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Dynamic simulation of combined cycle power plant cycling in the electricity market

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ABSTRACT

The energy markets deregulation coupled with the rapid spread of unpredictable energy sources power units are stressing the necessity of improving traditional power plants flexibility. Cyclic operation guarantees high profits in the short term but, in the medium-long time, cause a lifetime reduction due to thermo-mechanical fatigue, creep and corrosion. In this context, Combined Cycle Power Plants are the most concerned in flexible operation problems. For this reason, two research groups from two Italian universities have developed a procedure to estimate the devices lifetime reduction with a particular focus on steam drums and superheaters/reheaters. To assess the lifetime reduction, it is essential to predict the thermodynamic variables trend in order to describe the plant behaviour. Therefore, the core of the procedure is the power plant dynamic model. At this purpose, in this paper, three different dynamic models of the same single pressure Combined Cycle Gas Turbine are presented. The models have been built using three different approaches and are used to simulate plant behaviour under real operating conditions. Despite these differences, the thermodynamic parameters time profiles are in good accordance as presented in the paper. At last, an evaluation of the drum lifetime reduction is performed.

1. Introduction

In the last few decades, the global energy demand has risen to a level never reached before. This, in turn, has led to several environmental problems such as air pollution, global warming, the reduction of the ozone layer and the depletion of fossil fuels. These aspects have forced the international administrations to promote the liberalization of the energy markets (see [1,2]) and the spread of renewable energy sources (RES) [3].

A major result of this process is a high penetration of unpredictable energy sources such as wind and solar, with big impact on the electricity market. Then, as already discussed by the Authors [4–6], flexibility, availability and fast cycling have become fundamental concepts to be competitive in this new electricity market. For this reason, thermoelectric units need to switch from base-load to cycling operation: an operation mode characterized by fast load ramps, short start-up and shut-down time that permits to enhance the power plant's competitiveness and to maintain the grid stability.

As outlined by Balling [7], the grid stability is often compromised by the high number of power plants fed by unpredictable renewable energy sources and by the absence of large-scale energy storage systems. Thus, investments focused on this research field are necessary to guarantee the stability of electrical grids in the European framework. Nevertheless, as presented by Keatley et al. [8] for the case of Ireland, the grid stability is also of particular concern to the owners and operators of fossil-fuel power plants because cycling operation of these units is required to integrate very high levels of wind power. Moreover, Balling [7] states that Germany conventional power plants will have to be started up and shut down several times weekly, or even daily, in the next five years. Obviously, conventional power plants cycling and energy storage systems are fundamental to maintain the grid stability but another promising option is offered by cogenerative hybrid systems with energy storage [9,10] and waste heat recovery units [11–15].

Therefore, new operating requirements for fossil-fuel power plants arise (two-shift operation, island operation, load-follow operation, black start capability and severe start-up) in order to stabilize power grid dynamics and ensure economic electricity supply. This new kind of operation strategy guarantees high profits in the short term, but determines a significant reduction in the

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Nomenclature

C_3, C_5	coefficients in Eq. (5)
F_r	Froude number
P_r	Prandtl number
R_e	Reynolds number
T	temperature [°C]
$\dot{m}$	mass flow rate $[\mathrm{kg\,s^{-1}}]$
Nu	Nusselt number
d	diameter [m]
h	heat transfer coefficient $[\mathrm{W\,m^{-2}\,K^{-1}}]$ or height [m]
l	pipe length [m]

Abbreviations

CCPP	Combined Cycle Power Plant
CS	Pump Control System
ECO	economizer
EVA	evaporator
HRSG	Heat Recovery Steam Generator
HX	heat exchanger
MSM	Matlab Simulink Model
PI	Proportional–Integral
RES	renewable energy sources
SAS	steam attemperator system
SH	superheater
ST	steam turbine
TP	ThermoPower library
TPL	Thermal Power Library

Greek letters

λ	thermal conductivity $[\mathrm{W\,m^{-1}\,K^{-1}}]$
ξ	operator in Eq. (2)

Superscript

n	operator in Eq. (6)

Subscripts

c	cold
des	design
f	fin
g	gases
hyd	hydraulic
i	inner
m	mean
o	outer
s	surface

lifetime of the most critical power plant devices, which are those subjected to thermo-mechanical fatigue, creep and corrosion (see i.e. Salonen et al. [16] and Lefton et al. [17]).

As presented by Tica et al. [18] and Alobaid et al. [19], improving start-up performance, load ramps and shut-downs is essential to be competitive but, as underlined by Benato et al. [6], the availability of procedures able to predict the residual life of power plant devices, considering the combined effects of creep, thermo-mechanical fatigue, corrosion and oxidation, is essential to optimize plants' operation and maintenance scheduling.

Furthermore, in the liberalized energy market, power plant operators need simulation tools able to test different operation strategies which allow them to manage the plant without excessively compromising its residual life. These tools can be very useful not only during the plant design phase but also in the daily operation, in order to better schedule load ramps and shut-downs and increase the gap between peak power and technical minimum load without neglecting environmental constraints [20].

Being combined cycles the most rapid, efficient and widespread technologies, they are the most concerned when dealing with flexibility. Usually, they provide spinning and cold reserve services or two-shift operation (since they often work with daily start-up and shut-down) thanks to their intrinsic flexibility which is higher than that of steam power plants [16].

In combined cycle gas turbine units, Heat Recovery Steam Generators (HRSGs) [21] and gas/steam turbines are the most critical components being exposed to creep and low-cycle fatigue degradation [22,23]. In particular, in multiple pressure level HRSGs, high pressure steam drums are among the most stressed components as they are characterized by great thickness and present many weakness points (down-comers, risers, steam tubes) which determine high values of stress concentration factors. Each fatigue load cycle deteriorates the metal parts and the accumulated damage ends up causing breakdowns and thus determining unplanned maintenance interventions; to this end, Carazas et al. [24] present a method for the reliability and availability evaluation of HRSGs installed in combined cycle power plants, in order to better identify the components more subjected to failures.

Considering the new market scenario, where flexibility is paramount, and the flexibility related problems, the Authors have developed an innovative method (lifetime calculation procedure) able to predict the power plant behaviour during cycling operation modes and estimate the power plant components' lifetime reduction [6].

As said, to estimate the lifetime reduction of metal components due to cycling, it is essential to foresee the trends of the main thermodynamic parameters (such as water/steam mass flow rates, temperatures and pressures) that describe the plant behaviour. Therefore, the core of the lifetime calculation procedure is the power plant dynamic model. Nowadays, dynamic simulation and, in particular, power plant dynamic analysis, is an essential step to achieve the desirable performance under the various kinds of constraints related to system design, plant operation and environmental impact. In literature, several mathematical models were proposed to investigate the combined cycle power plants Heat Recovery Steam Generator (HRSG) behaviour using different simulation tools. Dumont and Heyen [25] developed a mathematical model of a once-through Heat Recovery Steam Generator while Ong'iro et al. [26] built a model of a two pressure level HRSG unit. Shirakawa et al. [27] built a dynamic simulation model able to optimize the start-up process of a combined cycle gas turbine unit. Alobaid et al. implemented a static and dynamic simulation model of a subcritical and supercritical Heat Recovery Steam Generator (see [19,28]) using the advanced process simulation software Apros [29] while, with the advanced processing simulation software Aspen Plus Dynamics [30], they investigate the Heat Recovery Steam Generator behaviour during start-up procedure [31]. A model of a natural circulation HRSG using the Modelica language was developed by Casella and Pretolani [32]. The study aimed at reducing the start-up time while keeping the life-time