term reliability at time t
R_{mean}	mean tube radius [mm]
$R_{randomfailures}(t)$	electrical–mechanical components reliability at time t
t	time period [h]
T	absolute temperature in Kelvin
T_{Fi}	ith random time to failure drawn form the reliability distribution [h]
t_r	creep time to failure (creep lifetime) [h]
T_{Ri}	ith random time to repair drawn form the maintainability distribution [h]
β	Weibull distribution shape parameter
η	Weibull distribution characteristic life [h]
μ	mean in the logarithmic domain, Lognormal distribution
σ	standard deviation in the logarithmic domain, Lognormal distribution
σ_{mech}	hoop stress acting on tube [MPa]
$\Phi(\cdot)$	standard normal distribution cumulative function

That index is deterministic and can only be used for maintenance efficiency management. In order to improve maintenance efficiency and to reduce maintenance costs, Ref. [3] proposed the use of reliability and maintainability concepts to define an availability index expressed by the ratio of the mean time to failure to the sum of the mean time to failure plus the mean time to repair.

The study indicates that the mean time to failure, calculated from the failure records, can be improved through the study of root-cause failure analysis and system reliability analysis. A reliability-based method is presented in Ref. [23] to evaluate heavy duty gas turbines performance, including the use of RCM concepts to reduce critical components failure rate.

This paper presents a system reliability-based method to identify the most critical components in a HRSG. The criticality of a component as for HRSG operation is associated with the component failure effect on the system operational condition. The higher the criticality of the component the greater is the amount of technical and economical resources used by the maintenance activities to keep the HRSG available for operation. The RCM concepts are used as a guideline in ranking the maintenance policy priorities for the critical components aiming at the system operational availability.

2. Method development

The method's first step consists in defining the system based on analyzing its functional and/or performance requirements. For the present paper the HRSG can be considered as a system. The examination of the system needs to be made in a well-organized and repeatable fashion so that the reliability analysis can be consistently performed, therefore insuring that important elements of a system are defined. The HRSG analysis is performed through the use of a functional tree that represents the functional links between the equipment subsystems.

The system breakdown structure used in the functional tree is the top-down division of a system into subsystems and components. This architecture provides internal boundaries for the system. For failure analysis, the resolution of that breakdown should be to the components level where failure data are available. Often the systems/subsystems are identified as functional requirements that eventually lead to the component level of detail. The functional level of a system identifies the function(s) that must be performed for the operation of the system. Although all HRSGs include 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, Refs. [16] and [18].

Taking into consideration that the reliability analysis is also based on the evaluation of the components failure consequences on the equipment performance; the method's second step requires that a tool must be used to select the critical components with respect to the potential effect of its failure on the equipment operational performance. That criticality must be judged on the plant level.

The present method suggests the development of the failure mode and effects analysis (FMEA) of each boiler component in order to define the most critical components for HRSG operation. The analysis tool assumes that a failure mode occurs in a component through some failure mechanisms; the effect of this failure on the equipment is defined through the criticality level [17]. For the definition of the equipment 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 HRSG unavailability or environmental degradation are classified with criticality values between 7 and 9. Table 1 presents the description of the effects associated with the highest criticality index.

The third step of the method 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 a 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 failure modes and effects analysis is executed the reliability analyst is capable of detecting the most critical components of the system. For those components or subsystems is important to develop a failure diagnosis procedure that allows a quick restoration to its normal operational condition in case of failure occurrence. That procedure must identify the possible root causes of the component failure aiming at directing the maintenance team efforts to investigate the most probable cause of the detected failure. If possible, the procedure should be the basis of