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Performance characteristics of part-load operations of a solid oxide fuel cell/gas turbine hybrid system using air-bypass valves

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Abstract

In spite of the high-performance characteristics of a solid oxide fuel cell/gas turbine (SOFC/GT) hybrid system, it is difficult to maintain high-level performance under real application conditions, which generally require part-load operations. The efficiency loss of the SOFC/GT hybrid system under such conditions is closely related to that of the gas turbine. The power generated by the gas turbine in a hybrid system is much less than that generated by the SOFC, but its contribution to the efficiency of the system is important, especially under part-load conditions. Over the entire operating load profile of a hybrid system, the efficiency of the hybrid system can be maximized by increasing the contribution of power coming from the high efficiency component, namely the fuel cell. In this study, part-load control strategies using air-bypass valves are proposed, and their impact on the performance of an SOFC/GT hybrid system is discussed. It is found that air-bypass modes with control of the fuel supply help to overcome the limits of the part-load operation characteristics in air/fuel control modes, such as variable rotational speed control and variable inlet guide vane control.

Keywords: Solid oxide fuel cell; Gas turbine; Hybrid system; Air-bypass mode

1. Introduction

A solid oxide fuel cell (SOFC) is considered to be a potential candidate for the next generation of power devices due to its high efficiency and low emissions. The high-temperature operating characteristics of the SOFC provide hot exhaust gas, which can be used as the heat source for either cogeneration or hybridization with a bottoming cycle. An SOFC/gas turbine (SOFC/GT) system is an example of the hybridization of an SOFC [1]. The role of the gas turbine in an SOFC/GT hybrid system is: (i) to produce additional electrical power with the high-temperature exhaust gas of the SOFC and hence improve system efficiency; (ii) to supply air to the SOFC; (iii) to pressurize the SOFC in the case of a pressurized hybrid system.

Generally, power systems are engineered to be operated under design-point conditions. Under real operating conditions, however, design-point conditions can rarely be maintained due to the varying power (or load) levels that depend on the customer requirements and/or environmental changes. In these situations, it is necessary to operate the system under optimum part-load performance conditions. Here, part-load performance is defined as the performance under conditions that generate less power than under the design-point conditions. Generally, power generation under part-load operating conditions is controlled by adjusting the fuel supply.

The performance characteristics of the SOFC/GT hybrid system under part-load conditions have been studied by many groups [2–4], and it has been concluded that the simultaneous control of air and fuel supplies provides better part-load efficiency than does control of the fuel alone. The gas turbine has an important role in the part-load performance of an SOFC/GT hybrid system due to its rapid reduction of performance at part-load operating conditions, which originates from the characteristics of its components, including the compressor and turbine.

Abbreviations: CAB, cold air-bypass; CABV, cold air-bypass valve; FC, fuel cell, fuel control; FOC, fuel-only control; HAB, hot air-bypass; HABV, hot air-bypass valve; TIT, turbine inlet temperature; VIGV, variable inlet guide vane; VRS, variable rotational speed.

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Nomenclature

A	active area (m^2)
F	Faraday constant (96,485 C mol^{-1})
h	specific enthalpy (kJ kg^{-1})
j	current density (A m^{-2})
LHV	lower heating value (kJ kg^{-1})
$\dot{m}$	mass flow-rate (kg s^{-1})
N	rotational speed (rpm)
P	pressure (Pa or bar)
T	temperature (°C or K)
U_f	fuel utilization factor
V	voltage (V)
$\dot{W}$	power (kW)

Greek letter

η	efficiency

Subscripts

1	compressor inlet
2	compressor exit
3	turbine inlet
4	turbine exit
a	air
b	bypassed air
c	cell
comp	compressor
d	design-point
f	fuel
FC	fuel cell
GT	gas turbine
HS	hybrid system
turb	turbine

In a previous analysis of the part-load performance characteristics of an SOFC/GT hybrid system [5], two kinds of simultaneous air and fuel control modes were considered: (i) variable rotational speed with fuel control, VRS + FC; (ii) variable inlet guide vane with fuel control, VIGV + FC. It was found that both of these modes could provide better efficiency than the fuel-only control (FOC) mode. Furthermore, the VIGV + FC mode could be used as an alternative to the VRS + FC mode, especially in the case of a large power class SOFC/GT hybrid system, which requires a large-class gas turbine operating at a constant speed during part-load operation [4]. Unfortunately, the VIGV + FC mode has a limitation at relatively low power generation. To satisfy the part-load power level under this mode of operation, the amount of air supplied to the system should be controlled by adjusting the angle of the VIGV located in front of the compressor inlet. If the angle of the VIGV is increased above a certain value (e.g., 40°), it causes the compressor to stall and limits the gas turbine operation.

In this study, air-bypass modes are considered as alternatives to the air control of part-load operation of an SOFC/GT hybrid system. The principle of the air-bypass mode is to bypass some of the compressor discharge air using by means of a valve, and to supply it to the turbine inlet stream without passing through the SOFC. This mode reduces the amount of air supplied to the SOFC without changing the amount of air supplied to the compressor. In the present study, the performance of an SOFC/GT hybrid system with two air-bypass modes, i.e., a cold air-bypass (CAB) and a hot air-bypass (HAB), is compared with other cases, and some strategies for the improved part-load performance of the hybrid system are considered.

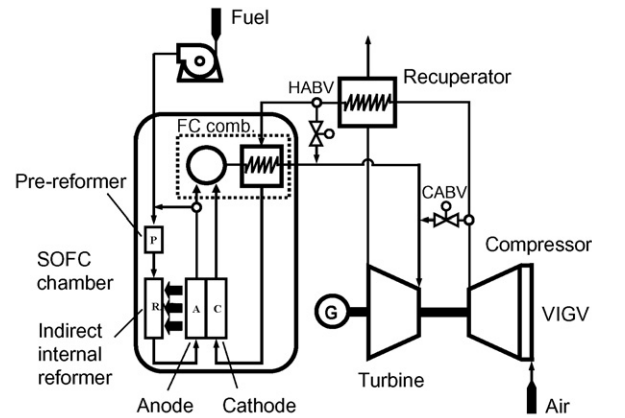

Fig. 1. Schematic diagram of the SOFC/GT hybrid system with air-bypass valves.

The configuration of the SOFC/GT hybrid system considered in this study is given in Fig. 1. This system is based on the 220-kW class Siemens–Westinghouse SOFC/GT hybrid system [1] and its specifications are given in Table 1. The SOFC and the gas turbine under the design-point conditions generated 175 and 47 kW, respectively.

Table 1
Specifications of SOFC/GT hybrid system under design-point conditions

Parameter	Value
Hybrid system	
Ambient conditions (°C, atm)	15.0, 1.0
System power (kW)	220.0
System efficiency (%)	59.3
SOFC	
SOFC power (kW)	175.0
Cell temperature (°C)	889.0
Steam-carbon ratio	2.5
Fuel utilization factor	0.85
Average current density (A m^{-2})	3200.0
Fuel inlet temperature (°C)	15.0
D.C. to A.C. conversion efficiency (%)	95.0
Gas turbine	
GT power (kW)	47.0
Pressure ratio	2.9
Turbine inlet temperature (°C)	840.0
Compressor isentropic efficiency (%)	78.0
Turbine isentropic efficiency (%)	82.0
Recuperator effectiveness (%)	89.0
Mechanical efficiency (%)	96.0
Generator efficiency (%)	95.0