Energy 68 (2014) 667–679

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Design methodology for flexible energy conversion systems accounting for dynamic performance

Leonardo Pierobon [a,*], Emiliano Casati [b,c], Francesco Casella [d], Fredrik Haglind [a], Piero Colonna [b]

[a] Department of Mechanical Engineering, Technical University of Denmark, Building 403, DK-2800 Kgs. Lyngby, Denmark
[b] Propulsion and Power, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands
[c] Dipartimento di Energia, Politecnico di Milano, Via Lambruschini 4, 20156 Milano, Italy
[d] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

ARTICLE INFO

Article history:
Received 22 October 2013
Received in revised form
13 February 2014
Accepted 2 March 2014
Available online 30 March 2014

Keywords:
Power plant dynamics
ORC
Flexible power systems
Multi-objective optimization

ABSTRACT

This article presents a methodology to help in the definition of the optimal design of power generation systems. The innovative element is the integration of requirements on dynamic performance into the system design procedure. Operational flexibility is an increasingly important specification of power systems for base- and part-load operation. Thus, it is crucial to discard, in an early phase of the design process, plant configurations which feature unacceptable dynamic performance. The test case is the preliminary design of an off-grid power plant serving an off-shore platform where one of the three gas turbines is combined with an organic Rankine cycle turbogenerator to increase the overall energy efficiency. The core of the procedure is a stationary model, capable of performing the on-design thermodynamic cycle calculation, and the design of the components of the system. The results of these simulations are used within the framework of a multi-objective optimization procedure to identify a number of equally optimal system configurations. A dynamic model of each of these systems is automatically parameterized, by inheriting its parameters values from the design model. Dynamic simulations allow then to discriminate among the initial set of solutions, thus providing the designs that also comply with dynamic requirements.

1. Introduction

The recent liberalization of the electricity markets, along with the rapid expansion of the utilization of non-dispatchable renewable energy sources, such as wind and solar radiation, is stressing the necessity-opportunity of improving the flexibility of power generation systems [1]. New power technologies play therefore a significant role in providing such flexibility, and the electricity industry has acknowledged that this need will increase in the near future [2]. In the case of base-load power plants, changes to the scheduling procedures are leading to the latest combined-cycle gas turbine units being designed to operate efficiently and reliably under a wide range of rapidly varying conditions. Furthermore, both new coal and nuclear power plants are conceived with increased capability of operating under fast-load variations. In addition, older power stations are retrofitted in order to increase dynamic operation performance [3]. Operational flexibility is mandatory for off-grid power systems, and often preserving high energy conversion efficiency is also demanded. The electrification of remote areas is widely studied [4], together with the powering of industrial installations with systems operating in island [5].

In this context, system dynamic modeling and simulation is becoming a powerful design tool, especially if the level of detail of system and component models can be tuned to the design needs. In a recent work, Garcia et al. [6] investigated options to increase the robustness of energy networks, by simulating energy flow scenarios in which multiple forms of energy commodities, such as electricity and chemical products, may be exchanged. They studied the interactions between the grid and such advanced hybrid energy systems, by using dynamic models of various units and simulating their operation. Concerning the detailed study of advanced power systems, Zhu and Tomsovic [7] analyzed distributed combined cycle plants based on micro gas turbines and fuel cells, with the aim of reducing the costs related to ancillary services in a deregulated

* Corresponding author.
E-mail address: lpier@mek.dtu.dk (L. Pierobon).

http://dx.doi.org/10.1016/j.energy.2014.03.010
0360-5442/

Nomenclature

Symbols

A	area [m^2]
F_h	fin height [mm]
F_p	fin pitch [mm]
F_t	fin thickness [mm]
H	head [m]
Nu	Nusselt number
P	power [kW]
Pr	Prandtl number
Re	Reynolds number
T	temperature [K]
U	overall heat transfer coefficient [kW m^{-2} K^{-1}]
V	volume [m^3]
$\bar{J}$	array of objective functions
$\overline{X}$	array of variables
$\dot{m}$	mass flow [kg s^{-1}]
b_1,b_2	parameters in Equation 6
c	speed of sound [m s^{-1}]
d	diameter [m]
h	heat transfer coefficient [kW m^{-2} K^{-1}] or specific enthalpy [kJ kg^{-1}]
l	length [m]
n	rotational speed [rpm] or exponent in Equation 5
p	pressure [bar]
pt	tube pitch
s	specific entropy [kJ kg^{-1} K^{-1}]
th	thickness [m]
u	velocity [m s^{-1}]

Abbreviations

AC	alternating current
AMA	arithmetic mean average
CC	combustion chamber
GA	genetic algorithm
GEN	electric generator
GT	gas turbine
HPC	high pressure compressor
HPT	high pressure turbine
LPC	low pressure compressor
LPT	low pressure turbine
ORC	organic Rankine cycle
OTB	once through boiler
PI	proportional integral
PT	pressure turbine
RSD	relative standard deviation
TUR	turbine

Greek letters

Δ	difference
λ	thermal conductivity [W m^{-1} K^{-1}]
ϕ	exponent in Equation 6
ρ	density [kg m^{-3}]

Subscripts

b	baffle
des	design
exh	exhaust gases
f	fouling
i	inner
o	outer
r	recuperator
S	thermodynamic static state
T	thermodynamic total state
t	tube
th	throat
w	metal wall

market. Alobaid et al. [8] developed a detailed model of a complete combined cycle, based on a steam Rankine unit cascaded to a gas turbine, in order to study and optimize its start-up procedure. Model-based control techniques for the same type of power plant are dealt with by Lopez-Negrete [9].

Notwithstanding the mentioned advancements, to the knowledge of the authors the integration of dynamic performance analysis into the design process has not been considered yet. Discarding plant configurations featuring unacceptable dynamic performance (e.g., ramp-up and -down time) at a very early design phase can be very valuable. A traditional design approach, mainly aimed at increasing steady-state efficiency, might lead to systems that cannot comply with dynamic requirements, even if aggressive control strategies are pursued.

This work is aimed at the development of an automated preliminary design methodology in which system transient performance can be seamlessly evaluated together with other typical design requirements. In order to test the automated design tool, a relevant test case has been selected, namely the power plant of an off-shore oil and gas platform in the North Sea, operating off-grid. The problem consists in evaluating if it is possible to increase the efficiency of the three GTs (gas turbines), by installing an ORC (organic Rankine cycle) turbogenerator powered by the exhaust gases of one of the GTs, and still comply with stringent dynamic requirements.

This paper is structured as follows: the novel design methodology is outlined in Section 2, while Section 3 deals with the description of the case study. A detailed description of the models is presented in Section 4. The results are thus reported and discussed in Section 5. Concluding remarks are given in Section 6.

2. Methodology

The objective of this study is to develop and demonstrate a methodology for the preliminary design of power generation systems that integrates the fulfilling of dynamic requirements into the automated procedure. This goal is attained by performing two main steps.

In the first step, N performance metrics are selected (e.g., the thermal efficiency, the overall system volume, the net present value), and a multi-objective optimization problem is solved in order to find a set of preliminary system designs which lead to optimal performance of the system at the rated operating point. The outcome is an N-dimensional Pareto front of system designs, which are optimal with respect to different objectives. In the second step, the dynamic performance of the system is assessed by simulating critical transients for each design on the Pareto front, and by verifying whether requirements and constraints involving dynamic variables are met or not. System designs which do not meet the dynamic requirements are discarded.