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Mathematical analysis of hybrid topologies efficiency for PEM fuel cell power systems design

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ABSTRACT

An efficiency mathematical analysis of the commonly used series and parallel hybrid topologies in distributed generation systems (DGS) is presented. The electrical architecture of the DGS consisting of PEM fuel cells, auxiliary storage devices and electrical loads allows regenerative power flow from the load bus. Criteria for a proper choice of the topology for a given load power profile are derived from the analysis and the inclusion of some practical considerations. A novel series-parallel hybrid topology for uncertain load power profiles is also disclosed. The proposed topology is compared with both series and parallel structures in terms of efficiency and number of converters under non-regenerative power conditions. The theoretical predictions of the mathematical analysis are verified by simulation using a Matlab/Simulink model that integrates a physical model of the PEM fuel cell with its control system, an electrical model of a battery with its state-of-charge regulator, and static models of DC/DC converters described in terms of efficiency.

1. Introduction

Fuel cells are an efficient alternative to provide electrical power to distributed generation systems (DGS), residential environments and portable applications. The fuel cell integration in DGS has been extensively analyzed and several works have been performed [1–8]. Similarly, results have been reported on the use of fuel cells in residential environments [9], electric vehicle power supply [10–12], and autonomous and portable applications [13,14].

Fuel cells are electrochemical devices that generate continuously electric energy from chemical reagents as far as fuel and oxidant are supplied [15]. The proton exchange membrane (PEM) fuel cells (FC) are under intense research due to its high power density, small size, low corrosion and high efficiency [16]. The PEM-FC require auxiliary systems to produce electric energy in a safe and efficient way and many manufactures provide autonomous fuel cell systems [17], common examples being the Ballard and Palcan power modules. Fig. 1 shows the auxiliary systems used in the 1.2 kW Nexa power module from Ballard. The Nexa modules are autohumidified and require a pressurized fuel storage. The oxidant (oxygen) is taken from the ambient air, and the fuel (hydrogen) pressure is controlled by a valve to maintain a safe anode–cathode pressure ratio. The hydrogen circuit has a purge valve to remove water particles and inert gases that deteriorate the output power. The system that supplies air to the cathode is constituted by an air pump and a humidity exchanger. A temperature management system controls a cooling fan to regulate the stack temperature at 65 °C. The resulting air flow is also used to evacuate the hydrogen in the purge process.

The most serious limitation of fuel cell applications is caused by their slow power slew-rate, with values between 250 and 300 W/s for the fuel cell described in the block diagram of Fig. 1. This is due to the constraint imposed by the fulfilment of the stoichiometric relation required to produce the demanded current precluding the oxygen starvation phenomenon [16,18,19].

The constraint of the power slew-rate limits the fuel cell bandwidth, and therefore an auxiliary storage device (ASD) is necessary to support high-frequency transients. The resulting electrical architecture is called hybrid, an example of it being depicted in Fig. 1. In this example, the fuel cell is isolated from the battery by using a switching DC/DC converter (DCDCi), which is controlled to limit the power requested to the fuel cell. Considering the energy flow, the battery is in series with the DCDCi converter and also with an additional switching DC/DC converter (DCDCv) controlled to regulate the load voltage. This topology is called *series hybrid* due to the interaction between the fuel cell and the battery.

The most used topologies are the parallel hybrid (PH) and series hybrid (SH) [20]. The parallel hybrid topology shown in the top of Fig. 2 uses a unidirectional DC/DC converter to isolate the fuel cell from the load DC bus, and a bidirectional DC/DC converter that exchanges energy between the ASD and the load. These topologies

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Nomenclature

Abbreviations

FC	fuel cell
ASD	auxiliary storage device
SOC	state-of-charge
PH	parallel hybrid
SH	series hybrid
SPH	series-parallel hybrid

Variables

I_{st}	fuel cell stack current
λ_{O_2}	oxygen excess ratio
$\eta_1,\ \eta_2,\ \eta_3$	switching DC/DC converters efficiency
P_L	load consumption power profile
P_R	load regenerative power profile
P_{fc_pL}	FC power delivered directly to the load (PH topology)
P_{fc_sL}	FC power delivered directly to the load (SH topology)
P_{fc_pB}	FC power delivered to the ASD (PH topology)
P_{fc_sB}	FC power delivered to the ASD (SH topology)
P_{BP}	ASD power delivered directly to the load (PH topology)
P_{BS}	ASD power delivered directly to the load (SH topology)
k_R	regenerative ratio
P_{BO_0}	ASD power profile for equal topologies efficiency
P_{BO_x}	ASD power profile for generic load profile
k_B	relative equalization power factor
k_x	relative ASD power factor
η_P	parallel hybrid topology efficiency
η_S	series hybrid topology efficiency
f_x	efficiency ratio

Physical intervals (interesting ranges)

$\eta_1,\ \eta_2,\ \eta_3,\ \eta_P,\ \eta_S$	$(0,1)$
k_R	$[0,1)$
k_B	$\left[0,\frac{1}{\eta_3}\right]$
k_x	$\left[0,\frac{P_L}{\eta_3 \cdot P_{BO_0}}\right]$
f_x	$[0,\infty)$

Additional subindexes

num	numerical calculation result
sim	numerical simulation result

support power flows from the load to the ASD (*regenerative operation*), and therefore their efficiencies are higher than those obtained in applications where the load is only a passive one-port.

On the other hand, the use of batteries in hybrid architectures is widely accepted due to their advantages in DC bus voltage regulation and overload capability [5,7].

Common criteria used in the selection of hybrid topologies are based on simplicity in the control of DC/DC converters, applications constraints, versatility, etc. However, most of the reported works [5,7,11–14,21,22] have not considered the topology efficiency as the main design criteria. The only exception is the work of Moore et al. [10] for hydrogen fuel cell-based vehicles with a battery as ASD. In Moore's work, the topology efficiency is obtained by simulation but the reported results depend on the particular load profiles considered and therefore cannot be extended to other profiles.

In this paper, a mathematical analysis of the efficiencies of SH and PH topologies is presented. The aim of the analysis is to

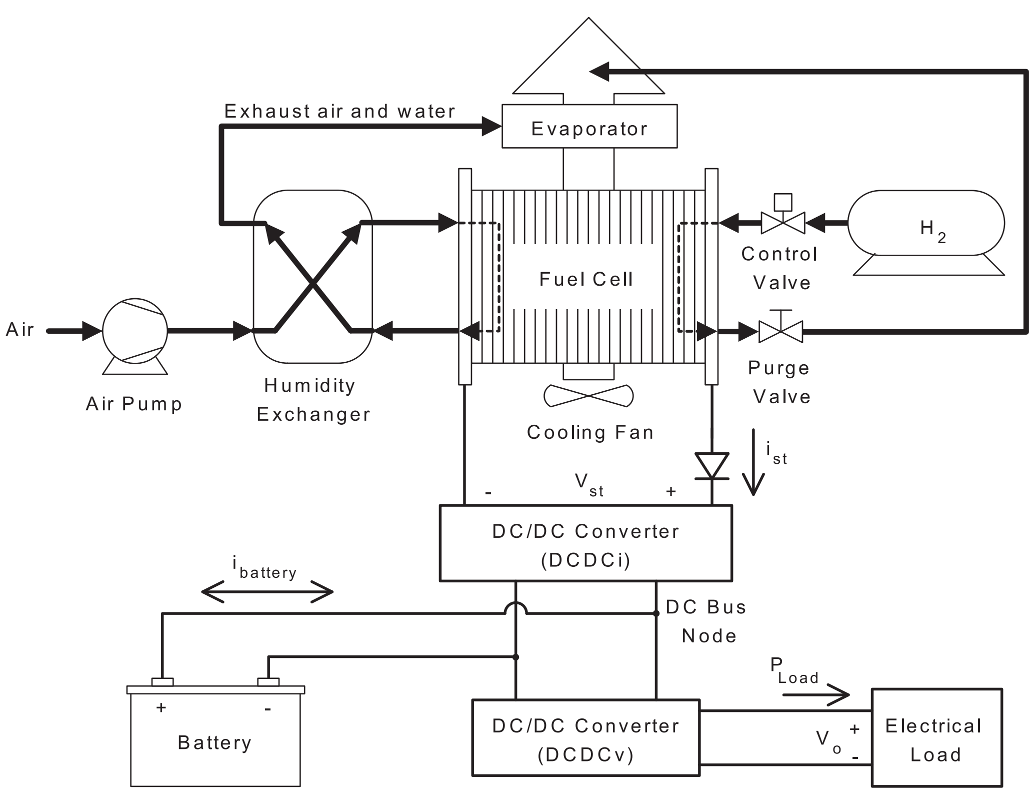

Fig. 1. Series hybrid fuel cell-ASD (auxiliary storage device) topology.