



Research Paper

Estimation of operating parameters of a SOFC integrated combined power cycle using differential evolution based inverse method

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HIGHLIGHTS

- Inverse analysis of a SOFC integrated combined power cycle is presented.
- Differential evolution (DE) based optimization algorithm is used.
- Six unknown operating parameters are estimated simultaneously.
- Net power, total irreversibility, energy and exergy efficiencies are taken as objective functions.
- Multiple combinations of operating parameters satisfy a given objective function.

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ABSTRACT

Inverse analysis is an efficient method to estimate parameters that characterizes a given system. It offers lot of flexibility at the designer's hand in selecting the most suitable combination of parameters satisfying a given set of objective functions. In this study, inverse analysis of a solid oxide fuel cell (SOFC)–gas turbine (GT)–steam turbine (ST) combined cycle (CC) power system is performed. The system's net power, efficiencies (energy and exergy) and the total irreversibility at compressor pressure ratio (CPR) 6 and 14 are considered as objective functions for the inverse problem. A differential evolution (DE) based inverse algorithm is used for simultaneously estimating six operating parameters of the plant. It was seen that the inverse technique was very effective in estimating the operating parameters of a hybrid SOFC–GT–ST plant correctly within the prescribed lower and upper bound of the parameters. Multiple combinations of parameters are obtained from the study and all these combinations of parameters satisfy the given single objective function/set of objective functions. Any objective function value be set and then operating parameters be determined accordingly using the inverse method. The results offer plenty of scope for selection of suitable operating parameters for the plant.

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1. Introduction

SOFC integrated hybrid GT based power system has widely been analysed with the help of mathematical modeling [1]. A huge number of hybrid SOFC–GT system configuration analyses are found in literature [2–12]. In a hybrid SOFC–GT system, usually the SOFC produces three to five times more power than the GT [13]. As such the power output from the bottoming GT plant is relatively less. Hence, SOFC when it is integrated with the bottoming GT cycle alone, small sized GTs are more suitable. Costamagna et al. [14] and Lai et al. [15] studied integration of SOFC into micro gas turbine (MGT) system.

It is more appropriate to integrate a SOFC stack either with a ST cycle or with a CC (not with the GT alone) because SOFC integrated GT or ST power plant using natural gas fuel demands the use of a HRSG and sometimes a pre-reformer (PR) for partial fuel reforming. Anode gas recycling is also sometimes used for fuel reforming but still a steam generator would be required for starting purpose. SOFC–GT–ST systems have not been investigated comprehensively and only a few analyses are done on combined SOFC–GT–ST systems [16,17]. Kuchonthara et al. [16] investigated the effect of GT inlet temperature (GTIT) and the pressure ratio on energetic performance of a SOFC–GT–ST (triple pressure) system. Arsalis [17] also analysed the design and off design operations of hybrid SOFC–GT–ST system. In SOFC integrated CC power plant, if the GT and ST plant don't produce sufficient power, economic feasibility of their integration may be an issue considering high capital/

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Nomenclature

A	constant
B	constant
E	reversible open circuit cell voltage (V)
ex	molar specific exergy (kJ kmol^{-1})
$\dot{E}x$	total exergy rate (kW)
F	Faraday's constant
G^0	Gibbs free energy (kJ kmol^{-1})
h	enthalpy (kJ kmol^{-1})
$\dot{m}_g$	mass flow rate of combustion gases (kg s^{-1})
$\dot{m}_s$	steam generated (kg s^{-1})
$\dot{m}_w$	water flow rate (kg s^{-1})
i	current density (A cm^{-2})
i_0	exchange current density (A cm^{-2})
$\dot{I}$	irreversibility rate (kW)
$\dot{n}$	molar flow rate (kmol h^{-1})
n_e	number of electron
p	partial pressure of constituent gases (bar)
p_0	reference pressure (bar)
R	universal gas constant ($8.3143 \text{ kJ kmol}^{-1} \text{ K}^{-1}$)
s	entropy ($\text{kJ kmol}^{-1} \text{ K}^{-1}$)
T	temperature (K)
V	actual cell voltage (V)
V_{act}	activation over-potential (V)
V_{conc}	concentration overpotential (V)
V_{ohm}	ohmic overpotential (V)
$\dot{W}_{net}$	net power (kW)
X	mole fraction

Greek letters

β	transfer coefficient
ρ	specific resistivity (ohm cm)
δ	thickness (cm)
η	efficiency (%)

Subscripts

av	average
ch	chemical
s	isentropic
tm	thermo-mechanical
gen	generator
g	combustion gases

Abbreviations

AC	air compressor
AFR	air flow rate
AR	air recuperator
BFP	boiler feed pump
BP	boiler pressure
CC	combined cycle
COND	condenser
CPR	compressor pressure ratio
DE	differential evolution
FC	fuel compressor
FFR	fuel flow rate
FR	fuel recuperator
GA	genetic algorithm
GT	gas turbine
GTIT	gas turbine inlet temperature
HP	high pressure
IP	intermediate pressure
LP	low pressure
OWH	open water heater
PR	pre-reformer
SOFC	solid oxide fuel cell
ST	steam turbine
STIT	steam turbine inlet temperature
TER	turbine expansion ratio

installation cost of these plants. Thus it requires that the bottoming GT and ST plant should also contribute sufficiently to the net power output of the plant. Some additional fuel may be supplied to the combustor (by-passing the SOFC) to enhance power output from the GT and the ST plant. This however should be done such that the maximum GTIT does not exceed the material limit. A new SOFC–GT–ST configuration with provision for both fuel and air preheating utilizing GT exhaust gas and steam extraction from the ST for fuel reforming in the PR was analysed by the present authors [18]. The effect of additional fuel burning on net GT and ST power was investigated in [18] and it was found that bypassing the SOFC and burning some amount of compressed fuel in the combustor causes significant increase in the GT and ST power. However it also causes reduction in the plant's efficiency simultaneously.

In the preset work, an inverse analysis is carried out for estimating operating parameters of the same SOFC–GT–ST configuration [18]. The system uses both fuel and air recuperation utilizing the GT exhausts prior to steam production in the HRSG of the ST cycle (single pressure). The system schematic is shown in Fig. 1. 30% fuel reforming is considered in the PR which is achieved by mixing steam extracted from the ST at the desired pressure. Fuel (Methane) and air are compressed in the fuel compressor (FC) and air compressor (AC) respectively. Certain amount of compressed fuel is fed into the SOFC anode via the FR and the PR. The amount of steam extracted for mixing with the fuel prior to its entry to the PR is taken as 2.5 times of the fuel flow rate (FFR). Some additional amount of compressed fuel flows directly into the combustor (by-passing the FR, PR and the SOFC) which

is burnt along with the SOFC off residual fuels (hydrogen, methane and carbon monoxide) and excess air. This is done mainly to increase the power output from the GT and particularly the ST plant. The compressed air stream is preheated in the air recuperator (AR) before it is fed into the SOFC cathode.

There have been a few studies which have approached the design of hybrid SOFC–GT systems as an optimization problem. For example, Möller et al. [19] deployed a genetic algorithm (GA) to optimize the system parameters of a SOFC–GT system with and without a CO_2 separation plant. Yi et al. [20], proposed a novel optimization strategy including a design of experiments (DOEx) approach for an internal reforming SOFC and intercooled GT hybrid cycle. Calise et al. [21] optimized the design of a hybrid SOFC–GT plant using GA based traditional single-level approach considering the yearly overall plant cost as the objective function and some thermodynamic parameters as decision variables. Autissier et al. [22] presented a design methodology for a pressurized SOFC–GT system and identified the most attractive configuration using an evolutionary algorithm multi objective optimization approach integrated into OSMOSE, a Matlab based software. Zhao et al. [23] compared the performance of an indirect ambient pressure hybrid SOFC–GT system working under two thermodynamic optimization strategies either working at maximum efficiency or producing maximum power output. For an SOFC and micro GT hybrid system, Wu and Zhu [24] proposed an improved iterative particle swarm optimization (PSO) algorithm to optimize the operating parameters under various loads. Yi et al. [25] analysed separately, an SOFC integrated GT and an SOFC integrated combined

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