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An efficient auxiliary system controller for Fuel Cell Electric Vehicle (FCEV)

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ABSTRACT

This article presents analysis of the systems in a Fuel Cell Electric Vehicle (FCEV) prototype with the aim of determining if it is possible to increase vehicle efficiency through strategic control of the auxiliary systems. To accomplish this, an overview of the vehicle design is given as well as an in depth analysis of the powertrain efficiency and control strategy. This leads to the development of a modified powertrain control algorithm which also oversees and controls the auxiliary power demand in real-time. The auxiliary control aspect of this algorithm follows predefined rules as determined through analysis of the individual systems, and based on the definitions of flexible useful and wasteful auxiliary power. The simulation results show that the proposed technique, applied to FCEV air conditioning system alone, improves the fuel economy in the neighborhood of 3.4% compared to conventional bang-bang controller. This magnitude of energy reduction is very significant in the automotive industry, especially when considering the number of vehicles in use in today's transportation sector. The resulting algorithm is adaptable to a number of different types of auxiliary systems and primary power sources, thereby not specifically tied to the fuel cell architecture for which it is developed.

1. Introduction

FUEL cell vehicles are a relatively new phenomenon in the automotive industry. As with any new technology new problems are presented due to the differences in behaviour when compared to conventional power sources such as internal combustion engines (ICEs). The University of Waterloo Alternative Fuels Team (UWAFT) designed and constructed a prototype fuel-cell vehicle as part of an North American student competition called ChallengeX. The research that this article presents is based on this vehicle prototype although it should be easily modifiable for other vehicles with different power sources.

Auxiliary systems such as air conditioning, headlights, power steering etc. are significant users of energy in any vehicle. The focus of the research in this paper is to determine how, without replacing the hardware components, these auxiliary systems can be made to have less of an impact on vehicle fuel economy. Every power source such as a fuel-cell has a characteristic efficiency curve over its power output range. As propulsion power is dictated directly by the driver of the vehicle and is not controllable, one way of altering the power output of the power source to improve efficiency is through modulation of the auxiliary load.

1.1. FCEV prototype background

UWAFT's powertrain design was chosen with the help of PSAT (Powertrain System Analysis Toolkit), a vehicle simulation tool built on Matlab™ [1] by Argonne National Laboratories (ANL). Using a methodology mirroring GM's own vehicle design process (VDP), UWAFT began running banks of simulations using the characteristics of the 2005 Chevrolet Equinox coupled with various fuel sources and powertrain architectures.

Based on the analysis of these simulations, UWAFT was able to decide on the powertrain hardware listed in Table 1. These components are linked via a high voltage bus as outlined in Fig. 1. Power flows from the FCPM as the primary power source via the DC/DC

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Nomenclature

FCPM	Fuel cell power module
ICE	Internal combustion engine
PWM	Pulse width modulated
D	PWM Duty-Cycle in percent [0–1]
$V_{BATT\text{-}OCV}$	Open-Circuit battery voltage
$R_{BATT\text{-}CHARGE}$	Battery internal series resistance when charging
$I_{BATT\text{-}CHARGE}$	Battery charging current
$V_{BATT\text{-}OCV}$	Open-Circuit battery voltage
$R_{BATT\text{-}SERIES}$	Battery internal series resistance
$P_{RESISTIVE\text{-}LOSS}$	Power dissipated by resistive losses
Ef_{path1}	Instantaneous efficiency of path 1
Ef_{path2}	Instantaneous efficiency of path 2
Ef_{FCPM}	Instantaneous efficiency of FCPM
Ef_{DCDC}	Instantaneous efficiency of DC/DC converter
$\overline{Ef}_X$	Time-averaged efficiency of component X
$Ef_{BATT-CHRG}$	Battery charging efficiencies
$Ef_{BATT-DisCHRG}$	Battery discharging efficiencies
$Ef_{PATH\ 2-CHRG}$	Average efficiency of the charging process
$Ef_{PATH\ 2-DisCHRG}$	Average discharge efficiency of the battery
$P_{NET-LOAD}$	Total powertrain electric load
α	Power split factor
β_i	Weighting factor for cost function *i* over the range of α's
γ_i	The Largest value for cost function *i* over the range of α's
Ef_{ELEC}	Overall powertrain electric efficiency
SOC	Battery state of charge
FC_{sw}	Cost of FCPM on/off cycling
P_{Out}	Sum of the power drawn by all the electrical loads in the vehicle
P_{Motors}	Propulsion power required by the motors
P_{Aux}	Total auxiliary power consumption
$P_{IN\text{-}New}$	New power input to powertrain
$P_{IN\text{-}Old}$	Old power input to powertrain
Ef_{New}	New powertrain overall efficiency
Ef_{Old}	Old powertrain overall efficiency
$P_{OUT\text{-}New}$	New power output from powertrain
$P_{OUT\text{-}Old}$	Old power output from powertrain
$Flex_{Pox}$	Positive flex power
$Flex_{Neg}$	Negative flex power
$P_{Comp\text{-}MAX}$	Maximum allowable compressor power
P_{Comp}	Current compressor power
$P_{Heat\text{-}MAX}$	Maximum allowable heater power
P_{Heat}	Current heater power

Table 1
UWAFT FCEV powertrain component list.

Device	Make/Model	Specifications
Fuel Cell Power Module	Hydrogenics/HYPM 65 kW	Max Power: 65 kW Voltage Range: 190–300 V Current Range: 0–300 A Mass: 415 kg
Hydrogen storage	Dynetek/ZM180	Max Pressure: 5000 psi Tank Capacity: 4.31 kg H2 Tank Weight: 92 kg Tank Volume: 178 L
DC/DC converter	UWAFT Custom	Input Voltage Range: 190–300 V Output Voltage Range: 300–385 V Converter Type: Boost Mass: 30 kg
Traction motors (x2)	Ballard/312V67	Peak Power: 67 kW Continuous Power: 32 kW Max Torque: 190 Nm Mass: 84 kg
Motor controllers (x2)	Ballard/312V67	Continuous Power: 67 kW Input Voltage: 260–385 V Output Current: 280 A RMS
Battery pack	Cobasys/NiMHax3 366–70	Voltage Range[a]: 322–392 V Capacity: 8.5 Ah Energy: 2.8 kWh Mass: 85 kg

[a] Open-Circuit voltage range.

converter to all of the vehicle loads including the motors, battery (when charging), auxiliary and parasitic components.

1) Fuel Cell Power Module (FCPM): The power module (FCPM) is a Hydrogenics 65 kW polymer electrolyte membrane (PEM) unit. It is a complete power delivery system with its own on-board micro-controller and air delivery system. Communicating with the vehicle via a controller area network (CAN), the FCPM reports all of its vital metrics to the vehicle and receives as input a power request. The power request command allows the vehicle control to, in effect, warn the FCPM controller when it is about to draw a specified amount of current. This allows the FCPM to spool up its air delivery blower and prepare itself for the required power flow.

An FCPM such as this one, consists of individual fuel cells connected in series like the individual cells in a battery. Each cell consists of an anode and a cathode separated by a polymer membrane [20–23]. The potential generated across each cell ranges from 1 to 1.7 V depending on the concentration of reactants and the current being drawn. Thus the voltage of the entire stack of cells in the FCPM varies significantly with the load or current draw. When operating with a battery connected to the FCPM's output, such as the nickel metal hydride (NiMH) battery pack used in this vehicle, this voltage fluctuation necessitates the use of a variable DC-DC