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Progress in solid oxide fuel cell-gas turbine hybrid power systems: System design and analysis, transient operation, controls and optimization

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HIGHLIGHTS

- Review of hybrid solid oxide fuel cell- gas turbine dynamic operation and control.
- Different types of hybrid system stall/surge control strategies are discussed.
- Optimization, CO_2 capture, hybrid system integration with other cycles is reviewed.
- Many control strategies for SOFC-GT dynamic operation are available & demonstrated.
- Studies suggest high efficiency and good controllability for SOFC-GT systems.

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ABSTRACT

This paper presents a review of system design and analysis, and transient control and optimization of solid oxide fuel cell-gas turbine (SOFC-GT) hybrid systems for different system configurations. The main feature of SOFC power systems is production of less harmful chemical and acoustic emissions at a higher efficiency compared to conventional power production technologies. Microturbines have been shown amenable to integration with a high temperature fuel cell due to the well-matched temperature and pressure characteristics of an SOFC and microturbine in a hybrid system. Different configurations of hybrid SOFC-GT systems are briefly discussed. The main focus of this paper is investigation of different control strategies and transient performance characteristics of hybrid SOFC-GT systems in the literature. Different control strategies including variable and fixed speed operation of shaft using PI control methods are discussed. Different types of bypass valves for hybrid system control such as recuperator bypass are used to control the inlet temperature of the air entering the stack. In addition, SOFC bypass valves are used to control the mass flow through the SOFC stack. Different control methods are described to avoid stall/surge in the compressor. The main components of a hybrid system and their effects on the system performance are thoroughly discussed. Impacts of heat exchangers on a hybrid system are also determined and pressure losses between the recuperator and combustor for three different conditions are evaluated. Effects of different system parameters such as Steam-to-Carbon ratio (S/C), fuel utilization and operating pressures on system performance are determined. Net efficiencies of different hybrid system configurations are compared. Other applications of a hybrid system such as those that include CO_2 capture and sequestration are investigated. Finally, system optimization and investigation of alternative fuels are discussed.

1. Introduction

Solid oxide fuel cells (SOFC) are electrochemical devices that convert chemical energy contained in fuel directly into electricity through electrochemical reactions. The SOFC electrochemical reactions occur at relatively high temperatures compared to the other types of fuel cells. The higher temperature operation allows for fuel flexibility and a potential for fast reactions and higher power density; SOFCs can operate

Abbreviations: ASME, American Society of Mechanical Engineers; DLR, German Aerospace Center; DOE, US Department of Energy; FCE, fuel cell energy; FC-GT, fuel cell-gas turbine; HRSG, heat recovery steam generator; IRSOFC-GT, Internal reforming solid oxide fuel cell – gas turbine system; MCFC, molten carbonate fuel cell; MIMO, multi input multi-output; MPC, model predictive controller; MTG, micro-gas turbine generator; NEDO, New Energy and and Industrial Technology Development Organization; NETL, National Energy Technology Laboratory; NFCRC, National Fuel Cell Research Center; PEMFC, proton exchange membrane fuel cell; PSOFC, pressurized SOFC; PT, power turbine; SCE, Southern California Edison; SECA, Solid State Energy Conversion Alliance; SOFC, solid oxide fuel cell; SOFC-GT-HS, solid oxide fuel cell-gas turbine hybrid system; TIT, turbine inlet temperature; TPB, triple phase boundary; TPG, thermochemical power group

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on natural gas, hydrogen, biogases, coal syngas and other fuels. The high operating temperature also lends itself well to cogeneration schemes which can significantly increase system efficiency.

1.1. Emergence of SOFC power plants

SOFC power plants are a proven clean-tech alternative for electric utility power generation in residential, commercial and industrial applications. SOFCs lend themselves well to stationary power and also to heavy duty transportation (e.g., locomotive) applications [1–8].

Features of SOFC power systems include production of less harmful chemical and acoustic emissions at higher efficiencies compared to conventional power production technologies [9–12]. An electrolyte that is most typically made of yttria-stabilized zirconia (YSZ), eliminates the need to manage the electrolyte evaporation and circulation associated with other non-solid-state fuel cell types. As a result of high operating temperature and oxidizing ion charge carrier (oxygen ion, $O^{=}$), higher fuel flexibility is achievable compared to other types of fuel cells. SOFCs are capable of converting carbon monoxide (CO) to electricity via electrochemical reaction [13], while other types of fuel cells such as proton exchange membrane fuel cells (PEMFC) are vulnerable to CO poisoning [14]. SOFC systems have operated using various types of fuels such as carbon monoxide (CO), natural gas, hydrogen (H_2), propane (C_3H_8), landfill gas, diesel and JP-8 [15–18]. Typically, the operating temperature of SOFC is higher than other types of fuel cells such as PEMFC, alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), and molten carbonate fuel cells (MCFC) [19,20]. Higher operating temperature of SOFCs and the presence of nickel catalyst enable them to directly reform natural gas in the anode compartment. SOFC systems convert reformed hydrogen and other gaseous fuel species (e.g., CO) usually produce by reformation of a hydrocarbon fuel through electrochemical reactions that produce electrical power and high grade heat for use elsewhere in the system (e.g., reformation, preheating reactants) and for combined heat and power (CHP) applications. The need for more costly materials construction and insulation that can withstand the high temperature conditions is a disadvantage. Nonetheless, fully integrated SOFC power generation systems have built and operated as stationary power systems in multiple applications in the power production range of 1 kW–20 MW [21,22].

Several designs of SOFC systems have been experimentally evaluated and demonstrated to-date. The typical configurations of SOFC cells include tubular, planar and monolithic [23]. Each of these cell configurations has advantages and disadvantages regarding the thermal shock resistance, manufacturability, power density and potential cost [24]. Among these, the tubular SOFC design has been manufactured by Siemens Westinghouse Power Corporation, Mitsubishi Heavy Industries, Rolls Royce and LG Fuel Cells Systems, Artex Energy, and others [25–28]. Monolithic SOFC cell designs have been primarily produced for research and development purposes. By far the most popular type of cell configuration in recent systems is the planar design used by most fuel cell system manufacturers including Bloom Energy, Versa Power, Fuel Cell Energy, Ceres Power, Solid Power, and many others. More than 100 companies are producing SOFC systems mostly in the U.S., Europe and Japan. The most prominent manufacturer of SOFC systems in the U.S. is Bloom Energy. The typical materials set used in SOFC cells and stacks is remarkably durable and robust even over long periods of time operating at high temperature. For example, the tubular SOFC design of Siemens Westinghouse Power Corporation has shown more than 85,000 h of operation with low cell degradation and the planar SOFC design has shown power densities up to 1000 $(\frac{W}{l})$ [29,30]. The initial market for the fuel cells is currently limited to areas with strict emission regulations, or where grid electric power is more expensive than the on site power and heat production [31]. The current high capital cost of such fuel cell systems is the main reason that SOFC technology has not become more widely deployed and such capital costs are currently being reduced and also have a significant potential for being reduced.

The SOFC- microturbine hybrid systems are also being considered in auxiliary power units (APU) in commercial airplanes to provide power to all electrical loads [32]. In recent years, the application of SOFC systems has been expanded to deep ocean power generation for methane hydrate recovery [33]. Aguiar et al. developed a High-altitude long-endurance (HALE) hybrid system for UAVs [34]. The overall system efficiency was at 66.3% (LHV) when operating on liquefied hydrogen for a three-stack system. Rajashekara et al. classified hybrid systems into two major types: (1) A high temperature fuel cell combined with other power generation systems such as reciprocating engine, and (2) The combination of fuel cell with wind plant and/or and solar power. Microturbines and gas turbines are being developed in the range of 30 kW–30 MW and 100–1000 MW, respectively [19]. In another study by the same group, a 440 kW hybrid system was developed to be used in commercial aircraft, cruise ships and trains. The system had the capability to operate in distributed power generation systems [35]. Chinda et al. presented a model of hybrid systems aimed for a 300-passenger commercial aircraft electrical power unit [36]. The components in the system were sized to meet the 440 kW input electrical load at the sea level full power condition. The parameters that limited the hybrid system performance were the SOFC temperature, TIT, and the exhaust temperature.

1.2. SOFC-GT hybrid systems background

Climate change, due to increasing greenhouse gas emissions and reduction in the availability of fossil energy resources, has motivated the gas turbine industry to consider more energy efficient strategies with reduced emissions for stationary power plants. Hybrid fuel cell-gas turbine (FC-GT) systems provide clean energy at high efficiency [37]. FC-GT hybrid power systems theoretically possess the highest efficiency and the cleanest emissions of all fossil fueled power plants in any given size class [38]. Integrated hybrid systems have the potential to operate at higher efficiency than a fuel cell or gas turbine alone. A market study by Research Dynamics Corporation concluded that hybrid systems could compete on electricity cost with other distributed generation (DG) technologies [30]. Technical elements of various SOFC-GT hybrid systems have been published by the ASME International Gas Turbine Institute (IGTI) proceedings including several purposeful hybrid sessions ([39–46]). SOFC-GT hybrid systems have been called one of the most promising technologies to meet US DOE demands for high efficiency and low emissions power generation [47]: (1) To achieve a higher electrical efficiency, (2) to minimize environmental pollution, (3) to produce electricity at a competitive cost, and (4) to capture and sequester CO_2.

In recent years, many hybrid systems have been mentioned in several US patents [48–58]. The integration of an SOFC stack with a gas turbine has been proven to be a promising concept, since SOFC-GT hybrid systems can achieve a net electrical efficiency and a global efficiency close to 70% and 85%, respectively [59–63]. Many researchers have accomplished fundamental studies concerning SOFC-GT hybrid systems [64–67]. Some of them performed thermodynamic analyses of hybrid systems [64–68]. In addition, exergy analyses of hybrid systems were performed by several authors [69–79]. In a study by Calise et al. a maximum electrical efficiency of 65.4% was achieved at the full-load operation [70]. Analyses demonstrated that a combined SOFC-GT system could achieve fuel to electricity conversion efficiencies at 65–74% for systems under 10 MW, and greater than 75% for larger systems [30,80–84]. As fuel cell technology advances, SOFC systems could possibly tolerate higher pressures so that they could be integrated into even more sophisticated hybrid systems with gas turbines characterized by higher pressure ratios and higher turbine inlet temperature (TIT).

In 1999, Rolls Royce funded a study to produce a turbo-generator that was estimated to cost approximately $400 per kW in full