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Simulation and optimization of a combined cycle gas turbine power plant for part-load operation

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A B S T R A C T

Combined cycle gas turbine (CCGT) power plants must often run at part-load conditions, as the electricity demand varies constantly. We present a method and necessary correlations for simulating the part-load operation of a typical CCGT plant in a commercial simulator (e.g. GateCycle). We show that assuming constant values for some equipment parameters (e.g. efficiencies) and ignoring the operating maps of key equipment can overestimate plant performance significantly at part-loads. Furthermore, a rise in the ambient temperature lowers the plant capacity, but increases the plant efficiency. Then, we propose a simulation-based optimization approach that yields an optimal operating strategy to maximize the overall plant efficiency for any part-load. Our strategy forms a basis for evaluating the two widely used operating policies (fuel flow control or FFC and inlet guide vane control or IGVC). Our proposed strategy increases the plant efficiency by as much as 2.63% (absolute) over FFC and 0.93% over IGVC. This work highlights the need for integrating the two cycles (gas turbine and steam) to optimize the plant performance. We find that FFC seems to prioritize the gas turbine and IGVC tends to prioritize the steam cycle, while our proposed strategy strikes an optimal balance between the two.

1. Introduction

Natural gas is quickly replacing coal as the preferred fuel for power generation worldwide due to its cleaner nature and lower CO_2 emissions (Boyce, 2012). Combined cycle gas turbine (CCGT) power plants that use natural gas as the fuel are among the most efficient with a thermal efficiency as high as 60% (Rao, 2012). As a result, CCGT plants are now undergoing widespread installations. Some countries such as Singapore produce more than 96% of their electricity from CCGT power plants (EMA Singapore, 2017).

A CCGT power plant generates power from two cycles: A Brayton cycle followed by a Rankine cycle. An air compressor followed by a gas combustor and then a gas turbine (GT) are the main components of the Brayton cycle. Multiple pumps feeding water to a heat recovery steam generator (HRSG) that in turn supplies steam at multiple pressure levels to steam turbines (STs) are the main components of the Rankine cycle. Power plants including the CCGT plants are often designed with surplus capacity due to the need to maintain spinning reserves mandated by their governments. Furthermore, the power demand fluctuates significantly with time each day. Therefore, a CCGT plant must often run at part-loads (which means off-design conditions). This lowers its thermal efficiency, wastes substantial non-renewable fossil fuels (natural gas in this particular case), and increases CO_2 emissions. Thus, simulating and optimizing the performance of a CCGT plant at part-loads is of much interest.

Much modeling work exists for simulating individual components of a CCGT plant. Kim and Ro (1995) reported a simulation program to evaluate the effect of configuration on the performance of a heavy-duty GT. Zhang and Cai (2002) defined several reduced parameters to express compressor and turbine characteristics, and used them to derive an analytical solution for predicting the part-load performance of a GT. Haglind and Elmegaard (2009) proposed two models to predict the part-load performance of an aero-derivative GT. One model used the actual performance maps of the compressor and turbine, but the other simpler model assumed turbine constants with compressor maps. Irrespective, both models offered good predictions of

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Nomenclature

Symbols

A	Area, m^2
C	Heat capacity, kJ/K
c_p	Specific heat, kJ/kg/K
c_1, c_2	IGV angle correction factors
h	Mass enthalpy, kJ/kg
LHV	Lower heat value, kJ/kg
m	Mass flow, kg/s
N	Shaft rotational speed, rpm
NTU	Number of transfer unit
P	Pressure, bar
PR	Overall pressure ratio
ΔP	Pressure loss, kPa
Q	Heat duty, kW
R	Gas constant
T	Temperature, K
U	Overall heat transfer coefficient, $kJ/(s\,m^2\,K)$
W	Power, MW

Greek letters

$\Delta\alpha$	IGV angle
γ	Specific heat ratio
δ	Expansion ratio
ε	Heat transfer effectiveness
η	Efficiency
κ	Constant
λ	Constant
ν	Specific volume
φ	$(\gamma-1)/\gamma$
ϕ	Cooling effectiveness
ψ	Flow coefficient
Ω	Combustor loading
Υ	Turbine blade cooling constant

Subscripts/superscripts

a	Air
b	Turbine blade
c	Compressor
ca	Cooling air
cc	Combustion chamber
cor	Corrected value
d	Design condition
f	Fuel
g	Flue gas
in	Inlet
map	Performance map
out	Outlet
Pump	Feed water pump
t	Turbine/turbine stage
w	Water/steam
*	Critical value

Acronyms

CCGT	Combined cycle gas turbine plant
ECON	Economizer
EVAP	Evaporator
HP	High pressure
HPP	High pressure pump
HRSG	Heat recovery steam generator
IP	Intermediate pressure
IPP	Intermediate pressure pump
LP	Low pressure
LPP	Low pressure pump
RHT	Reheater
RP	Recirculation pump
SPHT	Superheater
ST	Steam turbine
TET	Turbine exhaust temperature
TIT	Turbine inlet temperature

mass flows and pressure profiles for the entire load range, and thermal efficiencies and exhaust temperatures for part-loads above 70%. Lee et al. (2011) developed a general simulation program for simple, recuperative, and reheat GTs. They used a stage-stacking method for the air compressor, and a stage-by-stage model for the turbine. Their method is useful when the compressor/turbine performance maps are not available. Song et al. (2015) combined two existing cooling models (Consonni, 1992; Holland and Thake, 1980) to accurately predict the cooling air flows for a GT, and analyzed their influence on the off-design performance. Tsoutsanis et al. (2014, 2015) introduced a novel map-tuning method to improve the accuracy and fidelity of GT models for predicting the performance under steady, transient, and degraded conditions.

Relative to the GTs, HRSG modeling has received much less attention. Its off-design simulation requires estimates of overall heat transfer coefficients (OHTCs). Xu et al. (2015) adopted a power law correlation for this by assuming the gas side to control the heat transfer. Kim and To (1997) and Haglind (2011) accounted for the properties of both gas and water/steam, and used different OHTC correlations for various heating surfaces. Zhang et al. (2016b) adopted Ganapathy's HRSG simulation method (Ganapathy, 1990), in which both HRSG design and exhaust gas parameters are considered to calculate the OHTCs at off-design conditions.

The steam turbines (STs) are often modeled using the Flugel equation (Haglind, 2011) or Stodola's method (Sanchez Fernandez et al., 2016).

Plant operation/control strategies obviously impact the performance of CCGT plants significantly. Kim and Hwang (2006) evaluated three part-load operation strategies (fuel flow control (FFC), variable speed control (VSC), and IGV control (IGVC)) for a single-shaft recuperative GT, and two strategies (FFC and variable area nozzle control (VANC)) for a two-shaft recuperative GT. VSC gave the best part-load performance for the former, and VANC for the latter. Haglind (2011) analyzed the effects of variable geometry GTs on the part-load performance of a single-pressure CCGT plant and found that the IGVs and VAN improved performance. Kim et al. (2003) showed that IGVC increases the performance of a single-shaft combined cycle, but not a two-shaft configuration. Jiménez-Espadafor Aguilar et al. (2014) analyzed eight operating strategies for a combined heat and power (CHP) plant based on two two-shaft GTs, and showed that IGVC offered the best regulation capacity. Barelli and Ottaviano (2015) proposed a novel combined cycle by adding an additional variable speed compressor upstream of the GT to adjust air flow in order to improve the operational flexibility and part-load performance.

The above discussion suggests that the existing work has addressed some components of CCGT plants individually. However, the off-design operations of other components such as water pumps, steam turbines, gas combustor, and generator have received little or no attention. Furthermore, a study addressing the off-design performance of all components in a holistic manner does not exist. Most studies on operating strategies have focused solely on the GT operation, and assumed a few pre-defined policies. The impact of steam cycle (SC) and its interaction with the GT operation have been not studied in a holistic or integrated manner.

This work aims to simulate and optimize the part-load operation of a CCGT plant while considering the off-design operation of

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