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Optimal PI controller design for active power in grid-connected SOFC DG system

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ABSTRACT

This paper is concerned with optimal control of grid-connected solid oxide fuel cell (SOFC) stack based on a model developed and validated in the literature. Recent studies have shown that control of SOFC is challenging due to its slow dynamics and firm operating limits. For an SOFC, while the primary objective is to supply the demand active power, it is crucial to operate fuel cell within its safe operating constraints. In order to meet these requirements, a proper control strategy is developed in this study. This control strategy employs an optimal robust PI controller to control active power of the plant and at the same time satisfies physical and operating constraints via employing two proportional-gained controllers, of fuel utilization factor controller and anode–cathode pressure difference controller in such a way to maintain the fuel utilization factor at its optimal value of 85% and also keep pressure difference between anode and cathode within the safe bound of 0–0.08 atm under transient conditions. A distributed generation (DG) system including an SOFC stack connected to the power grid through an IGBT inverter is implemented in MATLAB/SIMULINK™ environment. Moreover, dynamics of fuel processor are included. In addition, differential evolution (DE) algorithm evaluated by integral of time multiplied by absolute error (ITAE) criterion is used to search for optimal values of PI controller parameters. Dynamics of the DG system are analyzed for the cases of conventional and proposed PI controllers under different load changes and short circuit condition to verify the performance of proposed PI controller. Simulation results show that the proposed controller can provide satisfactory performance for load changes and short circuit condition at the cost of keeping the SOFC performance beyond its operating constraints.

1. Introduction

The concerns of finite natural resources, global warming, ever-increasing demands for electrical power generation, and steady progress in power deregulation have created interests in distributed generation (DG) concept [1,2]. DG can help reinforce the grid, reduce power losses in transmission section and improve power quality to end-users [2–7]. Fuel cells are one of the dominant distributed energy resources employed in DG [8]. Fuel cells play a critical role in power generation due to their high energy conversion efficiency, relatively low or zero emission of pollutant gaseous, quiet operation and high reliability. Among different fuel cell technologies, solid oxide fuel cell (SOFC) is one of the most promising one that shows great potential in DG applications, owing to its solid electrolyte, capability of internally reforming gaseous fuels and also its high efficiency [9]. The SOFC, like other types of fuel cells, directly converts chemical energy of a fuel to electrical energy. The electrical efficiency of an SOFC power plant can reach 70% [10]. Control of SOFC system is challenging due to its slow dynamics, firm operating constraints and difficulty with modeling [11]. For an SOFC, while the primary objective is to supply the demand active power, it is crucial to operate the fuel cell within its safe operating constraints. Therefore, proper control schemes must be implemented. Most studies so far have concentrated on improving material properties of SOFC. Until recent years, control of SOFC has not been a main concern. In order to efficiently control SOFC, it is important to realize its dynamic characteristics first. Modeling and control are two integral parts of the advanced process control strategies which are intricately dependent on each other. From the view point of process control, the models should be easy to use for designing controllers and yet be detailed enough to give a sufficient account of the system dynamics [12]. There are many ways to design a control system. In many practical cases, the designer has a model of the system but the system parameters are subject to uncertainty. In this case, robust control can be used to design a control system with a guaranteed level of performance as long

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Nomenclature

F	Faraday's constant (C/mol)
I_{demand}	Demanded current to be drawn from SOFC (A)
I_{SOFC}	SOFC real output current (A)
K_{H_2}	Hydrogen flow valve molar constant (mol/(s atm))
K_{H_2O}	Water flow valve molar constant (mol/(s atm))
K_i	Integral gain of PI controller
K_{O_2}	Oxygen flow valve molar constant (mol/(s atm))
K_p	Proportional gain of PI controller
K_r	Constant (mol/(s A))
N_0	Number of cells in series in the SOFC stack
p_{H_2}	Partial pressure of hydrogen gas (atm)
p_{H_2O}	Partial pressure of water (atm)
p_{O_2}	Partial pressure of oxygen gas (atm)
q_{fuel_in}	Inlet fuel flow (mol/s)
$q_{H_2\_consumed}$	Consumed hydrogen flow (mol/s)
$q_{H_2\_in}$	Inlet hydrogen flow (mol/s)
$q_{H_2\_out}$	Output hydrogen flow (mol/s)
$q_{O_2\_in}$	Inlet oxygen flow (mol/s)
R	Universal gas constant (J/(mol K))
r	Total Ohmic loss of SOFC stack (ohm)
r_{H-O}	Ratio of Inlet hydrogen to Inlet oxygen flow
T	Absolute temperature in SOFC (K)
τ_f	Time constant of fuel processor (s)
τ_{H_2}	Time constant of hydrogen flow (s)
τ_{H_2O}	Time constant of water flow (s)
τ_{O2}	Time constant of oxygen flow (s)
U_f	Fuel utilization factor
$U_{f,max}$	Maximum fuel utilization factor
$U_{f,min}$	Minimal fuel utilization factor
$U_{f,optimal}$	Optimal fuel utilization factor
V_{SOFC}	SOFC stack voltage (V)

as the system uncertainties remain within the assumed bounds [13]. The Proportional-Integral (PI) controller is widely used in the power system applications and process industries. The main reason is its simple structure, which can be easily realized and built in practice. Also, PI controller is appropriate for step references which the transient responses must be controlled by appropriate selection of the controller parameters. There are many tuning rules in the literature which specify the PI controller parameters [14]. The simplest method to find the parameters is trial-and-error tuning; however, developing methods that result in optimal performance of PI controllers is of significant interest. By applying modern optimization techniques, it is possible to tune a PI controller.

Nearly all the studies that have been developed in the scope of fuel cell control are based on building an exact model of the fuel cell to design controllers [15–22]. In [15] an alliance of a linear feed-back and nonlinear feed-forward controller was formed to improve transient response of inlet oxygen for a nonlinear fuel cell dynamic model. However, for better performance of the plant, a multivariable control architecture is required in order to coordinate the power conditioning unit of the fuel cell and the traction motor controller. Lately, an integrated SOFC dynamic model for power system simulation was provided in [16] and the need for a trade-off between the SOFC stack integrity and power grid demands was highlighted. Then, in [1] dynamics of fuel processor and some control strategies of the fuel cell system were added to the model and dynamic performance of the expanded SOFC stack (in stand-alone application) was analyzed and evaluated, but without including the inverter and power grid. A model predictive controller was designed in [17] for a hybrid PEM fuel cell system with ultra-capacitors as an auxiliary power source in order to avoid excessive oxygen starvation (which damages the stack and limits the power response of the fuel cell) during high current demand. A feed-forward controller was also employed to solve the oxygen starvation problem in [18], however the system was not very robust because of deficiencies of feed-forward controller. A detailed dynamic model for a simple SOFC hybrid system was presented and a multi-loop feed-back control strategy was proposed in [19] which the plant was stable under a strict linear region of operation, however it was very sensitive to fuel flow overestimation, and thus not robust to degradation or malfunction of fuel flow measurement equipment. In [20], a master controller keeping constant fuel utilization and air ratio, and a regular feed-back PID temperature controller were utilized for a planar SOFC model in load changes of ±40%, however for higher load changes more effective control strategy is required. In [21], in order to design a robust controller capable of rejecting disturbances caused by fluctuations of distribution grid, two robust controllers, which were synthesized by solving an H_∞ mixed-sensitivity optimization, were designed for a linearized SOFC power plant that was originally developed in [16] however a more realistic grid was not included. A control strategy in [22] was proposed based on adaptive control strategy in order for rapid changing of output power level of SOFC power plant, but, in a stand-alone application.

The SOFC model that was chosen for control study in this work has been studied by several authors for the scopes of dynamic modeling and control [1,11,16,21,22]. Even though the model is a simplified dynamic model of SOFC systems, it is clearly challenging from the control viewpoint due to SOFC's slow dynamics and firm operating constraints [21].

In this paper, we employ an optimal robust PI controller to control the active power of SOFC stack, while maintaining the SOFC performance beyond its operating limits. Differential evolution (DE) algorithm as an optimization method is being used to obtain the optimal parameters of PI controller under load changes and three-phase short circuit condition. DE is a novel stochastic nonlinear optimization algorithm [23–27]. To evaluate the potential answers in DE, The integral of time multiplied by absolute error (ITAE) is chosen as a popular performance criterion, since it can provide controllers with a high load disturbance rejection and minimize the system overshoot while keeping the robustness of the system [28]. In the present work, the SOFC stack is connected to the power system grid through a three phase IGBT inverter, which is equipped with an active power control loop. A transformer, following the inverter, steps up the SOFC AC voltage to the power grid voltage level. Simulation model of the SOFC DG system was built in MATLAB/SIMULINK™ environment.

2. SOFC DG system configuration

SOFC DG systems can operate either in grid-connected or stand-alone applications. This paper is concerned with the former. The DG system consists of a 100-kW SOFC stack as power generation plant including 450 cells in series connected to a 440 V/60 Hz three-phase power grid through an IGBT inverter, followed by a three phase transformer to step up the AC voltage to the grid voltage level. The inverter uses hysteresis switching and controls the active power generated by SOFC stack. In addition, the stack is