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Original articles

Modelling and analysis of an original direct hybridization of fuel cells and ultracapacitors

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Abstract

The feasibility of fuel cell applications has been demonstrated throughout the world illustrating all the potentialities of this technology. Research efforts are currently focused on improving life time and reducing costs. Power variations imply fluidic variations for a fuel cell system. Because of a non-infinite dynamic of the gas supplies, bad local conditions (low gas concentrations, pressure stresses, water accumulation, etc.) can occur within the electrodes degrading more or less their lifetime. This phenomenon is increased in the case of a H_2/air fuel cell because of the relatively slow response time of the air compressor. These conditions are mostly created by the application of severe and frequent load peaks or by the interactions with power converters' current harmonics. To reduce this effect, hybridization with an electrochemical storage component (typically ultracapacitors) is generally suggested via one or two power converters, requiring the implementation of an energy management. Moreover, in most of these architectures, the fuel cell is not protected against the current harmonics generated by its own power converter. Here is proposed a structure called direct hybridization where fuel cells and ultracapacitors are directly associated at the elementary scale, permitting the double protection sought, limiting the interactions with the power electronics and providing a natural energy management (no external control required). Firstly, the authors will establish a large signal model for this original system. Secondly, they will analyse certain properties of this integrated component in terms of dynamic capabilities under current steps through comparisons between simulations with experiments.

Keywords: Fuel cell; Ultracapacitor; Direct hybridization; Large signal modelling; Parameterization

1. Introduction

Fuel cells (FC) are one of the most promising energy sources: they present high efficiencies, high energy density and do not generate locally-polluting waste products. A H_2/air fuel cell system has a relatively-slow dynamic response:

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voltage drops appear after a current step (in [26] due to mass flow controller time response, and in [29] due to air compressor dynamics). This phenomenon is called cathode fuel starvation and is responsible of irreversible degradations [27]. Recommendations given by [29] are to apply current steps with a slope limitation to avoid the impact of the air compressor dynamics (around 1 s time response). A H_2/O_2 fuel cell system do not require an air compressor and its dynamic response is significantly better (typically a few milliseconds to tens of milliseconds depending particularly on the design of the gas channels and the double-layer effect) [30]. However, a common point is that the fuel cell lifetime is reduced by the application of severe and frequent load peaks. Interactions with power converters' current harmonics have been observed (even if this last impact remains to investigate deeper), as membrane resistance degradation suggested in [8], an ageing accelerated by 13% in a 1000 h comparative test between constant current and boost converter current profiles in [23] and additional losses caused by a 100 Hz modulated power demand in [26]. Improvements in converters' architectures, controls and switching elements technology are under process to mitigate harmonics back propagated to the fuel cell as in [13] for isolated DC–AC converters or in [32] for DC–DC converters with high voltage ratio.

A well-known solution to protect a fuel cell against severe load peaks is to associate it with another power source which is able to supply these load peaks, letting the fuel cell supplying the average value of the load, as in [1] for military application, in [5] for a vehicle application or in [10] for an aircraft application. Hybridization of a fuel cell generally consists in providing the high frequency, high amplitude or both peaks by the storage (depending on its energy capacity) allowing the fuel cell to provide a current having less variation [31]. Ultracapacitors (UC) are classically selected if load peaks are low energy: for an aeronautical application, the mass of an emergency system was reduced by 30% in a theoretical study [10] and the experimental validation made by [18]; for vehicle applications and double-hybridization cases (high energy peaks provided by batteries and low energy/high power peaks by UC), a tramway application is presented by [9] and a military application in [17]; also stationary systems find advantages in FC hybridization by UC as shown by [28]. Various architectures exist: with two converters (cascade structure with UC at the centre [12,33], cascade structures with FC at the centre [20] or parallel structures [22]) or with one converter [10]. Many control strategies can be adopted to control the power sharing including, inter alia, direct sharing methods (frequency, slope limitation, band sharing) [10], rule-based methods (fuzzy logic [2], state machine) [25], optimization-based methods (global, real time) [25]. These solutions provide the best power control of the fuel cell (due to high control degree offered by the power converters) but require significant development (converters' sizing, architecture and control strategies) increasing mass, cost and failing risk of the system.

In all the previous cases, both power sources (FC and UC) are connected through power converters. But in these kinds of architectures, the fuel cell is generally not protected against the current harmonics generated by its own power converter with classical DC–DC structures. The direct hybridization of a fuel stack was performed by [15] with batteries (a modelling of this association is given in [3]) and by [14] with UC applied to pulsed load applications. A direct hybridization of a FC stack with an UC pack submitted to a load profile mission (aeronautical application) has been introduced by [11], a sizing method is given in [10] and the experimental validation is made in [18]. This solution permits to satisfy the double protection sought: against load peaks and against current harmonics generated by the fuel cell power converter.

In this paper, the authors are going to evaluate the modelling of a variant of this direct hybridization concept detailed more precisely in [19]. It consists in implementing the concept not at the whole stack scale, but at the scale of each cell of a fuel cell stack to go further in terms of integration (Fig. 1). Here the authors will only consider two elementary patterns in series constituted by two FC monocells with an elementary UC connected in parallel of each one. This first step is necessary before studying such a complex concept in terms of integration with a real FC stack. Firstly, the authors will establish a large signal model for this original system. Secondly, they will illustrate results of simulation with the association of the FC and UC models. The time scale targeted by the modelling is important related to the difficulty of obtaining a relevant model both on very short time horizons and steady state. The simulations will be compared to experiment at various time scales in order to evaluate the proposed modelling.

2. Modelling of the studied direct hybridization

The authors consider two elementary patterns in series, each pattern being constituted by one FC monocell in parallel with an elementary UC. The gas supplying is parallel, and each cell has its own temperature control

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