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Research Paper

Compact steam bottoming cycles: Model validation with plant data and evaluation of control strategies for fast load changes

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HIGHLIGHTS

- Dynamic process modeling of compact steam bottoming cycle for offshore applications.
- Validation of dynamic process model with industrial plant data from a compact steam bottoming cycle installation.
- Model based control structure design for fast load changes in compact steam bottoming cycle.

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ABSTRACT

Power plants installed on offshore oil and gas installations need to be operated in a flexible manner in order to accommodate the variability in heat and power demands. The present paper describes steady-state process model validation based on data from an actual offshore oil and gas installation, dynamic model validation, and evaluation of control strategies for fast load changes. The offshore process configuration consisted of two gas turbines with a once-through heat recovery steam generator located downstream of each gas turbine. One steam turbine received the combined steam mass flow from the two steam generators. The validation data, focusing on the steam bottoming cycle, consisted of one year of operation. Subsequently, a dynamic process model based on a simplified process layout was developed in the open physical modeling language Modelica and validated with reference steady-state and transient software data. The results from the evaluation of control strategies showed the benefits in utilizing feedforward control for the operation of the heat recovery steam generator under fast load changes, and the effectiveness of attemperation to avoid excessive excursions of live steam temperature during transients.

1. Introduction

The offshore industry for oil and gas extraction and processing relies on flexible and secure supply of heat and power to the platform for the daily operations. Gas turbines are normally installed to provide the platform with heat, electricity, and mechanical drive. The utilization of the energy available in the exhaust gas of the gas turbines of the platform can improve the performance of the system [1]. By implementing waste heat recovery units (WHRU) or bottoming cycles, the energy efficiency on the platform can be increased and the associated CO_2 emissions can be reduced. Several studies have evaluated different bottoming cycles for implementation on offshore oil and gas platforms. Pierobon et al. [2] investigate three different technologies for waste heat recovery in offshore oil and gas platforms on a specific offshore platform with gas turbines with a rather low exhaust temperature. The analyzed technologies include steam bottoming cycle, air bottoming cycle, and organic Rankine cycle (ORC), concluding that ORC is the most promising technology long term to best utilize the exhaust energy in the case study, however, steam bottoming cycles were also considered a suitable technology. Another promising technology for implementation offshore is CO_2 bottoming cycles with the potential to increase the net plant efficiency with 10–11%-points compared to a simple cycle gas turbine [3]. Other studies have considered hybrid systems with electrification from land combined with gas turbines [4]. All the analyzed technologies and cycles in the literature have their pros and cons. ORCs have a disadvantage at high temperatures (above 400 °C) due to working fluid degradation; steam cycles need water treatment that can be bulky for an offshore installation; electrification has a disadvantage for providing heat; CO_2 cycles are still immature. Because of the maturity of the technology, the ease in supplying heat from steam extractions, the possibility to recover heat from high-temperature sources, and recent advances in making the components lighter and

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Nomenclature

A_{heat}	heat transfer area (m^2)
d_{hyd}	hydraulic diameter (m)
F_a	tube arrangement factor (–)
h	specific enthalpy (J/kg)
K_s	Stodola's flow area coefficient
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_{LTE,rec}$	recirculated mass flow rate for feedwater temperature control (kg/s)
$\dot{m}_{steam}$	steam mass flow rate (kg/s)
Nu	Nusselt number
p	pressure (bar)
$p_{HPOTBout}$	boiler pressure (bar)
$p_{inletHRSGsteam}$	pressure (bar)
$p_{inletST}$	pressure (bar)
$p_{livesteam}$	pressure (bar)
Q	heat transfer (W)
T	temperature (°C)
$T_{HPEO,out}$	water temperature at oulet of economizer (°C)
$T_{HPSOs,out}$	steam temperature at oulet of boiling section (°C)
T_{fluid}	temperature fluid (°C)
$T_{inletHRSGgas}$	temperature of exhaust gas at HRSG inlet (°C)
$T_{livesteam}$	live steam temperature (°C)
$T_{ouletHRSGgas}$	temperature of exhaust gas at HRSG outlet (°C)
T_{wall}	temperature wall (°C)
t	time (min)
t_r	reference value from steady-state simulations in Thermoflow
t_s	simulation result in Dymola
U	overall heat transfer coefficient (W/m^{2}K)
V	volume (m^3)
$\dot{W}_{ST}$	active power output (W)
$w_{dry,loss}$	dry steam turbine exhaust losses (kJ/kg)
$w_{st,loss}$	steam turbine exhaust losses (kJ/kg)
x	vapor quality (–)
x_m	mean step steam quality (–)
y	moisture content (–)
α_g	heat transfer coefficient gas side (W/m^{2}K)
α_s	heat transfer coefficient steam side (W/m^{2}K)
β	Baumann coefficient (–)
η_{dry}	dry step efficiency (–)
η_{step}	corrected step efficiency (-)
λ	thermal conductivity (W/m K)
ρ	density (m^3)
FF	feed forward
GT	gas turbine
HP	high pressure
HP OTB	high pressure once-through boiler
HPE	high pressure economizer
HPS	high pressure superheater
HPSO OTB	superheater high pressure once-through boiler
HRSG	heat recovery steam generator
LP	low pressure section
LTE	low temperature economizer
ORC	organic Rankine cycle
OTSG	once-through heat recovery steam generator
PC	pressure controller
PI	proportional and integral feedback control
PID	proportional, integral, derivative
PT	pressure transmitter
RE	relative error
ST	steam turbine
TC	temperature controller
TPL	thermal power library
TT	temperature transmitter
WHRU	waste heat recovery unit

more compact [5], steam cycles are still considered as one of the most attractive technologies for this application.

Steam bottoming cycles are, as of June 2018, operating on three Norwegian offshore oil and gas installations, as the only bottoming cycles in operation on the Norwegian continental shelf. One of the installations is the Oseberg Field Center where the drum-based heat recovery steam generators (HRSGs), originally installed in 1999–2000, were replaced by once-through heat recovery steam generators (OTSGs) in 2011–2012 for increased compactness and reliability. In general, the offshore steam bottoming cycles have had reliability issues, mostly related to the HRSG. Design considerations for offshore compact steam bottoming cycles are discussed in [6], showing the importance of weight, volume footprint and flexibility as design criteria. Different plant layouts and operating scenarios at both design and steady-state off-design conditions are analyzed in [7,8]. Single-objective optimization of the weight-to-power ratio and multi-objective optimization of weight and power are performed in [5] to arrive at low weight and high power solutions. Riboldi and Nord [9] evaluated the effectiveness of combined cycles in offshore oil and gas installations for cogeneration of heat and power exemplifying the attractiveness to do so. A knowledge gap in the literature for these cycles and applications is related to dynamics and flexibility. Pierobon et al. [10] present a methodology to discard optimal process designs based on dynamic requirements by means of dynamic simulations, applied to ORCs in offshore oil and gas installations. Benato et al. [11] study the dynamics of an air bottoming cycle applied to offshore applications. The use of feedforward control for compact OTSGs is mentioned by Brady [12], but only qualitatively. For dynamic studies on control strategies for compact steam bottoming cycles, no work is available in the open literature to the authors' knowledge.

For combined gas and steam turbine cycles, and steam bottoming cycles, several works related to dynamics are available in the literature. This includes model validation [13], part load operation [14], startup [15], system response to step disturbances [16], as well as steam cycle component design [17] and dynamics [18,19]. However, the cited works consider non-compact designs. Compact steam bottoming cycles, preferably with low footprint and weight, have special considerations related to material selection, process layout, and component design, all of which effect the system dynamics.

On offshore oil and gas installations, the power demand is high and changes over time both in day-to-day operation and over the lifetime of the installation. The power plant should be flexible to always be able to adjust to the needs of the oil and gas processes on the platform while being compact with low weight. Key aspects of operational flexibility include part load efficiency and emissions, and the transient performance under load changes. A validated dynamic process model can help to develop understanding on the transient performance of the system, and to evaluate control strategies and the feasibility of operation of new process designs at the design stage. The novelty of this work are the analyses of the dynamic performance of a compact steam bottoming cycle designed for offshore installations, and the development of a control strategy, using model based control design, to operate under fast load changes for such a cycle. This is moving one step forward from previous study related to steady-state off-design operation for compact steam bottoming cycles [7]. Although the case study in this paper was applied to an offshore installation, a compact steam cycle can also be attractive on ships and other locations with space and weight constraints. This expands on the applications for this work. Another valued aspect of the paper is the model validation with industrial plant