Energy Conversion and Management 127 (2016) 312–323

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A battery-fuel cell hybrid auxiliary power unit for trucks: Analysis of direct and indirect hybrid configurations

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ARTICLE INFO

Article history:
Received 22 June 2016
Received in revised form 29 August 2016
Accepted 6 September 2016

Keywords:
Autothermal reforming
Diesel
PEM fuel cell
Hybridization
Auxiliary power unit
Topology

ABSTRACT

The idling operation of engines in heavy duty vehicles to cover electricity demand during layovers entails significant fuel consumption and corresponding emissions. Indeed, this mode of operation is highly inefficient and a noteworthy contributor to the transportation sector's aggregate carbon dioxide emissions. Here, a potential solution to this wasteful practice is outlined in the form of a hybrid battery-fuel cell system for application as an auxiliary power unit for trucks. Drawing on experimentally-validated fuel cell and battery models, several possible hybrid concepts are evaluated and direct and indirect hybrid configurations analyzed using a representative load profile. The results indicate that a direct hybrid configuration is only applicable if the load demand profile does not deviate strongly from the assumed profile. Operation of an indirect hybrid with a constant fuel cell load yields the greatest hybrid system efficiency, at 29.3%, while battery size could be reduced by 87% if the fuel cell is operated at the highest dynamics. Maximum efficiency in truck applications can be achieved by pre-heating the system prior to operation using exhaust heat from the motor, which increased system efficiency from 25.3% to 28.1%, including start-up. These findings confirm that hybrid systems could offer enormous fuel savings and constitute a sizeable step on the path toward energy-efficient and environmentally-friendly heavy duty vehicles that does not necessitate a fuel switch.

1. Introduction

Fuel cell systems offer capacity for energy savings and emissions reductions if used as auxiliary power units (APUs) for long-haul sleeper trucks. Idling of the motor to generate cabin power yields an electrical efficiency of 4% [1] to 11% [2], whereas commercially available internal combustion engine-based gensets achieve 20% [1]. Fuel cell systems operated on diesel fuel, however, have major potential for this application. Through the application of different fuel cell technologies powered by autothermal diesel reforming, net system efficiencies of between 22% and 34.6% can be achieved [3]. Utilizing this setup, Rechberger et al. demonstrate 30% net electrical efficiency [4]. The use of diesel fuel that is already available on-board for vehicle propulsion means it would be possible to operate both the propulsion and on-board power supply with a single fuel, without the need for idling of the engine to cover the latter. System architectures and detailed system simulations for diesel-based fuel cell systems using high-temperature polymer-electrolyte fuel cells (HT-PEFCs) and polymer-electrolyte fuel cells (PEFCs) based on experimentally validated data are published in Samsun et al. [5].

The present paper discusses the hybridization of a diesel-fueled HT-PEFC system with batteries for APU applications in trucks. The starting point is an integrated 5 kW_{el} HT-PEFC system that can be operated on diesel and jet fuel. This system was developed and tested as a pure fuel cell system [6]. The case for hybridization of the fuel cell system arises on the basis of the following three considerations:

1. The fuel cell system must be capable of start-up using external power, since it cannot produce electricity during the start-up phase.
2. The APU system can respond much better to rapid changes in the power demand of the truck cabin without being restricted by the limited dynamics of the diesel reformer-based fuel cell system.
3. The fuel cell stack can be operated in a limited load window at optimal efficiency. This in turn extends the operational life of the fuel cell stack, avoiding extreme loads.

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http://dx.doi.org/10.1016/j.enconman.2016.09.025

Nomenclature

APU	auxiliary power unit
DC	direct current
HT-PEFC	high-temperature polymer-electrolyte fuel cell
OS	operating strategy
PEFC	polymer-electrolyte fuel cell
SOC	state of charge

Abbreviations

α	charge transfer coefficient
A	area
E	energy
N	number
F	Faraday constant
I	current density
I	current
λ	stoichiometry

m	concentration loss term parameter
p	partial pressure
P	power
Q	charge
r	resistance
R	universal gas constant
T	temperature
u	utilization
z	number of electrons

List of indices

$_c$	cell
$_{el}$	electrical
$_f$	fuel
$_{int}$	internal
$_0$	initial/standard

The hybridization of fuel cell vehicles is analyzed by Pede et al. [7] with the goal of reducing the size of the stack, the extent of power transients during normal operation, and start-up and recovering braking energy. Being highly cycle-dependent, the authors [7] estimate the amount of energy saved by braking energy recovery to be between 3.5% and 20%. In the case of APU applications, this option is not available, since the APU is not operated during drive mode based on the assumed load demand profile explained in the upcoming sections. This has a negative effect on the resulting efficiency. However, peak shaving and cold start advantages are considered to be more effective for reformate-based systems such as that studied in this work.

Despite the large number of publications on the hybridization of fuel cell systems, the majority focus on hydrogen-fueled fuel cell vehicles and renewable energy systems. The work reported here is unique in this respect, since different hybrid architectures are compared with respect to their advantages and disadvantages for a diesel-based fuel cell system for APU applications. Pregelj et al. [8] present a model-based approach to battery selection for a similar APU system.

Many publications have focused on hybrid architectures for fuel cell systems. Hybrid systems are classified as either direct (passive) or indirect (active) hybrids. Wilhelm [9] gives an overview of hybridization concepts for fuel cells and compares a pure fuel cell system with direct and indirect hybrids using a rating matrix. Zhao and Burke [10] compare different topologies for a fuel cell vehicle with a reference system without energy storage. Meanwhile, Bernard et al. [11] refer to indirect hybrids as being the established, preferred topology with less constraints compared to direct hybrids. The direct hybrid, however, features the cheaper, simpler and more efficient topology.

In the case of direct hybrids, the fuel cell is directly connected to a battery, resulting in a simple hybrid topology. However, active power control is not possible. With indirect hybrids, at least one component is connected to a voltage converter. This component can therefore be dimensioned and operated independently. The disadvantage of indirect hybrids is the more complex system topology and reduced efficiency due to losses at the voltage converter.

There are different approaches to eliminating the disadvantages of direct hybrids. In a direct coupling of the fuel cell and battery with the bus, only a switch may be present for connecting or disconnecting the fuel cell and bus [11]. Both units operate at the same voltage as long as the switch is closed. By comparison to a permanent coupling, this configuration underlines the advantage that the open cell voltage of each component need not be equal. The disadvantages of this configuration are, firstly, the highly constrained dimensioning, since the voltage deviations of both components must be the same at the point of operation. Secondly, the output power is less than that in the indirect hybrid, as the fuel cell power is limited by its high voltage drop against the small voltage drop of the battery. In addition, the bus voltage and currents regulate themselves based on the impedance of each unit with the lack of power management. The power split is then dependent on the share of internal resistance, which leads to a small change in the power supplied by the fuel cell and a large change in the battery power for a given share of the power demand. The uncontrolled system variables can exceed their limits and this can lead to system breakdown. In a possible application with low average energy demand, the battery covers energy demand while the fuel cell in turn charges the battery.

The direct coupling of a hydrogen-fueled HT-PEFC with a Li-ion battery pack using switches is examined by Andreasen et al. [12]. The components are connected via two switches per battery branch. On the basis of the experiments conducted, it is concluded that if the stack voltages are properly dimensioned in relation to the voltage of the battery, the direct connection of both components presents a simple and efficient means of extending the range of the vehicle. In their concept, the switch with the resistance is closed first so as to connect the fuel cell and battery. The resistance is necessary in order to limit the switch on currents, but leads to a large voltage drop. Therefore, the second switch without resistance is subsequently closed to maximize system efficiency. The fuel cell voltage is controlled by the battery voltage and state of charge (SOC). In this way, battery charging is passively controlled.

Morin et al. [13] present a novel approach for direct hybridization, implemented at the scale of single cells of a fuel cell stack. Each elementary supercapacitor is connected to either one or two cells. The analysis shows that the coupling of one fuel cell with one supercapacitor is the most advantageous approach to realizing this concept, which was previously patented by Nissan. The system dimensioning analysis by Wu et al. [14] shows that the number of supercapacitors in the series, matched to the maximum open circuit voltage of the stack, enables the maximum buffering effect of the hybrid system. Bernard et al. [15] propose an alternative approach to the conventional direct hybrid topology, in which power sharing is actively controlled by adjusting the operating pressure of the fuel cell. The battery imposes its voltage on the fuel