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Synthesis on power electronics for large fuel cells: From power conditioning to potentiodynamic analysis technique

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ABSTRACT

The work addressed in this paper deals with a synthesis on power electronic converters used for fuel cells. The knowledge gap concerns conceptually different electronic converter architectures for PEM (Proton Exchange Membrane) fuel cells able to perform three types of functionalities: The first one is the capacity of emulating an active load representative of electrical drive constraints. In that case, frequency and fuel cell current ripple can be set independently to investigate the dynamic behavior of the fuel cell. The second one is power conditioning applied to large high power and segmented fuel cell systems ("Large" represents several tens of cells and multi-kilowatt stacks), which is a non trivial consideration regarding the topological choices to be made for improving efficiency, compactness and ensure operation under faulty condition. A multi-port resonant isolated boost topology is analyzed enabling soft switching over a large operating range for a thirty kilowatt segmented fuel cell. A splitting current control strategy in case of a segment is under fault is proposed. Each considered converter topologies meet specific constraints regarding fuel cell stack design and power level. The third functionality is the ability for the power electronics to perform analysis and diagnosis techniques, like the cyclic voltammetry on large PEM fuel cell assemblies. The latter technique is an uncommon process for large fuel cell stacks since it is rather performed on small electrochemical cells or little assemblies. Moreover potentiodynamic analysis requires the control of the fuel cell voltage according to particular voltage cycles leading to fuel cell current non-linearities, which is rather unusual, since the fuel cell current is almost always regulated.

1. Introduction

Fuel cells (FCs) are nowadays more and more technologically foreseen to be applied in many transportation systems, from electric vehicles (EV's), small city-freight captive fleet vehicles, up to light rail applications like urban tramway, but also applied to stationary multi-source renewable systems. They are used as fuel cell–battery hybrid systems in assistance for DC–DC traction powertrains [1], sharing, together with energy storage systems, drive mission profile constraints. Fuel cells can be used for traction but also as auxiliary power units (APUs) like for example in trucks [2]. Fuel cells are also used in association with novel power electronic interfaces for grid-connected fuel cell power generation systems [3]. For ensuring power conversion functions, different converter structures can be utilized like multiphase interleaved step-up converters for high power applications in order to split current constraints and adapt the FC voltage to high voltage onboard DC networks [4]. Moreover, multiport power converters are also encountered in plug-in/V2G (Vehicle-to-grid) fuel cell vehicles [5]. In order to face up to power increase constraints in EV's or electric power applications, fuel cell converters are now modular and electrically designed with multi-device, multi-leg or interleaved structures [6–8]. Béthoux et al. have proposed a design of a DC–DC converter with high voltage input–output ratio DC–DC converter with a high voltage input–output ratio [9]. Some topologies also use a variable voltage of the DC bus of the vehicle [10]. A fuel cell DC–DC power conversion is also encountered for the energy management of renewable power sources, like the coupling of fuel cell and solar arrays for which high-flexibility DC load is needed [11], or used as standalone renewable fuel cell hybrid power source with adapted control of the load [12]. In the field of control for fuel cell systems in transportation, specific strategies are also investigated like for example for braking energy regeneration control in fuel cell hybrid buses [13], or real time strategies for power management within fuel cell vehicles [14].

The work presented in this paper is a synthesis on power electronic converters used as power conversion interfaces for large PEM (Proton Exchange Membrane) fuel cells dedicated to auxiliary or traction applications, or as electronic subsystems able to

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Nomenclature

Section 2: Active load for fuel cell representative of electrical drive constraints

I_{fc}	5 kW PEM fuel cell current, A
U_{fc}	5 kW PEM fuel cell voltage, V
U_c	active load DC link filtering voltage, V
F	switching frequency, Hz
ΔI_{fc}	fuel cell current ripple, A
B_{hI}, B_{hU}	fuel cell current, DC link voltage hysteresis bandwidths, A, V

Sections 4 and 5: Converter topology for segmented fuel cell

V^{FC}	fuel cell voltage, V
V_{Load}	capacitor output voltage, V
f	converter frequency, Hz
f_r	resonant frequency of the resonant isolated boost converter, Hz
m	transformer ratio
I_{ref}	reference current, A
I_{FC}	fuel cell current, A
$I_{FC1,2,3}$	segmented fuel cell currents, A
I_{Load}	converter output current, A

Section 6: Buck (step down) converter topology for large PEM fuel cell operating in potentiodynamic mode

V_{ref}	reference of the cyclic voltage, V
V_{FC}	fuel cell voltage, V
B_{hV}	cyclic fuel cell voltage hysteresis bandwidth, V

perform analysis techniques on large PEM fuel cell assemblies. Large fuel cells concern several tens of cells in series and multi-kilowatt assemblies. The paper addresses electrical topologies following a graduated approach and taking into account different ranges of constraints. The research guideline is the power increase and the choice for an appropriated and efficient converter structure for PEM fuel cell modules ranging from 5–10 kW single stack, up to the 30 kW segmented power fuel cell. The studied power converter topologies are all conceptually different, a DC–DC chopper with variable load for the 5 kW stack, a resonant isolated boost soft-switching-based structure for the 30 kW segmented stack, and a reversible Buck (or Step-down) DC–DC converter for the large PEMFC stack operating in potentiodynamic mode.

The plan of the paper is as follows: First in Section 2 an active load for 5–10 kW single fuel cell will be presented; it has been designed and realized within the framework of the SPACT project (in French: "Système Pile à Combustible pour Applications Transport") supported by the French Ministry of Research, and has the characteristic of being representative of electrical drive powertrain constraints. Section 3 will confront the multi-stack design versus the segmentation concept. Sections 4 and 5 will address a multi-port resonant isolated boost (step-up) topology for the 30 kW segmented fuel cell, propose a splitting current control strategy in case of fault, and advanced technology considerations for the design of a 30 kW converter pre-prototype. Finally Section 6 will explore the reversible DC–DC Buck (Step-down) converter for the operation of a large stack (100-cell and multi-kilowatts) in potentiodynamic mode for applying the cyclic voltammetry technique.

2. Active load for fuel cell representative of electrical drive constraints

An electronic active load for a 5 kW PEM fuel cell generator from French Helion Company has been designed, realized and experimentally validated (see Fig. 1). The objective of this active load is to get an experimental tool in order to reproduce in laboratory the constraints of powertrain equipment: mission profile and pulsed current due to the power electronic interface with the load converters [15]. The active load has been tested first using laboratory power equipment and in a second stage on the 5 kW Fuel Cell testing bench in FCLAB in Belfort, France. Moreover, this equipment appears necessary to study the experimental behavior of fuel cell generators considering lifetime, failure indicators and reliability which require long duration tests. Such reliability tests are very difficult to be realized directly on vehicles; hence experimental tests with simulated load appear necessary.

2.1. Active load topology and control

The 5 kW PEM fuel cell stack is composed of 42 cells, the active surface of each cell is 375 cm^2, its voltage varies between 29 V for the nominal current (the current density is 0.5 A/cm^2) and 42 V at no-load.

In order to simulate the electrical constraints, two working modes are considered:

- Static mode: the load current is stabilized and the power can vary until its rated value of 5 kW.
- Dynamic mode: the load current varies according to mission profiles (load current steps or ramps).

Moreover, the active load generates high frequency harmonic current which constitutes the second important constraint criterion. Pulsating current of fuel cells generated by inverter load should have been studied for different converter topologies [16], as well as the hysteresis effects for transient load use [17].

Among the basic electrical converter architectures, a structure Boost-chopper composed of transistor H_p and diode D_p from IXYS Dual Power HiPerFET™ Module VMM 300-03F (300 V/290 A) semiconductor technology appears as the best choice taking into account its simplicity and the need to control the fuel cell current. The Boost-chopper using the MOSFET (Metal Oxide Semiconductor Field Effect Transistor) technology offers a maximum of flexibility

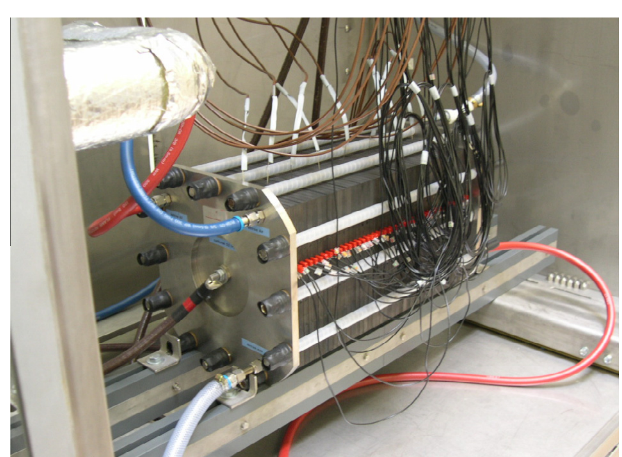

Fig. 1. 5 kW – 42-cell PEM fuel cell (Helion).