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Adaptive control for robust air flow management in an automotive fuel cell system

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HIGHLIGHTS

- A dynamic compressor model is developed that can predicts compressor surge.
- An MRAC algorithm is designed to prevent compressor surge with more acceptable convergence.
- System simulation is carried out to confirm feasibility of MRAC under dynamic environment.
- By algorithm comparison, MRAC is proven to be more feasible for surge rejection.
- MRAC comes to be more reliable under nominal dynamic operating schedules.

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ABSTRACT

Surge control in a centrifugal air compressor is crucial to ensure the reliable operation of a fuel cell system, but few studies have reported on compressor surges in fuel cell systems. This study presents an effective surge control algorithm with a surge predictive compressor model under various operating conditions of an automotive fuel cell system. Unlike previous studies on the air management systems of an automotive fuel cell, this study presents an analytic compressor model which is a nonlinear dynamic model with surge prediction capability. In this study, a model reference adaptive control (MRAC) is introduced, to avoid compressor surge during the dynamic operation of a fuel cell system. The adaptive control was compared with the nominal feedback control in the air management system of an automotive fuel cell operating within normal conditions, under transient and steady-state responses. Also, when a surge was detected in the system, the adaptive control algorithm was fast enough to recover the air mass flow rate to normal ranges. Based on these results, it can be concluded that the MRAC algorithm shows better performance than the nominal feedback control algorithm with respect to the transient behaviors and surge recovery of an automotive fuel cell system.

Contents

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Nomenclature

A	active area (cm^2)	*Ind*	inducer
i	current density (A/cm^2)	*Imp*	impeller
E	electric potential (V)	*1*	inlet
m	air flow rate (kg/s)	*2*	outlet
c_p	sonic velocity (m/s)	*FC*	fuel cell
p	pressure (Pa)	*Nern*	nernst voltage
Q	heat transfer (W)	*mem*	membrane
T	temperature (K)	*react*	heat generation
V	volume (m^3)	*g*	gas side
θ	valve position (–)	*cool*	coolant side
L	length (m)	*conv*	convection
ω	motor speed (rad/s)	*amb*	ambient condition
U	tip speed (m/s)	*n*	number of cell
J	motor inertia (kg m^2)	*sto*	stoichiometry
τ	torque (N m)		

Subscripts and superscripts

c	compressor
f	manifold

1. Introduction

In recent decades, the gasoline combustion engine has been widely adopted as an individual transportation system due to its high efficiency, reliability, performance and robustness. However, the use of conventional fossil fuels is contributing to significant energy problems and global warming [1,2]. For these reasons, the fuel cell has received increasing attention as an attractive technology with the ability to mitigate a number of these energy problems [3–6]. A fuel cell is a power propulsion system with a renewable energy source, which produces electricity, water, and heat through the electrochemical reaction of hydrogen and oxygen [7–9]. Fuel cells are widely used in many applications today. Among the various types of fuel cells, the proton exchange membrane fuel cell (PEMFC), is widely used in automotive applications due to its low temperature, fast transient response, high power density, and high efficiency [10–13].

When the PEMFC is employed in an automotive power propulsion system, various operating pressures can be advantageous for structural integrity and maintenance. However, a pressurized air flow rate can damage the fuel cell system. When there is an abrupt decrease in system load, the air flow rate needs to be reduced rapidly to avoid system damage. But since the response of the outlet pressure of the compressor is slower than the air flow rate, the operating condition of the compressor might deviate from the surge safety envelope.

When the operating conditions are outside of the surge safe envelope, the system pressure can oscillate, and this condition is indicated in the compressor. When a surge is detected in the fuel cell system, the pressure and air flow rate simultaneously oscillate. While the pressure oscillation is harmful to the membrane electrode assembly, the oscillation of the air flow rate affects the kinetics of the electrochemical reaction. When the air flow rate oscillates, the distribution of local temperatures distribution can become uneven due to the irregular electrochemical reactions in the active area of the cathode catalyst layer [14]. Consequently, successfully controlling compressor surge is very critical to the reliable performance of the system.

Many researchers have worked on methods to evaluate and control the surge phenomenon.

Marelli et al. introduced a turbocharger compressor for heavy duty vehicle application to investigate surge phenomena. They focused on finding the line in which a compressor surge happens [15]. Senlitsch et al. analyzed a flow reversal in the centrifugal compressor system using the DMD method. [16]. Leufven et al. characterized a large database of automotive compressor maps to develop a surge and choke capable compressor flow model. Also, they validated the developed model with experimental data [17]. A model of a centrifugal compressor was designed by Hafaifa et al. to identify the surge phenomena. The model designed in his study was validated using a test bench for investigating surge control [18]. Karim et al. presented a CFD analysis near the surge region to predict the surge phenomenon in a centrifugal compressor [19]. Dehner et al. conducted a simulation of a mild surge in a turbocharger compression system that was represented through an extrapolated steady-state map [20].

Furthermore, various types of surge control algorithms for compressors have been designed during the last few years.

Seena et al. proposed the active surge control of a centrifugal compressor using a state observer. They considered the time delays in either the mass flow or pressure rise measurements [21]. Lin et al. designed a fuzzy logic controller and speed controller for surge control. They also carried out a comparison between a fuzzy controller and a back-stepping controller [22]. Shehata et al.