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LTE: A procedure to predict power plants dynamic behaviour and components lifetime reduction during transient operation

A. Benato [a,b,*], S. Bracco [c], A. Stoppato [a], A. Mirandola [a]

[a] Department of Industrial Engineering (DII), University of Padova, via Venezia 1, 35131 Padova, Italy
[b] "Giorgio Levi Cases" Interdepartmental Centre for Energy Economics and Technology, University of Padova, via Marzolo 9, 35131 Padova, Italy
[c] Department of Naval, Electrical, Electronic and Telecommunication Engineering (DITEN), University of Genova, via all'Opera Pia 11a, 16145 Genova, Italy

HIGHLIGHTS

- A procedure for the estimation of the lifetime reduction is proposed.
- The plant dynamic model is the core of the proposed procedure.
- A three pressure level combined cycle power plant is selected as test case.
- Different transient conditions are analyzed.
- The lifetime reduction of the high pressure superheater and drum is computed.

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ABSTRACT

The liberalization of the European energy markets combined with the rapid spread of unpredictable renewable energy sources have stressed the need of improving the traditional power units flexibility. Fast start-ups/shut downs and rapid load variations have become priority objectives because they guarantee high profits in the short term but cause a lifetime reduction due to thermo-mechanical fatigue, creep and corrosion. To this purpose, in the present work, an innovative procedure, able to predict the power plant dynamic behaviour during load variations, identify the most stressed components and estimate their lifetime reduction is presented and tested. Being combined cycles the most efficient, flexible and widespread technologies, the selected test case is a 380 MW combined cycle unit. To predict the plant dynamic performance a dynamic model has been built in Modelica language and several transient conditions investigated. The high pressure steam drum and superheater are the most stressed components. Results show a 52.9% reduction in superheater collectors life if the load variation is 50% faster than the reference case. On the contrary, a 35.8% lifetime increase is observed if the load variation is 50% slower. For the same conditions the high pressure steam drum life is reduced by 31.9% and increased by 16.3%, respectively. Also the superheater tube bank lifetime reduction is computed. The proposed procedure can be considered a valuable innovative tool to assist power plant designers and operators.

1. Introduction

The world energy scenario is changing over and over again, in terms of both electricity generation mix and needs of energy consumers; furthermore, environmental and economic issues have to be tackled and solved. To better understand and deal with the aforementioned context, first of all it is necessary to know what happened in the past and what are future needs. In the past years, in Europe, the gas and electricity industries have been characterized by inefficiencies and a lack of competition for a long time due to legal monopolies in production, natural monopolies in domestic transport and distribution networks, and limited international trade [1]. For these reasons, following the examples of United Kingdom and Norway, the European Commission issued the Directive 96/92/EC [2], concerning common rules to liberalize the power sector and create an Internal Electricity Market (IEM henceforth) [3]. Moreover, during the past two decades and especially since 2003 [4], climate changes and other environmental issues, such as air pollution, the reduction of the ozone layer and the

* Corresponding author at: Department of Industrial Engineering (DII), University of Padova, via Venezia 1, 35131 Padova, Italy. Tel.: +39 049 8276752; fax: +39 049 8277599.
E-mail address: alberto.benato@unipd.it (A. Benato).

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Nomenclature

C_3, C_5	coefficients in Eq. (13)
D	total creep-fatigue damage (–)
D_{CF}	cumulative fatigue damage index (–)
D_L	limit damage (–)
D_c	creep damage (–)
K_f	effective stress concentration factor (–)
K_t	theoretical stress concentration factor (–)
N_0	number of cycles before failure (cycle)
N_k	number of fatigue cycles (cycle)
P_r	Prandtl number
R_e	Reynolds number
T	temperature (°C) or thermal stress (MPa)
T_{gm}	average flue gases temperature (°C)
T_s	surface temperature (°C)
$\dot{m}$	mass flow rate (kg s^{-1})
Nu	Nusselt number
d	diameter (m)
d_i	inner diameter (m)
f_e	thickness correction factor (–)
f_m	mean stress correction factor (–)
f_s	surface finish correction factor (–)
f_u	overall correction factor (–)
f_{T^*}	temperature correction factor (–)
h	enthalpy (J kg^{-1}) or heat transfer coefficient (W m^{-2} K^{-1})
k_e, k_v	plasticity correction factors (–)
l	length (m)
p	pressure (Pa) or mechanical stress (MPa)
r	radial component (–)
t_r	time of failure (yr)
z	axial component (–)

Abbreviations

CCGT	combined cycle gas turbine
ECO	economizer
ETS	Emissions Trading System
EU	European Union
EVA	evaporator
FLC	Fatigue Life Calculation Tool
GT	gas turbine
HP	high pressure
HRSG	Heat Recovery Steam Generator
HX	heat exchanger
IEM	Internal Electricity Market
IP	intermediate pressure
LP	low pressure
LTE	LifeTime Estimation
PDS	plant dynamic simulator
PV	Photovoltaic
RES	renewable energy sources
RH	reheater
SH	superheater
ST	steam turbine

Greek letters

$\Delta\sigma_D$	material endurance limit (MPa)
$\Delta\sigma_k$	stress range (MPa)
Δ	difference
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
σ	stress (MPa)
θ	circumferential component
ε	strain (με)
ξ	operator in Eq. (10)

Subscripts

f	fin
g	exhaust gases
hyd	hydraulic
i	inner
in	inlet
k_{th}	k-esimo
m	mean
o	outer
out	outlet
s	surface

depletion of fossil fuels, have become public concerns, keeping in mind the Montreal and Kyoto Protocols. In order to tackle these problems, the European Union launched the Emissions Trading System (ETS) (see Directives 2003/87/EC [5] and 2009/29/EC [6]), established new common rules for the Internal Electricity Market (Directives 2003/54/EC [7] and 2009/72/EC [8]) and promoted the use of energy from renewable sources (RES) [9]. These Directives, coupled with economic mechanisms established to boost the spread of RES, have introduced significant changes in the EU national markets and, as a consequence, in Italy.

As underlined by Antonelli and Desideri [10], the most generous renewable support scheme worldwide has transformed Italy from a country with no significant photovoltaic (PV) energy production into one of the world leading countries in terms of installed photovoltaic power capacity. These massive investments in solar and wind [11] capacity have produced, on the one hand, a high penetration of renewables but, on the other hand, an urgent need of flexible power plants fed by fossil fuels. Note that, from 2008 to 2013, the power generation from wind and solar has increased by 23 TW h while, due to the financial crisis, the Italian energy demand has decreased by 43 TW h [11]: two aspects that have drastically changed the Italian generation mix and the power plants management strategies. Turconi et al. [12] remark that the increase of renewable sources in the power sector is an important step towards more sustainable electricity production; however, introducing high shares of variable renewables, such as wind and solar, cause dispatchable power plants to vary their output to fulfil the remaining electrical demand and part-load operations significantly affect the average power plant efficiency.

Therefore, in order to be competitive in the Italian deregulated electricity market, traditional energy systems need to be flexible, that is they have to be able to ramp up and down quickly and efficiently and to run at low output levels, without excessively increasing daily operation costs and emissions. As assessed by Van den Bergh and Delarue [13] cycling of conventional generation units, that change their power output by means of ramping and switching (starting up and shutting down), is an important source of operational flexibility in the electricity generation system; moreover, in Ref. [13] the importance of including full cycling costs in the unit commitment scheduling is highlighted too. Steam power plants and combined cycle units are requested to switch from base-load to cycling operation mode in order to meet the users demand and compensate the variability of unpredictable renewable energy sources. Since 2003, after a strong investment