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Stabilised control strategy for PEM fuel cell and supercapacitor propulsion system for a city bus

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ABSTRACT

Fuel Cell (FC) buses have been developed as a long term zero emission solution for city transportation and have reached levels of maturity to supplement the coming London 2020 Ultra low emission zone implementation. This research developed a scaled laboratory Fuel Cell/Supercapacitor hybrid drivetrain implementing DC/DC converters to maintain the common busbar voltage and control the balance of power. A novel and simple hybrid control strategy based on balancing the currents on the common busbar whilst maintaining a stable FC output has been developed. It has been demonstrated that the FC power output can be controlled at a user defined value for both steady state and transient load conditions. The proposed control strategy holds the promise of extending FC life, downsizing power systems and improving the FC operating efficiency.

Introduction

Mechanised transportation is one of the largest sources of greenhouse gas emissions [1], where 30% of CO2 emissions from OECD countries is attributed to transport [2]. The harmful emissions from heavy traffic in a city not only contain greenhouse gases, contributing to climate change, but also particulate and NOx emissions that affect human physical health and well-being. In 2008 it was estimated that over 4000 premature deaths were brought forward as a result of long-term exposure to particulates in London [3]. The seriousness of city pollution resulting from the transportation sector has been acknowledged and thus the introduction of clean transport technologies that can effectively bring environmental benefits is of increasing priority.

One such technology is the Fuel Cell (FC), which is a clean and efficient power source that has undergone substantial development and is now a commercially viable means of offering a potentially clean solution. Various fuel cell technologies exist, where each technology has its own specific advantages, disadvantages and is for different applications. Proton Exchange Membrane Fuel Cells (PEMFC) have relatively high power densities and low weight; it can achieve high efficiency and operates at low temperature, and reflects why this is the most commonly used FC type for transportation applications [4]. The PEMFC uses hydrogen as its fuel and air as a reactant to generate electricity through an electrochemical process with water as the only waste product. The FC circumvents the combustion and mechanical processes, of a conventional internal combustion engine, into a single chemical step to generate electricity [5]. The PEMFC was not a practicable option for wider applications until the early 1990s owing to the need for significant amounts of rare and costly materials. Important advances in PEMFCs have been achieved, such as reducing the platinum catalyst loading from 25 mg/cm^2 to 0.05 mg/cm^2 [6]. This has resulted in the cost of the

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Nomenclature

I_{fc_in}	Current output from the Fuel Cell
I_{fc_out}	Current output from the boost converter on the common busbar
I_{fc_ref}	Reference value for the boost converter current output on the common busbar
I_{load}	Current to/from the traction motor
I_{SC_in}	Current to/from the Supercapacitor
I_{SC_out}	Current to/from the Buck/Boost converter on the common busbar
V_{fc_in}	Voltage across the Fuel Cell
V_{fc_out}	Voltage across the Boost converter on the busbar
V_{load}	Voltage across the traction motor controller on the busbar
V_{SC_in}	Voltage across the supercapacitor
V_{SC_out}	Voltage across the Buck/Boost converter on the busbar

PEMFC dropping significantly since 2000, making the PEMFC a viable solution for transportation applications [7].

By replacing the internal combustion engine of conventional vehicles, FCs can be used to power the vehicle using electrical energy only, therefore achieving zero operating emissions since water is the only waste product. After initial assessments of FC vehicle technology and the introduction of hybrid technology in the early 2000s, researchers started to consider hybridising FCs with different energy storage technologies to provide more effective solutions [8–10]. A number of studies have suggested that the use of FCs is limited by an inability to react quickly to the power demand transients presented by transportation applications because of their low power density characteristics [11–13]. Hence, hybridisation of FC technology with electrical energy storage options has been utilised to shield the FC from transient peak power demands and effectively reduce the size of the FC required on-board the vehicle [13,14]. When compared with batteries, recent studies have proposed that Super-capacitors (SC) are a more effective energy storage technology for hybridisation with FCs in terms of responding to dynamic loads, shielding high current loads, reducing energy throughput and preventing overheating [15–17].

The development of hybrid propulsion systems can utilise the benefits of each of the system components to meet the load demands, however, the technologies used, topologies and energy management of such systems allows for a wide range of possible solutions. The literature contains many examples of FC based hybrid propulsion systems each with different aims and utilising different technologies. One approach to such a system was presented by Wu. et al. where the FC and SC were directly connected to give passive control of the hybrid system [11]. This approach provides an advantage in avoiding the need for DC/DC converters but at the cost of losing direct control of the power sharing of the system components and stability of the load voltage. The work presented in Refs. [18–21] considered FC/battery hybrid propulsion systems, where a relatively small FC was used as a range extender and the battery as the main power source. This was able to significantly increase the range of the vehicle, however, the work presented in this paper is concerned with FC dominant hybrid systems, where the FC acts as the primary power source. Many possible configurations for FC based hybrid power systems exist. Much of the literature employs DC/DC converters in the hybrid system to provide direct control of some or all of the hybrid system components [17,21–33]. The work of Latha et al. presents the pros and cons of each of these system configurations and goes on to develop a novel reconfigurable hybrid propulsion system based on the use of DC/DC converters [22]. Another approach for a FC hybrid propulsion unit is to use a DC/DC converter to control the FC output, as seen in Refs. [25,30]. This has the advantage of using only one converter, however this comes at the expense of control of the DC-link voltage or power sharing control. The most popular configuration makes us of a unidirectional DC/DC converter for the FC and a bidirectional DC/DC converter for the SC, where these are connected via a common DC-link, as seen in Refs. [17,24,26–29,32,33]. This configuration is particularly useful when using a SC energy storage system as the voltage across the SC can be independent from the rest of the system. Since SCs have a wide voltage range over their State-of-Charge (SoC), it allows for better utilisation of the stored energy. Each of these systems utilise a different control strategy to split the power sharing between the FC and energy storage system but generally use the battery or SC to meet the short transient load changes to minimise the load variations on the FC. Even so each of these control strategies results in significant variations to the FC output. In the work of Torreglosa et al. the hybrid system was controlled with 8 different states of operation depending on the battery SoC, load demand and tramway speed [25]. The battery met much of the transient response with the FC operating at a number of different outputs. In the work of Bougrine et al. control strategies based on using the SoC as the state variable were developed to control the FC output [26]. The SC met the transient power demands thus damping the rate at which the FC output varied. Allaoua et al. presented a control strategy where all of the transient power demands are met by the SC and the FC is used only to meet the steady state power demands of the load [28]. This resulted in significant changes to the FC output when the load demands changed from transient to steady state. The system most closely resembling that developed in this paper was developed by Benyahia et al., where interleaved boost and bi-directional DC/DC converters were used with the FC boost converter was used to regulate the DC busbar voltage [24]. It was shown that the system was able to maintain a stable voltage on the busbar but as with all of the control strategies presented, the FC output was variable.

The work in this paper follows on from the research carried out in Ref. [13], where a laboratory FC system consisting of a FC, DC/DC boost converter and a resistor bank was constructed and tested. This paper extends the work through the integration of a SC module, traction motor and load system to form a FC/SC hybrid propulsion test bench. The configuration chosen makes use of two DC/DC converters, one unidirectional DC/DC converter for the FC and another

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